

Chapter 7

Invasive Species: Implications for Industrial Cooling Water Systems

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1 Introduction

Non-indigenous organisms can get introduced to new areas by human activities, lifting the barriers for dispersal from other biogeographic areas. When these species arrive, they may die if the conditions are not good for survival. However, if the conditions match with their requirements, for example, with respect to habitat and climate, they can survive, establish, and reproduce. Subsequently, when their populations flourish and disperse fast, we speak of species invasion. Such species interact with native species and flourish at the expense of the local native populations. They can affect the new habitat environmentally, ecologically, and economically (Van der Velde et al. 2006).

Invasive species are often characterized by features such as rapid reproduction, fast growth rate, and tolerance to wide range of environmental conditions, reaching high population densities. Invasive species are not a random selection of species (Karatajev et al. 2009). Many invasive species are sessile and have planktonic propagules (larvae, spores, etc.), which enhance their chance to travel long distances, attached to substrata or suspended in water, carried over the ocean or from lake to lake by shipping, fishing, angling, and other human activities. These species are profiting from anthropogenic eutrophication. For example, plants take up the nutrients directly when there is light, while filter-feeding animals take up detritus

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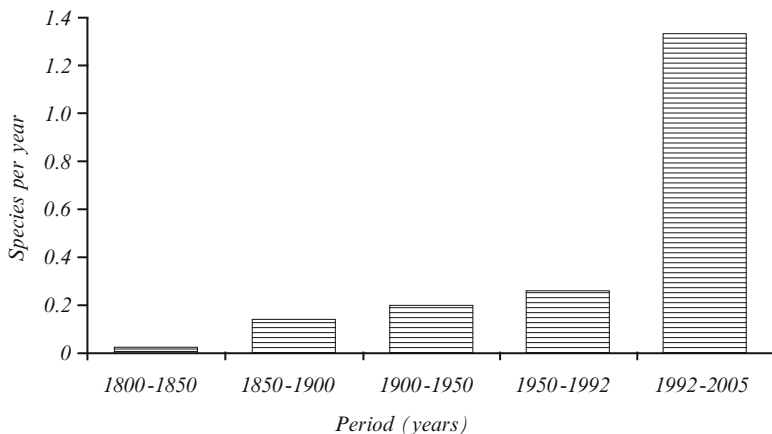


Fig. 7.1 Annual average number of non-indigenous species colonizing the freshwater sections of the river Rhine (modified after Leuven et al. 2009)

and plankton even in the dark. Furthermore, hard substrata are provided by water works, dam construction, riparian protection, etc. so that these species can build up high density populations in human-influenced areas. In industrialized areas also, cooling water is discharged, which makes the survival of subtropical exotic species in temperate areas possible. The consequence of all these developments is that the global biofouling scenario has become more complex with the introduction and establishment of new species (Fig. 7.1), resulting in higher costs for control than before. In this chapter, we shall discuss the key features of some of those prominent non-indigenous species, whose success as invasive species merits close examination. Many of these species are transported by ships, either via ballast water or via ship hulls, as part of the fouling assemblage. Another main cause of their introduction is the shellfish culture industry. Also, canals connecting seas or rivers for shipping purposes contribute to the wide dissemination of these species. In addition to threatening the biodiversity of the locality, some of the introduced species continue to place enormous burden on the economy of the countries affected (Van der Velde et al. 2006, 2010). Biofouling of industrial cooling water systems is but one aspect of their wide-ranging economic impact (Rajagopal et al. 2010a). Many of the recent invasive species are sessile benthic in their habitat and hence are potential biofouling organisms (Fig. 7.2).

Of all biofouling organisms, bivalves (mussels, oysters, and clams) and barnacles in particular are known to have successfully invaded new geographical locations and caused serious fouling problems to industrial cooling water systems. However, there is a wide range of other sessile species which can potentially cause macrofouling problems such as hydroids, tube worms, tube-building amphipods, bryozoans, and ascidians. We treat some important marine, brackish water, and freshwater-invasive sessile bivalves and some other important invasive fouling species, giving emphasis to control aspects. Measures to control the invasive bivalve species will also control the other indigenous biofouling species, depending on their tolerance.

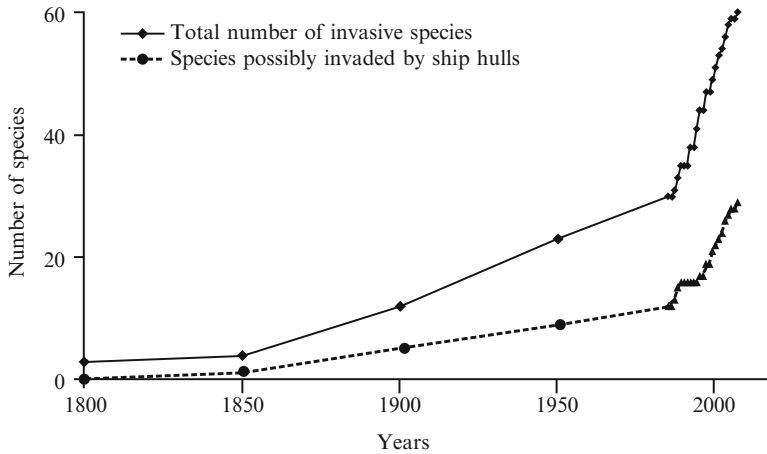


Fig. 7.2 Total number of invasive species and species possibly invaded by ship hulls in river Rhine from 1800 to 2007

2 Bivalvia

Bivalves are molluscs possessing two calcareous valves which protect the soft living body. The two valves can be opened to allow the siphons to pump water in and out, in order to obtain oxygen and food. Food consists of organic suspended matter (detritus, phyto-, and zooplankton) that is sorted into an edible fraction which is transported to the mouth and digested and an inedible fraction which is ejected as pseudofaeces (particles stuck together by mucus) by valve movements. Undigested food (faeces) and pseudofaeces sink to the bottom and contribute to sedimentation and form food for other macroinvertebrates. All bivalves are filter feeders. They have also a foot which can extend out of the valves and by which they can move as long as they are not totally fixed to one place. The byssus gland in the foot produces byssus threads, by which the animals can fix themselves to hard substrata. All fouling bivalve species produce, as juvenile and adult, many byssus threads (e.g. mussels, dreissenids) or only one as juvenile (e.g. Asian clams). The life cycle of bivalves is, in general, with a planktonic phase (fertilized eggs, larvae, trochophora, veliger, pediveliger), a settlement phase (settling pediveliger, plantigrade, spat), a juvenile and an adult phase. In the adult phase the gonads are developed. The bivalves are usually dioecious; there are males and females which spawn by releasing eggs and sperm into the water. But hermaphroditism, self-fertilization, brood care, and protandry can also occur. Larvae can settle in the cooling water circuits and grow fast, as there are hardly any predators, and there is plenty of oxygen and food coming along. During settlement, they show gregarious behaviour, resulting in carpets of bivalves covering the entire available surfaces.

3 Oysters: Ostreidae

Oysters generally constitute a serious biofouling pest in coastal power stations using seawater for condenser cooling purposes. They attach to surfaces by cementing one of the two calcareous valves to the substratum. Therefore, oyster fouling creates more problems than mussel fouling, because unlike in the latter, the shell remains attached to the substratum even after the death of the animal. Moreover, because of their normal distribution in the supra and midlittoral zones, oysters possess a great capacity to tolerate variations in temperature, salinity, and desiccation.

3.1 Pacific Oyster *Crassostrea gigas* (Thunberg 1793)

Crassostrea gigas is a common Pacific marine oyster enjoying wide distribution in the coastal and estuarine environments. It has a rough shell that is highly fluted and laminated. Shells are usually whitish with purple streaks and spots. It is a commercially important species with appreciable quantities being fished and cultured. Since *C. gigas* was introduced for shellfish culture from Japan, it is also known as the Japanese oyster. The Pacific Oyster was introduced from Asia across the globe. It is nowadays distributed throughout Great Britain and Ireland, and widely along the Atlantic coast of continental Europe (Spain, Portugal, France, Belgium, The Netherlands, Germany, Denmark, Sweden, and Norway) (Wrangle et al. 2010). In North America, the Pacific oyster is found from Southeast Alaska to Baja California. It is cultivated primarily on oyster farms in protected coastal estuaries; however, wild beds exist in Washington and British Columbia. The oyster prefers firm surfaces and usually attaches to rocks, debris, or other oyster shells. However, they can also be found on mud or mud-sand bottoms. The shell can reach 23 cm in length in ideal conditions. *C. gigas* is a valuable shellfish resource and is the most widely cultured oyster in the world, having been introduced in countries like United States, France, England, New Zealand, and Australia. It is known to settle into dense aggregations and imperil native intertidal species. *C. gigas* feeds primarily on phytoplankton and protists (CIESM 2000; NIMPIS 2002). It is known to spread through placement of hatchery-produced seed. Its introduction from France to Britain is thought to have been through ships' hulls (Fletcher and Manfredi 1995; Eno et al. 1997).

C. gigas is known for its tendency to colonize areas of coastline many kilometres away from its parent organisms. Spat have been documented spreading up to 1,300 km on ocean currents. Once established, they have the potential to smother other marine life, such as scallops, destroying habitat, and causing eutrophication that affects water quality. This could result in limitations of food and space availability for other intertidal species (NIMPIS 2002). *C. gigas* ingests bacteria, protozoa, a wide variety of diatoms, larval forms of other invertebrate animals, and detritus (PWSRCAC 2004).

They develop first as males, and after a year, start to function as females. Spawning is temperature-dependent and occurs in the summer months. Temperature plays a role in the maturation of the gonads, which sustain during the winter months

at temperatures of 8–11°C (Fabioux et al. 2005). *C. gigas* females can produce between 30 and 40 million eggs per spawning. Fertilization takes place externally. The planktonic larvae develop for 3–4 weeks before attachment. Pacific oysters have high growth rates (75 mm in the first 18 months) and high rates of reproduction. *C. gigas* can live for up to 10 years and reach an average size of 150–200 mm (CIESM 2000). High temperatures combined with a poor food quality during low tide as those reached on clear summer days are an important stressor for oyster spat and it was found that, at a temperature of 32°C, spat of *C. gigas* showed poor growth (Flores-Vergara et al. 2004). Bourles et al. (2009) reported *C. gigas* living in an Atlantic pond at water temperatures ranging from 3 to 30°C.

Carrasco and Barón (2010) analyzed the potential geographic range of *C. gigas* based on surface sea water temperature satellite data (SST) and atmospheric (AT) temperature climate charts with the coast of South America as a study case. They found that in its native range, self-sustaining populations maintain in thermal SST regimes ranging from 14.0 to 28.9°C for the warmest month and –1.9°C for the coldest month of the year. For settlement, these figures are for AT 15–31°C (warmest month) and –23 to 14°C (coldest month).

3.2 European Flat Oyster *Ostrea edulis* (Linnaeus 1758)

Ostrea edulis is native to Europe and the Mediterranean and is usually found in coastland, estuarine habitats, marine habitats, and riparian zones. It is found at the Atlantic coast of Norway, Sweden, Ireland, the U.K., Denmark, the Netherlands, Germany, France, Morocco, the Mediterranean Sea, the Black Sea, France, Italy, Greece, Croatia, Ukraine, Portugal, and Spain (Diaz-Almela et al. 2004; Ruesink et al. 2005; Jonsson et al. 1999; Kennedy and Roberts 1999; Jackson 2003).

The oyster prefers the firm bottoms of mud, rocks, muddy sand, muddy gravel with shells, and hard silt (Jackson 2003). *O. edulis* can be found in muddy areas attached to hard surfaces at depths of 9 m. It has been introduced to the northwestern Atlantic Ocean for aquaculture, before which it had long (for 6,000 years) been harvested for food (Diaz-Almela et al. 2004). As an introduced species, its geographic range includes Japan, Tonga, Fiji, US, Canada, Namibia, Israel, Mauritius, New Zealand, and South Africa (Carlton 1992; Ruesink et al. 2005; Ray 2005). *O. edulis* can grow up to 20 cm or more and live up to 20 years. It has a rough scaly shell, the two halves of which are different in shape; the left shell is concave and attached to the substratum and the right is flat and acts as a lid. The inner surface of *O. edulis* is smooth and white or bluish-grey and shiny with some dark blue spots. The narrow ends of the shell have stretch ligaments which hold the shells together.

As in the case of other oysters, *O. edulis* feeds mostly on phytoplankton. Autotrophic flagellates and diatoms are also important food for *O. edulis* (Jonsson et al. 1999). It is a protandric hermaphrodite that changes sexes twice during one season. They are males early in the spawning season and become females later and vice versa. Jonsson et al. (1999) have reported that completion of larval

development depends upon the proper intake of omega-3 polyunsaturated fatty acids. *O. edulis* start their lives as males and mature sexually as males between 8 and 10 months. After this period, they change sex regularly. Temperature can affect the sex of *O. edulis*; if the temperature reaches 16°C, *O. edulis* becomes a female every 3–4 years. Cooler water temperatures force the oysters to revert back to males. During reproduction, female gametes are released into the pallial cavity where they are fertilized by externally released sperm. Females produce between 500,000 and 1,000,000 fertilized eggs per spawning period. The eggs are incubated for about 8–10 days (depending on temperature) and released into the water. In their native range, *O. edulis* spawns between late June and mid-September. Young oyster spat can be seen from late summer in Strangford Lough, Northern Ireland (Kennedy and Roberts 1999). In the Adriatic Sea, the larvae are present from May till September, with a peak in July (Bratos et al. 2002). Gonadal maturation occurs during season of high suspended matter, followed by single spawning period (Ruiz et al. 1992).

Depending on temperature tolerance, *O. edulis* exists as a number of physiological races. In Spain, one low temperature race occurs which requires 12–13°C for spawning. A temperature of 25°C is required in the Norwegian fjords for spawning, and in France, *O. edulis* spawns between 14 and 16°C. In Canada, spawning was recorded at 18°C (Burke et al. 2008). After hatching, the larvae spend 8–10 days in a pelagic state before settlement. In this pelagic state, *O. edulis* goes through two metamorphoses. After the first metamorphosis, the trochophore transforms into a veliger with two ciliated wing-like protrusions. A second metamorphosis changes the veliger into a bivalve small oyster that uses its byssus threads to cling to suitable substrata. Prior to attachment, *O. edulis* explores the substrate with its foot protruded in the front, which functions as a tactile sense organ. Metamorphosis can be delayed if a suitable attachment site is not available (Cole 1938).

Healthy larval growth and survival rates occur at salinities as low as 20‰ and some can even survive at 15‰ salinity. Burke et al. (2008) recorded salinities between 18 and 30‰ for spat and recorded more than 225,000 larvae per m³ water and 22,000 individuals per spat collector. Feeding rate (measured as faecal matter production) decreased at 18‰ and ceased at 16‰. Spat exposed to such a low salinity did not regain their vitality again (Rodstrom and Jonsson 2000). Very low salinities combined with high temperatures caused the highest mortality (Rodstrom and Jonsson 2000) as also was demonstrated by Hutchinson and Hawkins (1992) at the combination 19‰ and 25°C. Further information about salinity–temperature responses can be found in Fisher et al. (1987) and Robert et al. (1988).

3.3 Pearl Oysters-Pteriidae

These oysters are known for their ability to produce pearls. This family consists of the genera *Pteria* and *Pinctada*. In these species, both the valves are similar and winged.

3.3.1 Pearl Oyster *Pinctada radiata* (Leach 1814)

Pinctada radiata, originating from the Indo-Pacific, is one of the important invasive marine bivalve species, successfully adapted to subtropical environment. The invasion of *P. radiata* has been reported from different areas of the Mediterranean and other subtropical and tropical parts of the world. The invasion of *P. radiata* has probably occurred both via the Suez Canal and intentional introduction for pearl oyster fishery. As a fouling species, it attaches by byssus to hard substrata and is found from very shallow to the mid-water depths. It can reach a shell length of 100 mm (Tlig-Zouari et al. 2009).

It occurs in a wide temperature range of 13–30°C, from the littoral zone on hard bottoms down till a depth of 150 m. It is a protandric hermaphrodite species with a sex inversion at a shell size of 32–57 cm. Males can be found as small as 23-mm shell length (Derbali et al. 2009).

Gonad maturity is controlled by water temperature and is nearly year-round in the Mediterranean with spawning mainly in summer and early autumn. Pelagic larvae are dispersed by water currents (Galil 2006). In Bahrain waters, spat settlement took over a long period (July to November). The most intense spat settlement was recorded throughout August, indicating that spawning started at the end of July. Most settlement can be found on dead oyster shells, at a depth of 0.5–1.5 m. Growth after settlement (July–August) was 0.204–0.248 mm day⁻¹ till December-January, in which period growth was slowed down by a drop in water temperature from 27–33 to 17–18°C (Al-Sayed et al. 1997a). In Bahrain, the shells can grow to 80 mm and they become especially large at salinities of 40–42‰. They become smaller at higher salinities of 50–60‰ (Al-Sayed et al. 1997b).

Qatari waters are rich in pearl oyster beds. Three pearl oyster species, viz. *P. radiata*, *Pinctada margaritifera*, and *Pteria marmorata*, were reported from Qatari waters. However, *P. radiata* is the most dominant species, representing about 95% of the total oyster catch (Mohammed and Yassien 2003). Though the biology and physiology of the pearl oyster *P. margaritifera* are well documented in the literature, there is lack of information on *P. radiata* (Mohammed and Yassien 2003).

Based on their recruitment pattern, Mohammed and Yassien (2003) suggested that *P. radiata* was a semi-continuous breeder in Qatari waters. However, different breeding seasons of this species are reported from nearby areas. Al-Sayed et al. (1993) have recorded continuous spawning from Bahrain waters, with peaks in hot summer. The spawning season of *P. radiata* in Kuwait was restricted between May and September (Al-Matar et al. 1993).

4 Mussels: Mytilidae

Mussels are mostly marine bivalves with valves equal in size and shaped in an elongated oval-triangular form. The shell is not thick, but has a thick periostracum. The shell lacks a prism layer. The anterior muscle is small. All mussels are biofoulers and important fouling genera are *Mytilus*, *Modiolus*, *Brachidontes*, *Septifer*, *Perna*, and *Limnoperna*.

4.1 *Mediterranean Mussel Mytilus galloprovincialis* (Lamarck 1819)

Mytilus galloprovincialis is a marine species which has succeeded in establishing itself at widely distributed locations around the globe, with nearly all introductions occurring in temperate regions and at localities where there are large shipping ports (Branch and Steffani 2004). Ship hull fouling and transport via ballast water have been implicated in its spread and its impact on native communities and native mussels has been highlighted in a number of studies (Carlton 1992; Robinson and Griffiths 2002; Geller 1999).

The mussel is dark blue or brown to almost black. The two shells are equal and nearly quadrangular. The outside is black-violet coloured; on one side the rim of the shell ends with a pointed and slightly bent umbo, while the other side is rounded, although shell shape varies by region. It also tends to grow larger than its relatives, up to 15 cm, although typically only 5–8 cm. In its native range, *M. galloprovincialis* can be found on exposed rocky outer coasts and sandy bottoms (Ceccherelli and Rossi 1984). As an invader, it typically requires rocky coastlines with a high rate of water flow. In fact, unlike the other 26 Asian and Atlantic molluscs introduced into Pacific regions, only *M. galloprovincialis* occurs in open coast such as high energy environments of the Pacific coast; all remaining species are restricted to bays and estuaries (Carlton 1992). It is known that *M. galloprovincialis* is capable of out-competing and displacing native mussels to become the dominant mussel species in many localities.

The native range of this mussel includes Mediterranean Sea, Black Sea, and adjacent part of the European Atlantic coast. Due to taxonomical problems, it is unclear whether it is occurring in the outer coasts of France, Britain, and Ireland as *Mytilus edulis* can have broad-shelled individuals too which means that identification is only possible based on a combination of characters and molecular data (Groenenberg et al. 2011). The introduced range includes Southern Africa, east and west North America, Hawaii, and north-eastern Asia (Branch and Steffani 2004). Shipping is believed to be the most probable original mode of introduction of *M. galloprovincialis* to South Africa (Grant et al. 1984, in Branch and Steffani 2004) and to Mexico (Carlton 1992). Late twentieth century distribution of *M. galloprovincialis* was probably enhanced by ballast water transport as well as ship fouling (Carlton 1992). Schneider (2007, 2008) demonstrated that *M. galloprovincialis* was more warmwater-adapted than its relative *Mytilus trossulus* and suggested that *M. galloprovincialis* would be more common due to global warming. Mussels at air exposure kept at 20°C lost their intra-valve water within approximately 60 h and became dead within 4 days, while mussels kept at 5°C survived (Angelidis 2007). In South Africa, where *M. galloprovincialis* invaded, *Perna perna* is an indigenous species. Attachment strength of *P. perna* is higher than that of *M. galloprovincialis*. *M. galloprovincialis* showed higher gamete production than *P. perna* and can more effectively colonize free space (Zardi et al. 2007).

As a filter-feeder, it feeds on a wide range of planktotrophic organisms. Filtration rates at 20 and 26°C are not different. Filtration at high phytoplankton concentration remained low for a standard individual of 1 g dry weight (0.2–0.4 L h⁻¹), but with lower phytoplankton concentrations 0.5–2.5 L h⁻¹ was measured (Denis et al. 1999). This species prefers fast moving water that is free of sediment and thrives in regions where upwelling brings in nutrient-rich water.

Reproduction involves simultaneous spawning of males and females. *M. galloprovincialis* has high fecundity and spawns at the time of the year when the water temperature is the highest (Bayne 1976). The larvae develop into juveniles, which settle and attach using byssus threads in 2–4 weeks (Matson 2000). Spawning is temperature-related and occurs in spring and summer, leading to post-larvae in late summer and early autumn in the plankton of intertidal zone of exposed rocky shores or near mussel culture rafts. Low numbers or absence of post-larvae in plankton samples near the surface away from the shore indicate that planktonic dispersion at larger distances is considered unlikely (Caceras-Martinez and Figueras 1998a). Gametogenesis in NW Spain takes place in spring and early winter. Several spawns may occur until early summer (Caceras-Martinez and Figueras 1998b). Settlement in the Dardanelles was high at 0.5 and 4 m, and low at greater depths until 12 m. Pediveligers can be found in the Dardanelles throughout the year (Yildiz and Berber 2010). Karayucel et al. (2002) found no difference in spat settlement between 3- and 7-m depth in the Southern Black Sea.

4.2 Golden Mussel *Limnoperna fortunei* (Dunker 1857)

Limnoperna fortunei is an epifaunal freshwater mytilid, native to Chinese and south-eastern Asian rivers, creeks, and estuaries. It occurs in temperate and subtropical areas. It became established in Hong Kong in 1965, and in Korea, Japan, and Taiwan in the 1990s. In 1991, it invaded the Plata Basin in South America, from where it invaded large areas over the continent. The introduction into South America was unintentional through the ballast water of ocean-going vessels. Attachment to vessels is the most important dispersion mechanism within South America (Boltovskoy et al. 2006).

L. fortunei is known to cause great economic damage to water intakes and cooling systems of facilities. In South America, it has similar impact as the zebra mussel during invasions (Karatayev et al. 2007). The filtration rate is one the highest ever measured for bivalves including *Dreissena polymorpha*, *Dreissena rostriformis bugensis*, and *Corbicula fluminea*. Sylvester et al. (2005) recorded 125–350 mL ind⁻¹ h⁻¹. Pestana et al. (2009) recorded a filtration rate of 724 mL ind⁻¹ h⁻¹ for *L. fortunei*. Just as in the zebra mussel, very high densities (hundreds of thousands per square metre) can be reached (Sylvester et al. 2005). Portella et al. (2009) recorded settlement up to 149,000 individuals per square metre at a Brazilian Power Plant reservoir at a depth of 0.5–1 m. The species was mixed up with the invasive hydroid *Cordylophora caspia*. *L. fortunei* can reach a shell length of 36 mm (Belz et al. 2010).

In South American water bodies, the reproductive output is reduced in winter time, while in summer a dip is found related to cyanobacterial blooms. There is a long period of larval occurrence, varying from 6 to 10 months per year (Boltovskoy et al. 2009a). The fastest development of larvae occurs at a water temperature of 28°C (Caltaldo et al. 2005). In South America, they occur mostly settled on the water hyacinth (*Eichhornia crassipes*). They feed selectively on phytoplankton and zooplankton, in particular cladocerans, rotifers, and euglenophytes (Molina et al. 2010).

L. fortunei can tolerate (90% survival) salinity shock up to 2‰ for a period of at least 10 days. High-salinity fluctuations are not tolerated for very long (Angonesi et al. 2008). *L. fortunei* has a broader environmental tolerance than *D. polymorpha* and can occur in regions dominated by acidic, soft (low calcium), high temperature, and contaminated water with low oxygen (Cataldo et al. 2003; Boltovskoy et al. 2006; Karatayev et al. 2007). Desiccation for 6 days is tolerated and cannot be a very effective control method (Montalto and de Drago 2003; Darrigran et al. 2004). The mussel has the potential to invade continents other than South America with stronger impacts than the zebra mussel (Boltovskoy et al. 2009b).

4.3 Brown Mussel *Perna perna* (Linnaeus 1758)

P. perna is native to the tropics and the subtropics and is widely distributed in Africa, Europe, and South America (Segnini de Bravo et al. 1998; Rajagopal 1997). It is a smooth-shelled, elongate low-shelled bivalve occurring in estuarine and marine habitats. The mussel is recognized by its brown colour (hence the name brown mussel). Its best identifying characteristic is an internal divided posterior retractor muscle scar. The shell of *P. perna* is thin around the edges and thickens posteriorly. The mussel reaches a maximum size of 90 mm in intertidal zones and a maximum size of 120 mm is reached in sublittoral zones. Maximum shell size is influenced by vertical distribution (Gulf States Marine Fisheries Commission 2003).

P. perna has invaded North America, around the Gulf of Mexico (Rajagopal et al. 2006a). It is thought to have been introduced by ballast-water releases from ships of Venezuela (Hicks and Tunnell 1995). In the Gulf of Mexico, the mussel was probably dispersed southward by long range and inshore currents (Gulf States Marine Fisheries Commission 2003). It is quickly becoming a nuisance in cooling water systems of power stations and other industries that use seawater. In the Gulf of Mexico, *P. perna* has been found colonizing jetties, navigation buoys, oil platforms, wrecks, and other artificial hard substrata, as well as natural rocky shores (Hicks and Tunnell 1995). According to Hicks and McMahon (2002), the long-term, incipient lower and upper thermal limits of this species are 7.5 and 30°C, respectively, similar to the seasonal ambient water temperature range of 10–30°C reported for other populations worldwide. Its narrow incipient thermal limits, limited capacity for temperature acclimation, and poor freeze resistance may account for its restriction to subtidal and lower eulittoral zones of cooler subtropical rocky shores. Salomão et al. (1980) reported that the salinity tolerance range of adult is 19–44‰.

Hicks et al. (2000) recorded even a wider salinity tolerance range of 15–50%. *P. perna* shows physiological compensation to salinity increases but not to salinity decreases, in contrast to *Perna viridis*, which can compensate for both changes in salinity (De Bravo 2003). In its native range, *P. perna* is an integral component of rocky shore ecosystems, where dense populations provide a complex three-dimensional matrix, which is home to a wide range of organisms such as limpets, polychaetes, barnacles, snails, and algae (Brereton-Stiles 2005).

In *P. perna* the sexes are separate and can be distinguished during breeding season by the mantle colour (Lasiak 1986). Gonad production in Venezuela correlated with chlorophyll a increase and temperature decrease. Somatic tissue increase correlated with increasing amounts of organic material, seston, and chlorophyll-a (Acosta and Prieto 2008). The mussels spawn through external fertilization by releasing eggs and sperm into the water. Spawning is thought to be triggered by a 3–4°C drop in temperature, brought about by coastal upwellings during the winter months (Carvajal 1969). Veliger larvae are formed after fertilization. The critical period for development is during and after metamorphosis. Metamorphosis of the brown mussel larvae is marked by the secretion of byssal threads 10–12 days post-fertilization. The survival of the larvae depends mainly upon settling on a stable, hard substratum, usually a rock, at the initial phase of metamorphosis in optimal temperatures between 10 and 30°C and salinity of 30.9–32.1%. Optimum temperature and salinities delay the completion of this initial stage allowing a greater amount of time for the larvae to settle on a substratum. The larvae settle in dense aggregations on rocky shores (Gulf States Marine Fisheries Commission 2003). In Venezuela, *P. perna* grew faster than *P. viridis* and showed higher survival due to coastal upwelling. Lower temperatures and higher plankton levels caused better gonad development. Moreover, under these conditions, its reproductive activity started earlier than that of *P. viridis* (Acosta et al. 2009).

4.4 Green Mussel *Perna viridis* (Linnaeus 1758)

P. viridis is a marine bivalve mussel native to the Asia-Pacific region, where it is widely distributed. The east–west distribution ranges from the Persian Gulf to the Indonesian coast west of New Guinea and some of the Pacific islands, where *P. viridis* has been experimentally introduced (Vakily 1989). It is a fairly large mussel, 80–100 mm in length, occasionally reaching 165 mm (Rajagopal et al. 2006a). The shell has a smooth exterior surface characterized by concentric growth lines and slightly concave ventral margin. The shell is covered with greenish (variable in older mussels) periostracum; periostracum is generally intact in young ones and with patches peeled off in older ones. The colour of the periostracum is bright green in juveniles, fading to brown with green edges as it matures. The inner shell surface is smooth and iridescent with a bluish green hue. The ridge which supports the ligament connecting the two shell valves is finely pitted. The beak has interlocking teeth: one in the right valve and two in the left. Wavy posterior end of the pallial line

and the large kidney-shaped retractor muscle scar are characteristic features. Anterior adductor muscle is absent in this species (Rajagopal et al. 2006a).

P. viridis generally inhabits the intertidal and subtidal zones and is primarily found in estuarine habitats where the salinities range from 18 to 38‰ and temperature from 11 to 32°C (Rajagopal et al. 1998a, b). It has a broader salinity and temperature tolerance than *P. perna* (Segnini De Bravo et al. 1998). Gonad maturation was reported to start in spring, when water temperatures increase to 8–10°C and spawning occurs at temperatures higher than 18°C. Gonad maturation coincides with particulate organic matter peaks (Duterte et al. 2009). At temperatures of 33 and 35°C, total mortality of larvae occurs after 24 h. At 24°C, larvae take longer to settle than at temperatures of 27, 29, and 31°C. Optimum larval development, growth, and survival occur at 31°C and for settlement at 29°C (Nair and Appukuttan 2003). The mussel attaches to hard substrata using byssus threads and is capable of relocating. Dense colonies (up to 35,000 mussels per m²) can develop in optimal temperature and salinity conditions, sometimes with thousands of individuals per square metre. The mussel is an efficient filter/suspension feeder, feeding on small zooplankton, phytoplankton, and other suspended fine organic material.

P. viridis has been introduced around the world through ship ballast, hull fouling, and experimental introduction for farming. The introduction of the mussel from the Indo-Pacific into the Gulf of Mexico has been attributed to fouling on boat hulls or ballast-water traffic (Chapman et al. 2003). It can quickly form dense colonies in a range of environmental conditions. Impacts include causing blockage in intake pipes of industrial plants, clogging crab traps and clam culture bags, and impeding commercial harvest. *P. viridis* can also out-compete many other fouling species, causing changes in community structure and trophic relationships. *P. viridis* is also capable of accumulating high levels of toxins and heavy metals and is linked to shellfish poisoning in humans. It is one of the most troublesome fouling species in many coastal power stations located in the tropics (Rajagopal et al. 2006a). Temperature permitting, the mussel can be expected to expand in Atlantic habitats because of its dispersed spawning nature, lack of local predators, fast growth, and high tolerance of environmental conditions.

Sexes in this species are separate and fertilization is external. Sexual maturity typically occurs at 15–30 mm shell length (corresponding to 2–3 months age). Spawning generally occurs twice a year between early spring and late autumn; however, in the Philippines and Thailand spawning occurs throughout the year (NIMPIS 2002). Year-round spawning with seasonal peaks has been observed in India also (Rajagopal 1991, 1997). Fertilized eggs develop into veliger larvae. Larvae remain in the water column for 2–3 weeks, after which they settle and attach onto hard substrate using byssus (Yap et al. 2003). During the planktonic period of *P. viridis*, larvae will be widely dispersed by physical processes, but may aggregate periodically at certain depths through a variety of biological processes, most notably diel vertical migration (Folt and Burns 1999; Hayes et al. 2005). The mussel settles in large congregations and adult populations may reach densities of 35,000 individuals per square metre (Ingrao et al. 2001). The life span of *P. viridis* is typically 2–3 years. Growth rates are influenced by environmental factors such as temperature,

food availability, and water movement (Rajagopal et al. 1998a). First year growth rates vary between locations and range from 49.7 mm year⁻¹ in Hong Kong to 120 mm year⁻¹ in India (Rajagopal et al. 1991).

Large populations of *P. viridis* can clog cooling water pipes and accumulate on pilings, buoys, and other man-made structures. In the same manner, the mussels may clog crab traps, clam culture bags, and other mariculture equipment, altering maintenance routines, harvest times, and may restrict water flow thus affecting product quality. Ecological damage stems from the fact that they out-compete many other species, causing changes in community structure and trophic relationships.

5 Zebra Mussel Family: Dreissenidae

This family consists of relatively small bivalves which, in spite of their name, are not closely related to the true mussels (Mytilidae) or oysters, but to heterodonts such as *Corbicula*. Their impact is similar and they can be considered the fresh or brackish water equivalents of the marine mussels. They form, just as the true mussels, dense covers with layers of up to 20 cm thick and maximum densities of hundred thousands per square metre. They have high filtering capacity. The life cycle stages are given by Conn et al. (1993). The important genera with respect to biofouling are *Dreissena* (species originating from European Ponto-Caspian area) and *Mytilopsis* (originating from America).

Adult dreissenids attach to natural hard substrata and to man-made structures made of concrete, metal, steel, nylon, fibreglass, or wood. Attachment is by a holdfast of proteinaceous byssal threads produced from a gland just posterior to the foot. Individual mussels attach using byssus to the shells of other mussels, forming encrusting mats many shells thick (10–30 cm). When such thick encrustations of mussels form on man-made structures or within raw water systems, they can affect the operation considerably. Dreissenid species can have major detrimental impacts on recreational boating and commercial shipping as well as on raw water-using industries, potable water treatment plants, and electric power stations (Ussery and McMahon 1995).

Being filter feeders, they compete with planktivorous zooplankton for food and can potentially affect natural food webs. Apart from that, they can also cause sedimentation of suspended organic matter in the form of faeces and pseudofaeces, shifting energy and nutrient balances from the pelagic to the benthic zone. The ensuing enhancement of water clarity favours increased photosynthesis by rooted aquatic macrophytes and benthic algae and negatively affects pelagic fish species that prefer slightly turbid conditions and become devoid of food by the filtering activity of the zebra mussels. Zebra mussels settle in high numbers with many byssus threads on native clams (Unionidacea), causing suffocation, starvation, and energetic stress, leading to death. Loss of native mussel populations has increased dramatically where zebra mussels are present, particularly in the Great Lakes and Hudson and Mississippi rivers. Dense colonization of hard substrata is beneficial to benthic invertebrates, as habitat complexity increases, so does availability of organic matter.

Dreissenid mussels are strong filter feeders. Each adult mussel is capable of filtering one or more litres of water each day, where they remove phytoplankton, zooplankton, algae, and even their own veligers (Snyder et al. 1997). Any undesirable particulate matter is bound with mucus and ejected as pseudofaeces (Richerson 2002). They cause changes in the structural characteristics of zooplankton like total abundance, biomass, and species composition. The general trend is a decrease in these characteristics in areas that support massive populations of *Dreissena*. There is an inverse relationship between zooplankton abundance and biomass and density of *Dreissena* mussels, which results from the predation pressure on zooplankton exerted by the mussel (Grigorovich and Shevtsova 1995). Dreissenid mussels (*D. polymorpha* and *D. rostriformis bugensis*) have caused impacts on unionid populations, when introduced in the Great Lakes and Rivers that flow from them. *Dreissena* infestations have caused upwards of 95% reduction in unionid numbers and extirpated eight species of unionids in some areas (Schloesser et al. 1998; Schloesser and Masteller 1999).

5.1 Zebra Mussel *Dreissena polymorpha* (Pallas 1771)

Zebra mussels have been nominated as among 100 of the “World’s Worst” invaders. They are native to the rivers and lakes in the Caspian and Black Sea areas, but are now established in the USA, Canada, Eastern, Western, and Southern Europe including UK, Ireland, Spain, and Italy. These mussels, with a maximum size of about 3 cm, attach to surfaces using many byssus threads. Growth of mussels starts at 3–6°C. The upper temperature limit appears to be 32–34°C, while salinity range is 0.007% (minimum) to 12% (maximum) in the Aral Sea. Normally they can tolerate salinity up to 6% and temperatures up to 29°C; however, they do not settle when currents are faster than 2 m s⁻¹. They have been known to interfere with the ecological functions of native molluscs and are responsible for considerable economic losses (Van der Velde et al. 2010 and literature therein).

Zebra mussels filter organic and inorganic particles between 7 and 400 µm, but they preferentially select algae and zooplankton between 15 and 40 µm. Larval stages feed on bacteria. The larvae may be transported during fish stocking. Juveniles and adults attach to anchors, outboard engine propellers, and boat hulls and are transported from one place to another. It has been reported that range expansion of this species within North America and Europe was very rapid due to downstream transport of planktonic larvae in rivers.

Zebra mussels are dioecious and fertilize externally. They spawn in relatively shallow water at a minimum temperature of 12°C; in deeper water they have no clear spawning period. The larvae are planktonic for several weeks before settling and attaching to substrata. It is estimated that a female produces up to 1.5 million eggs per year, though survival to adult stage may be less than 1%. Fertilized eggs hatch into trochophore larvae (40–60 µm). After spending several days (8–180 days or more, depending on water temperature) as free-swimming developing larvae, they settle as plantigrade mussels and attach to substrata as juveniles. Under optimal

conditions, they mature within the first year of life, though maturity in the second year is more common. Zebra mussels have a life span of 3–5 years.

5.2 *Quagga Mussel Dreissena rostriformis bugensis* (Andrusov 1897)

The Quagga mussel is native to two rivers in the Ukraine. Its release into Great Lakes waters is linked to discharge of ship ballast water (Mills et al. 1999). It extended its area also in Eastern Europe. Recently, it invaded Western Europe through the Netherlands, from where it spreaded very fast over large areas (Van der Velde et al. 2010 and literature therein). *D. rostriformis bugensis* is morphologically very similar to *D. polymorpha*, but they can be distinguished based on their shell morphology. Since its introduction, it has begun to replace *D. polymorpha* as the most dominant invasive *Dreissena* and is able to colonize at much deeper depths. *D. rostriformis bugensis* has begun impacting zooplankton abundance, biomass, and species composition, causing decreases in native diversity. They affect recreational boating and commercial shipping as well as raw water-using industries, potable water treatment plants, and electric power stations.

D. rostriformis bugensis typically occurs in fresh water but can thrive in salinities up to 1‰ and can reproduce in salinities below 2–3‰. Salinities exceeding 6‰ will cause mortality (Ussery and McMahon 1995; Wright et al. 1996). A study conducted by Ricciardi et al. (1995) revealed that, given temperate summer conditions, adult *D. rostriformis bugensis* may survive overland transport (e.g. on small trailered boats) to any location within 3–5 days drive of infested water bodies.

In both North America and in Europe, *D. rostriformis bugensis* is slowly dominating *D. polymorpha* populations. Some industries even built their intake structures and piping at depths too low for *D. polymorpha* colonization; however, when *D. rostriformis bugensis* were discovered at lesser water depths, these new structures became vulnerable to colonization (Mills et al. 1999; Richerson and Maynard 2004).

D. rostriformis bugensis is a prolific breeder. This species is dioecious and exhibits external fertilization. A fully mature female mussel is capable of producing up to one million eggs per season. Spawning starts at a minimum temperature of 8°C. After fertilization, pelagic larvae, or veligers, develop within a few days and these veligers soon acquire minute bivalve shells. Free-swimming veligers drift with the currents for 3–4 weeks, feeding by their hair-like cilia while trying to locate suitable substrata to settle. Mortality in this transitional stage from planktonic veliger to settled juveniles may exceed 99% (Richerson 2002).

5.3 *Dark False Mussel Mytilopsis leucophaeata* (Conrad 1831)

Mytilopsis leucophaeata is a highly euryhaline species which means that it is capable of living in a wide range of salinities and occurs in brackish waters (Rajagopal et al. 2002a). It is native to the Gulf of Mexico and a part of Atlantic coast of the US

and was introduced to Europe and North America (Therriault et al. 2004). Local dispersal could involve fouling on boats or transport in live wells or bilge systems. *M. leucophaeata* can attach to man-made and natural structures and is a major fouling species in industrial cooling water systems. The three dreissenid species that are spreading most rapidly and belonging to the family Dreissenidae, false dark mussel *M. leucophaeata*, the zebra mussel *D. polymorpha*, and the quagga mussel *D. rostriformis (bugensis)*, are difficult to distinguish. As of now, there is no simple, reliable method for morphologically separating veligers or immature states of these mussels. Rajagopal et al. (2002a) and Verween et al. (2010) describe *M. leucophaeata* as a biofouling and nuisance organism, causing problems in industrial cooling water systems. Cooling water conduits of a power station provide an ideal habitat for *M. leucophaeata*. Given these conditions, settlement occurs readily and growth can be rapid until it begins to interfere with the operational systems. Bergstrom (2004) reports that *M. leucophaeata* also causes severe fouling on cages, boats, ropes, etc. and that the species competes with barnacles and other filter feeders.

The salinity range at which *M. leucophaeata* is recorded is 0.2–26.4%. *M. leucophaeata* does not tolerate salinities higher than 31%. The temperature range at which *M. leucophaeata* has been recorded is 7–30°C (Van der Velde et al. 2010, and literature therein).

M. leucophaeata are dioecious with external fertilization. Verween et al. (2010) have monitored that in European waters, *M. leucophaeata* has yearly spawning period of 4 months with spawning peaks within that period. Spawning starts at a minimum temperature of 12°C, but in other areas higher minimum temperatures are recorded (Van der Velde et al. 2010 and literature therein). Larval stages show wide temperature (between 10 and 30°C) as well as salinity (between 0 and 25%) tolerances with mortality. Maximal survival of 4-h-old embryos was found at 22°C at salinity 15% (Verween et al. 2007). *M. leucophaeata* has a life span of 5 years and can grow up to a shell length of 27 mm (Van der Velde et al. 2010 and literature therein).

5.4 *Black-Striped Mussel, Mytilopsis sallei (Recluz 1849)*

Mytilopsis sallei is found in intertidal and shallow waters, for example, coastal lagoons, usually not any deeper than a few metres. *M. sallei* occurs naturally in the West Indies, along the Caribbean coast of Central and South America from Yucatan to Venezuela, and in southern peninsular Florida, USA (Bax et al. 2002).

M. sallei is a small, fingernail-sized mussel, with shell lengths ranging 8–25 mm, with a maximum width of 9.68 mm and a maximum height of 12.58 mm. It shows variation in shell coloration, from black through to a light colour, with some small individuals having a light and dark zig-zag pattern. The right valve overlaps the left valve and is slightly larger. *M. sallei* has wide temperature (up to 35°C), salinity (fresh water up to 35‰), and oxygen tolerances. *M. sallei* has high fecundity, rapid growth, and fast maturity rate. Raju et al. (1975) recorded 50% as upper salinity for

M. sallei. During their lifespan, individuals change sex, with a proportion of mussels in any population present as hermaphrodites. Eggs and sperm are released into the water column, where external fertilization takes place. Tens of thousands of eggs are released. Spawning appears to be triggered by changes in salinity. In its native range, *M. sallei* has two periods of intense spawning activity, apparently stimulated by rapid drops in salinity resulting from seasonal freshwater outflow (Puyana 1995; in Bax et al. 2002). A pelagic larva develops within a day of fertilization and then settles (NIMPIS 2002; CSIRO 2001). Juveniles grow rapidly and are considered mature after 1 month. Maximum size is reached within 6 months, and mussels live for about 12–13 (maximum 20) months. *M. sallei* settles in clusters and is rarely seen as a single individual (NIMPIS 2002). It attaches to all types of substrata but prefers vertical surfaces and objects. It is capable of shedding its byssus and reattaching to new surfaces. Younger mussels develop byssus apparatus at shorter intervals, and hence move more often, but adults are relatively passive (Udhayakumar and Karande 1989; Morton 1981; NIMPIS 2002; CSIRO 2001; Bax et al. 2002; Rajagopal et al. 2006b).

M. sallei has been reported from Australia (Darwin harbour; Bax et al. 2002), Hong Kong, Taiwan, Japan, Fiji (CSIRO 2001), India (Mumbai and Vishakhapatnam harbours; Anil et al. 2002) and Singapore (Sin et al. 1991). Hull fouling is often an important factor in incursions, such as the introduction of *M. sallei* to Darwin Harbour, Australia in the 1990s (Hutchings et al. 2002). However, spread via ballast water appears less likely because of the short duration of the larval stage (CSIRO 2001). It can be introduced to new areas via fouling on aquaculture equipment (CSIRO 2001).

M. sallei is a major fouling species, forming dense monocultures. It is a suspension feeder, feeding on zooplankton, phytoplankton, and other suspended particulate organic matter (NIMPIS 2002). It has been responsible for massive fouling on wharves and marinas, seawater systems (pumping stations, vessel ballast, and cooling systems), and marine farms. In preferred habitats, it forms dense monospecific groups that exclude most other species, leading to a substantial reduction in biodiversity (NIMPIS 2002; CSIRO 2001). *M. sallei* dominates the intertidal pier community within the Government Dockyard in Victoria Harbour, Hong Kong and thereby altered the whole ecosystem (Morton 1989). In India, *M. sallei* displaces much of the native fauna in Mumbai waters (Subba Rao 2005).

6 Asian Clams: Corbiculidae

6.1 Asiatic Clam, *Corbicula fluminea* (Müller 1774)

The Asiatic Clam is native to freshwater systems in south-eastern China, Korea, south-eastern Russia, and the Ussuri Basin (Aguirre and Poss 1999). In the United States, *C. fluminea* has been introduced and spread to 38 states of the USA and the District of Columbia (Foster et al. 2000). It also invaded South America (Callil and

Mansur 2002) while Europe was invaded after the 1980s, subsequently showing a very fast dispersal over nearly the whole of Europe (Vincent and Brancotte 2002).

It has caused millions of dollars worth of damage to intake pipes used by power, water, and other industries. *C. fluminea* occurs in estuarine habitats and freshwater lakes and water courses; it requires well-oxygenated waters and prefers fine, clean sand, clay, and coarse sand substrata in which they bury (Aguirre and Poss 1999). They can tolerate salinities of up to 13‰ for short periods (Aguirre and Poss 1999) and temperatures between 2 and 30°C (Balcom 1994). It is generally intolerant of pollution and is usually found in moving water because it requires high levels of dissolved oxygen. *C. fluminea* spreads when it is attached to boats as juveniles or is carried in ballast water, used as bait, sold through the aquarium trade, and carried with water currents. Many native clams are declining as *C. fluminea* out-competes them for food and space reaching very high densities in sediments (PNNL 2003).

The introduction of *C. fluminea* into the United States has resulted in the clogging of water intake pipes, affecting power, water, and other industries. Nuclear service water systems (for fire protection) are very vulnerable, jeopardizing fire protection. In 1980, the costs of correcting this problem were estimated at one billion dollars annually. *C. fluminea* causes these problems because juveniles are weak-swimmers, and consequently they are pushed to the bottom of the water column where intake pipes are usually placed. They are pulled inside the intakes, where they attach as juveniles, breed, and die. The intake pipe became clogged with live clams, empty shells, and dead body tissues. Buoyant, dead clams can also clog intake screens.

C. fluminea is a hermaphrodite (both sexes are found on one organism) and is capable of self-fertilization (Rajagopal et al. 2000). The larvae are released through the exhalant siphon and sent out into the water column. Spawning can continue year around in water temperatures higher than 16°C. The water temperature must be above 16°C for the clams to release their larvae. In North America, spawning occurs from spring to fall (Aguirre and Poss 1999). Maximum densities of *C. fluminea* can range from 10,000 to 20,000 m⁻², and a single clam can release an average of 400 juveniles a day (PNNL 2003) and up to 70,000 per year. Reproductive rates are highest in fall (Aguirre and Poss 1999). Larvae spawned late in spring and early summer can reach sexual maturity by the next fall (Aguirre and Poss 1999). *C. fluminea* has a lifespan of about 2–4 years (PNNL 2003); the maximum lifespan can be as much as 7 years (Aguirre and Poss 1999).

7 Other Important Invasive Fouling Species

Apart from the bivalves, which form the major component of the invasive fouling species, organisms such as barnacles, tube worms, and hydroids also are important from the viewpoint of biofouling in industrial cooling water systems. Practical experience confirms that barnacles are inherently better equipped to colonize different man-made structures due to their possession of the unique cypris larvae (Crisp 1984). A good introduction to the barnacles is provided by Southward (2008).

7.1 *Amphibalanus improvisus* (Darwin 1854)

The brackish water barnacle *Amphibalanus improvisus* (synonym *Balanus improvisus*) is an estuarine species and has a wide geographic distribution around the world (Newman and Ross 1976; Furman 1990). *A. improvisus* might be originated from the east coast of the US and be transported to Europe early in the nineteenth century from where it has spread extensively during the twentieth century (Gislén 1950; Sneli 1972; Southward and Newman 1977; Furman et al. 1989; Leppäkoski 1999).

The species feeds itself by filtering detritus. The barnacles reach the adult stage at a basal diameter of 6–8 mm. Some individuals can reach an age of 4 years (Subklew 1969). *A. improvisus* is hermaphroditic. They can reproduce by cross- as well as self-fertilization (Furman and Yule 1990). An individual can produce several broods per year. Two broods have been reported in the Baltic Sea. Under favourable conditions, it produces broods with intervals of 6 weeks or even with intervals of 4–5 days. Reproduction by release of nauplii starts in spring when the temperature rises above 10°C and ends when the temperature falls below that level in autumn (Luther 1987). Free-swimming nauplius larvae hatch out into the water, where they live as part of the zooplankton for 2–5 weeks, feeding on phytoplankters. This duration may be as short as 1–2 weeks at optimum conditions when temperature is around 14°C. The nauplii pass six stages to reach the last one called cypris stage (0.5 mm long). The cypris, a non-feeding stage, searches for a suitable substratum and finally settle using cement secreted by specialized cement glands (Furman et al. 1989). Settlement occurs at temperatures above 20°C. The cypris larva cements itself to a substratum and metamorphoses into the typical barnacle.

The species is eurythermal, but is sensitive to temperatures below zero. It is sensitive to desiccation and therefore does not occur at places that fall dry frequently. It is sensitive to strong water turbulence. The species tolerates pollution very well. The species is extremely euryhaline during all stages and can withstand a very wide range of salinities from sea water to fresh water and, therefore, it is able to penetrate landward in estuaries, canals, and harbours (Rainbow 1984). Its occurrence is most frequent at salinities of 5–15‰. Normally, it does not occur at salinities higher than 25‰ (O'Connor and Richardson 1994). The adults can easily be transported attached to ship hulls after which planktonic larvae can be released. The duration of the larval stage is relatively short, which restricts the dispersal possibilities of the larvae (Furman et al. 1989). Settlement as high as 37,200 numbers m⁻² has been observed near the intake gates of Velsen power station in the Netherlands (Van der Gaag et al. 1999). The maximum settlement was observed at 2 m depth.

7.2 *Ficopomatus enigmaticus* (Fauvel 1923)

The brackish water serpulid tube worm, *Ficopomatus enigmaticus* (formerly named *Mercierella enigmatica*), is a major fouling organism on surfaces such as power station intakes, canal walls, and ship hulls (Straughan 1972). *F. enigmaticus* is capable

of settling in water velocities up to 55 cm s^{-1} and able to build massive (8.5 cm thick) layers of calcareous tubes within a year (Ten Hove 1979). *F. enigmaticus* was originally a subtropical species and dispersal occurred probably through navigation (Dixon 1981). The species is widely spread in the brackish water of harbours, estuaries, and lagoons. This species is believed to have originated from Australia (Allen 1953) or from the subtropical austral region (Dixon 1981). Their distribution is reported from northern and southern hemisphere, Denmark to North Africa, Mediterranean, Black Sea, Caspian Sea, South Africa, Japan, Southern Australia, Hawaii, California, New Jersey, Gulf of Mexico (Texas), Uruguay, North Argentina, Thames estuary (England), and canal de Caen (France) (Rioja 1924; Monroe 1938; Allen 1953; Kirkegaard 1959; Ten Hove and Weerdenburg 1978; Dixon 1981; Rajagopal et al. 1995). In The Netherlands, this species was reported in the harbour of Vlissingen (Flushing, SW Netherlands) and Noordzeekanaal (near Amsterdam and Velsen) (Wolff 1969; Van der Velde et al. 1993). In the tropics, the closely related *Ficopomatus ushakovi* (Pillai 1960) occurs, which is also an euryhaline species (Ten Hove and Weerdenburg 1978; Zibrowius 1983), often confused with *F. enigmaticus*, e.g. by Hill (1967), Lacourt (1975), and Straughan (1968, 1970, 1972).

F. enigmaticus can osmoconform at salinities of 1–55‰; at salinity below 1‰, osmoregulation takes place (Skaer 1974). The species can be found in pure sea water as well as in fresh water, but the species flourishes only in brackish water. In the Netherlands, the species occurs at salinities of 3.2–10‰ (Wolff 1968; Van der Velde et al. 1993). The development of the larvae is rapid at salinities of 10–30‰. Salinity lower than 3‰ is unfavourable for the development towards the trochophore larval stage (Hartmann-Schröder 1967). At low salinities, tube building is hampered by lower calcium concentrations than in salt water. *F. enigmaticus* can tolerate short periods of extremely high salinities from 55‰ till fresh water (Van der Velde et al. 1993).

The northern boundary of the distribution of *F. enigmaticus* is the July isotherm of 15.5°C (Vaas 1975). Frost periods damage this species, while tube formation stops below 7°C (Van der Velde et al. 1993). The species flourishes often at power station outfalls under these conditions. The maximum settlement of *F. enigmaticus* ($10 \times 10^6 \text{ m}^{-2}$) was reported from Millpond at Emsworth, UK (Thorp 1987). Ten Hove (1979) suggested that competition with other animals, mainly for space, may decide the settlement success of *F. enigmaticus*. Evidence from panel studies suggests that space was a limiting factor for the successful settlement of *F. enigmaticus* in regions like the Noordzeekanaal, since their settlement was associated with competitively superior species like the bivalve *M. leucophaeata* and the hydroid *C. caspia* (Rajagopal et al. 2002b). The tube growth of *F. enigmaticus* was found to be very fast in the first few weeks (up to 10 mm week^{-1} in the first 4–6 weeks). Later, growth decreases and the tubes attain a length of 60–70 mm within 1 year. They can grow to 10 cm with a diameter of 1.5 mm.

The animals are male or female. Reproduction takes place depending on the temperature regime. The minimum temperature for reproduction seems to differ

between populations. Dixon (1981) and Hartmann-Schröder (1967) report that the water temperature in, for example, the Thames (Great Britain) must be 17–18°C, while Thorp (1994) at Emsworth (West Sussex, Great Britain) observed reproduction at water temperatures from 10°C. In areas where the temperature is higher than these levels, reproduction can occur the whole year round. In temperate areas, gametogenesis takes place during January–July, but the release of the sperm and eggs takes place in August–September, when the water temperature is the highest. The duration of the planktonic larval stage can vary from 1 to 3.5 months. They feed on unicellular green algae. Larval settlement takes mainly place in October–November (Dixon 1981). Settlement of *F. enigmaticus* may occur almost on any solid substrate. When other individuals of this species were already present on the substrate, larvae were attracted to settle there (Straughan 1972). Animals of 10 mm length (not tube length) can reproduce already (Fischer-Piette 1937); in temperate areas, it takes 4 months, and this generation will reproduce in the next season. The animals can reach the age of 4–8 years (Ten Hove 1979). The fully grown attached worms are suspension feeders and take all suspended matter (detritus, diatoms, flagellates, and ciliates) in the size range 2–16 µm (Dixon 1977). The species occurs at permanent water levels, but can tolerate a dry falling period of 4–5 days (Kühl 1977). Water with low oxygen level is tolerated for some days (Kühl 1977).

The effect of chlorine on *F. enigmaticus* is unknown. Some serpulids such as *Pomatoceros triqueter* and *Hydroides elegans* (under the name *H. norvegica*) showed better growth when chlorine was added to the sea water of the cooling water systems of an oil refinery (Zibrowius and Bellan 1969).

7.3 *Cordylophora caspia* (Pallas 1771)

C. caspia (synonym *C. lacustris* Allman) is a colonial hydrozoan originating from the Ponto-Caspian area that occurs in brackish waters and in fresh waters with altered ionic composition (Arndt 1965; Kinne 1956). *C. caspia* is generally found on submerged objects such as stones, wooden piles, and macrophytes. *C. caspia* has nowadays a worldwide distribution from the cold boreal and antiboreal to the subtropical regions (Roch 1924; Arndt 1984). The species is common in estuaries, lagoons, and coastal lakes, where colonies can grow large in brackish water (Arndt 1989). Well-developed colonies of *C. caspia* are usually found at salinities between 2 and 12‰ with relatively constant conditions and considerable tidal influence (Arndt 1989). Vervoort (1946) recorded a salinity range of 0.3–10‰ with optimal development at a salinity of 1–5‰, but also occurrence of poorly developed colonies at lower (0.08‰) and higher salinities (up to 35‰). *C. caspia* has also been reported from fresh water (Fulton 1962) under favourable conditions such as fast flow, high oxygen availability, positive ion anomalies (calcium, magnesium, and sodium), and permanent twilight (Kinne 1956; Arndt 1989). *C. caspia* shows many growth forms

described by Schulze (1921). According to Arndt (1973), different colonies can have different optima for temperature and salinity. Temperatures below 10°C are generally suboptimal for *C. caspia*. The species is very plastic to variation in temperature (10–31°C), pH (6–9), oxygen tension, and light (see also Hutchinson 1993). Microsatellite studies showed that in *C. caspia*, cryptic diversity is present (Schable et al. 2008) and another genetic study showed that perhaps various species are hiding under the name *C. caspia* (Folino-Rorem et al. 2009).

C. caspia shows a temperature and drought-resistant stage, called the menont. This stage makes dispersal over larger distances by ships, floating wood or waterfowl possible. The distribution of *C. caspia* over the globe is very discontinuous (Roch 1924; Arndt 1984). Menonts can grow out to polyps even in concentrated sea water (ca. 40‰) (Vervoort 1946).

Hydroids are often the first macrofouling colonizers on experimental panels and provide rough substratum for the subsequent settling of other fouling species. In *C. caspia*, the colonies are formed by asexual budding, which leads to increase in the number of countable units rather than increase in size of a single unit (Fulton 1963). The hydroid colonies are found to feed mainly on copepods and dipteran larvae, which are paralyzed by nematocysts in the tentacles (Mace and Mackie 1970). Several parameters including light, ionic concentrations, nutrition, oxygen tension, the presence of symbiotic organisms, substratum, and temperature have been reported to influence the growth in *C. caspia* (Kinne 1956; Fulton 1962). The sexual generation (hydromeduse) originates also by budding from the polyp. When the medusa stays in reduced form on the polyp, it develops into a gonophore. Male and female gonophores develop on the same colonies at short distance below the hydranths and are covered by a thin periderm. The development to planula larva takes place within the female gonophores (Vervoort 1946). Many gonophores of *C. caspia* release the planula larvae covered with cilia into the water, where they live planktonically. The planula settles on a suitable substratum and forms an adhesive disc, from where the upright polyp develops. The disc and polyp are covered with the periderm consisting of a chitin-like substance. Jormalainen et al. (1994) studied growth and reproduction of *C. caspia* in the northern Baltic Sea. Mean size of the uprights varied cyclically. During early summer, growth and sexual reproduction showed a clear peak towards mid-summer, and thereafter sexual reproduction ceased but growth continued.

In Noordzeekanaal, Netherlands, Rajagopal et al. (1995) observed the settlement of *C. caspia* between May and October, when the temperature and salinities were relatively high. The maximum biomass of 5.2 kg m⁻² (dry wt, after 118 days) was recorded near the Velsen power station. High settlement of hydroids in the condenser tubes (i.e. Velsen power station) affects the heat transfer efficiency and therefore necessitates frequent manual cleaning, even after using intermittent chlorination as a control measure (Rajagopal et al. 2002b). Chlorination leads only to curtailing of the growth of the hydroids, as it cannot kill the whole polyps. Hence, they can grow out again (Rajagopal et al. 2002b; Folino-Rorem and Indelicato 2005). Thermal control is another option. Folino-Rorem and Indelicato (2005) found that *C. caspia* polyps died within 8 h of exposure to temperatures of 37.7 and 40.5°C, but survived within that period below 36.1°C.

8 Control Methods

Domination of aquatic systems by invasive species brings into focus the need for effective control measures, which may have to be tailored to suit the characteristics of the species in question. Quite often, colonization by these organisms becomes so intense that normal control measures may be found inadequate to deal with the fouling situation, unless special attention is paid to the tolerance of the species to the method used (see Fig. 7.3). Recent publications have highlighted different aspects of the issue related to invasive species and their control (Rajagopal et al. 2010a, b).

Two of the most commonly used fouling control measures in coastal power stations are chlorination and heat treatment (Rajagopal et al. 1996). A variety of other control methods has also been proposed for controlling exotic species: oxygen deprivation, thermal treatment, desiccation, radiation, high-pressure jetting, mechanical filtration, removable substrata, molluscicides, ozone, antifouling coatings, electric currents, and sonic vibration. However, the utility of many of these methods is yet to be commercially demonstrated. Mechanical measures, such as using screens and traps, can effectively eliminate mussels and their shells from the system. Desiccation is an effective, readily applied, and environmentally neutral technique that can be used against invasive mussels. It would be most effective in raw water systems such as navigation locks and water intake structures, which are designed for periodical dewatering for maintenance.

8.1 Comparative Tolerance of Various Bivalve Species

Many of the predominant invasive species are extremely tolerant to many conventional control measures (Rajagopal et al. 2006b). Biofouling in industrial cooling water systems is generally dominated by a few species which are adapted to the conditions within the cooling water systems (Rajagopal et al. 2010a). It is possible that invasive species are the most prolific among them. In such situations, it would be necessary to know the relative tolerance of the dominant species to the control strategy being adopted. For example, *M. leucophaeata* is a common fouling organism in CWS of power stations in Netherlands, where it can coexist at relatively high salinities with *M. edulis* and at low salinities with *D. polymorpha* (Rajagopal et al. 1995, 2002a, 2003). *M. leucophaeata* and *D. polymorpha* are invasive species in Netherlands. A comparison of the chlorine tolerance of these three species showed that *D. polymorpha* was the least tolerant among the three. The chlorine residual levels required to control a mussel fouling community consisting of *M. leucophaeata*, *M. edulis*, and *D. polymorpha* are to be chosen based on the tolerance of *M. leucophaeata*, which is the most tolerant among the three (refer to Rajagopal 2012 for details). Previous studies have shown that various factors can also significantly influence chlorine tolerance such as mussel size, spawning season, acclimation temperature, and status of byssal attachment (refer to Rajagopal et al. 2010a for details). Therefore, chlorine bioassays using mussels (or similar organisms) need to be carried out after taking the above factors into consideration (Rajagopal et al. 2002c).

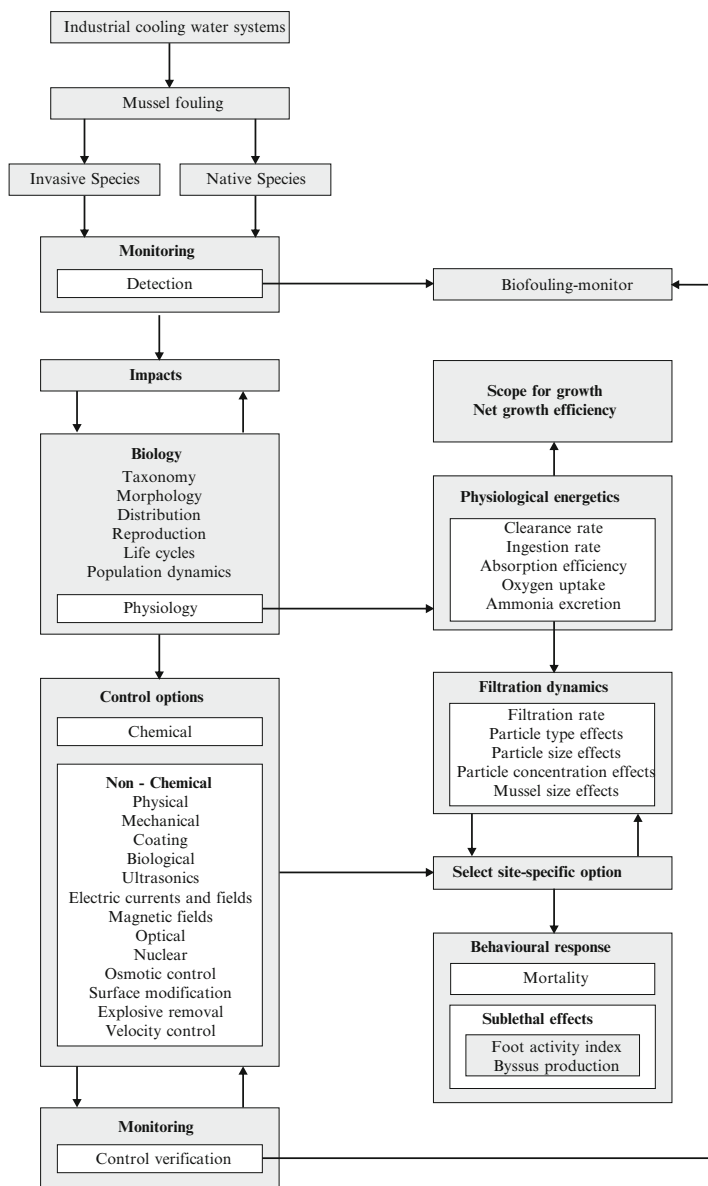


Fig. 7.3 Schematic representation of the options available for invasive species control in industrial cooling water systems

In a fouling control programme involving heat treatment, the heated effluents, instead of being discharged, are re-circulated through the pre-condenser sections (Jenner 1982; Jenner et al. 1998). This recirculation is continued until the water flowing through the conduits has attained sufficient temperature to kill all the fouling organisms existing inside. Generally, the temperature difference between intake and

outfall (ΔT) is maintained below a stipulated limit to prevent any potential damage to the environment, resulting from the discharge of heated effluents. Nevertheless, there are problems with this method, particularly the production penalty due to excess heat on the turbines (Rajagopal et al. 2010b). It requires major design modifications of the cooling systems in stations already operating. Furthermore, it is often expensive or technically difficult. In spite of this, many power stations have successfully adopted heat treatment for fouling control.

Time-temperature-mortality curves of marine bivalves (as well as many other organisms) are typically characterized by a steep increase in mortality within narrow ranges of temperature, the range being typical of the organisms being tested. Interestingly, near extinction of invasive mussel *P. perna* from Texas Gulf of Mexico waters was observed in the summer of 1997, when the mean surface-water temperatures approached its incipient upper limit of 30°C (Hicks and McMahon 2002). Jenner (1982) and Rajagopal et al. (2005b) have observed that in most of their experiments on the response of mussels to temperature, either all animals were killed or all survived. Hence, the point of death was fairly sharp defined with little variation from one individual to the other. Similarly, Wright et al. (1983) and Rajagopal (1997) recorded only small differences between temperatures causing little or no mortality and those producing a complete kill in *Crassostrea virginica*, *Mulinia lateralis*, *Argopecten irradians*, *Mercenaria mercenaria*, *Spisula solidissima*, *P. viridis*, and *P. perna*. The simplicity and effectiveness of thermal treatment of mussel control make it a viable alternative to chlorination and, therefore, can be recommended to affected industries.

Data available in literature showed that 100% mortality of all bivalve species could be achieved by raising the temperature to 42°C and maintaining that temperature level for about 120 min (Rajagopal et al. 2010b). Published data on *M. edulis* (Rajagopal et al. 2005a), *M. leucophaeata* (Rajagopal et al. 2005b), and *C. gigas* (Rajagopal et al. 2005c) from the Netherlands obtained under comparable experimental conditions are presented in Fig. 7.4. As described earlier, *M. leucophaeata* and *C. gigas* are invasive species in The Netherlands and elsewhere in Europe. The exposure time required for 100% mortality of *C. gigas* at different temperatures was much longer than that required for *M. edulis* and *M. leucophaeata*. In most of the cases, it is also reported that the treatments that are effective against bivalves are also successful against most other fouling organisms. Therefore, antifouling treatments must be based on the most tolerant species present. Heat treatment as an alternative to chlorination must be explored by the utilities and, if found economical, must be practised more widely.

9 Concluding Remarks

Industries all over the world will have to cope with an increasing number of invasive species that find their way into their cooling water intakes. This has been amply demonstrated in the case of species such as Asiatic clams, Zebra, and Quagga

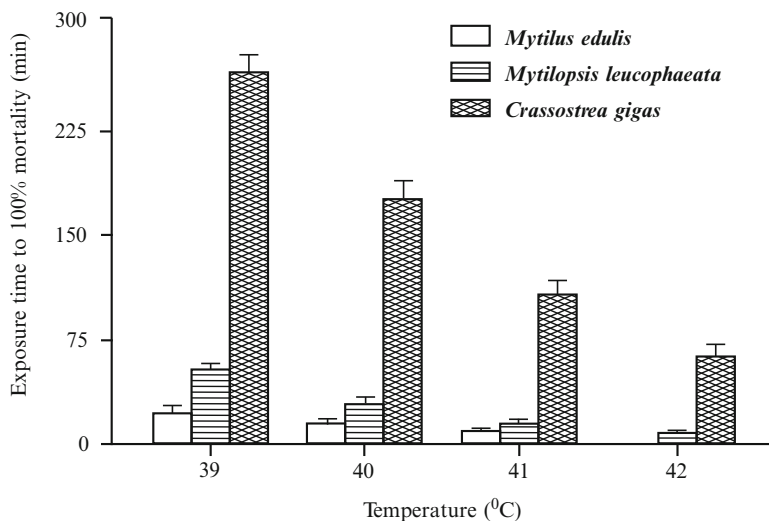


Fig. 7.4 Comparison of exposure times to reach 100% mortality of *Mytilus edulis* (Rajagopal et al. 2005a), *Mytilus leucophaeata* (Rajagopal et al. 2005b), and *Crassostrea gigas* (Rajagopal et al. 2005b) at different temperatures (all from The Netherlands). Test methods and mortality determinations were similar in all temperature tolerance studies of the different species (modified after Rajagopal et al. 2005c)

mussels in the Great Lakes and in the river Rhine (Figs. 7.1 and 7.2). Operators and engineers have to be aware of new invasive species in their cooling water circuits. It is advisable to monitor the systems continuously for the presence of new species. Often it may happen that the invaders are much better equipped to tolerate adverse environmental conditions than the native species they replace. Hence, the control measures adopted should be such that they address the invasive species rather than the native ones (Fig. 7.3). Tolerances with respect to control measures differ between species (Fig. 7.4). Control measures used for the most tolerant species are also expected to control other less tolerant species. Unfortunately, adequate toxicity data are not available for several of the potential biofouling invasive species. This lacuna needs to be addressed and it is expected that researchers would pay attention to generation of such data, so that environmentally acceptable control measures can be evolved for the ever-increasing number of exotic biofoulers.

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