Chapter 14
Impact of Invasions on Water Quality in Marine and Freshwater Environments

Pedro Reis Costa, José Carlos Martins, and Paula Chainho

Abstract Water quality of marine and freshwater environments, including brackish waters, can be highly impacted by the introduction, establishment, and spread of non-native species. Phytoplankton are among the most common arrivals, with the bloom-forming species, such as toxic freshwater cyanobacteria and marine dinoflagellates, being of particular concern. Their massive population increase may lead to water discolouration, reduced transparency, changes in nutrients cycling, events of anoxia, and release of potent toxins contaminating the food web and drinking water. Top-down control that regulates primary productivity is carried out by filter-feeding organisms. Bivalve mollusks are often the dominant filter feeders in many aquatic systems. The high filtration rates of some non-native bivalves may significantly increase the ecosystem filtration capacity, resulting in drastic changes of phytoplankton biomass and composition. Invasive bivalves also have a marked role removing other suspended particles, which result in increasing water clarity with subsequent growth of submerged vegetation. This apparent benefit may not be innocuous because changes in phytoplankton composition may lead to dominance of toxic algae species. Biomagnification of contaminants filtered from the water column, biofouling, and increase of sedimentation are among other detrimental effects associated with the increase of non-native bivalve populations. In this chapter, the main impacts on water quality raised by non-native phytoplankton and bivalve species are reviewed.

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14.1 Introduction

It is estimated that at least 7000 to possibly more than 10,000 species of organisms are in transit in ship ballast waters alone every day. These species include unicellular organisms, invertebrates, and fish (Carlton 1999). Not taking into account bacteria and other microorganisms, phytoplankton and zooplankton species are the most frequent and abundant organisms introduced to new environments via ship ballast waters. Some phytoplankton species are of particular concern, such as bloom-forming and toxin-producing dinoflagellates (e.g., *Gymnodinium catenatum*), which in addition to vegetative cells have a resting stage (cysts) in their life cycle that favours their transport in the bottom sediment of ballast tanks.

Phytoplankton species, especially those that lead to harmful algal blooms, are regularly monitored by most coastal countries. The tight sampling frequency carried out by each national monitoring program, with the aim of identifying and quantifying the occurrence of toxic phytoplankton in aquaculture-producing areas, has revealed toxigenic phytoplankton species previously known from other geographic ranges (Lewitus et al. 2012). The sudden and abrupt occurrence of algal blooms leads to changes in water quality via two general types of impacts: (1) mechanical or physical damage from high population densities, such as particle irritation or production of a mucous barrier; and (2) chemical effects, such as anoxia or hypoxia, and production of toxins or other metabolites.

The introduction of new toxigenic algae species may modify ecosystem functioning. For example, high levels of emerging and nonregulated toxins can be accumulated by filter-feeding bivalve mollusks, raising new concerns for environmental managers, seafood producers, policy makers, and scientists. The natural development and persistence of algal blooms is controlled by zooplankton grazers and filter-feeding bivalve mollusks. Invasive bivalve mollusk species are often more tolerant to ecosystem changes, and some species seem able to minimise the assimilation of toxins (Burmester et al. 2012), which associated with their high reproduction and growth rates makes them important new resources for fisheries and aquaculture. For these reasons, some bivalve mollusk species have been intentionally introduced. These mollusks easily spread and colonise new ecosystems with devastating ecological effects, such as the decline of native species, changes in community structures, and loss of planktonic productivity, but they can also affect water clarity via alteration of nutrient cycling, organic enrichment of sediment, and transfer of waterborne contaminants to other organisms. Moreover, prolific non-native bivalve species have caused major economic losses, mainly related to activities such as clogging water intake pipes, blocking power plants, damaging irrigation systems, and affecting ship engines (Booy et al. 2017).

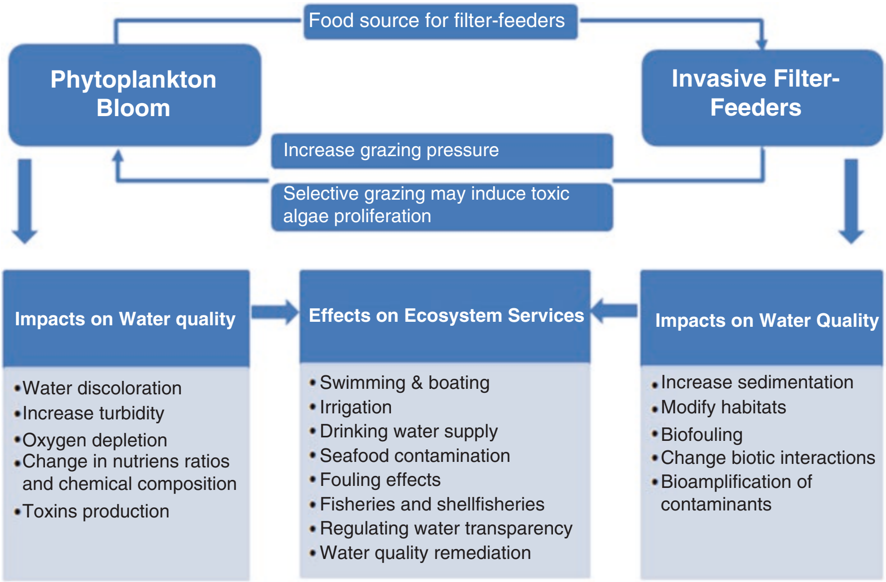

Fig. 14.1 Conceptual diagram of the relationship between phytoplankton blooms and filter-feeding bivalves and derived impacts on water quality and ecosystem services described in other chapters of this book

This chapter describes the impact of selected non-native phytoplankton species and filter-feeding organisms on water quality, with particular emphasis on bivalve mollusks invading marine and freshwater environments, including brackish waters (Fig. 14.1).

14.2 Impacts of Invasive Phytoplankton on Water Quality

Identifying a new phytoplankton species in a given geographic location is often difficult because of the taxonomic complexity of phytoplankton and a lack of comprehensive historical data. The species listed in Table 14.1 are among the most important invasive phytoplankton species known to cause significant ecological and economic impacts in all aquatic system types.

In freshwater, the diatom *Didymosphenia geminata* and the cyanobacteria *Cylindrospermopsis raciborskii* and *Chrysosporum ovalisporum* are key examples of invasive phytoplankton species. *Didymosphenia geminata* is a colonial diatom that has historically been found in the Northern Hemisphere (Whitton et al. 2009). In the past two decades, *D. geminata* blooms have been reported from hundreds of rivers, not only in its native range but also in the Southern Hemisphere. Although somewhat controversial, the situation in New Zealand has gained the most attention where *D. geminata* is extraordinarily prolific because of its probable recent introduction. On the other hand, *Cylindrospermopsis raciborskii* and *Chrysosporum*

Table 14.1 Examples of impacts of invasive bloom-forming phytoplankton species and bivalve mollusks on water quality of freshwater and marine environments

Taxa		Impact	Native area	Introduced area
Freshwater cyanobacteria	*Chrysosporum ovalisporum*	Toxins production (CYN), reduced transparency, water chemical alterations	Middle East	Iberian Peninsula
	Cylindrospermopsis raciborskii	Toxins production (CYN, PSP), reduced transparency, water chemical alterations	America	Europe
Freshwater diatoms	*Didymosphenia geminata*	Sediment covering (extensive thick mats), water chemical alterations	North America, Europe and Asia (North Hemisphere)	New Zealand
Marine dinoflagellates	*Alexandrium minutum*	Toxins production (PSP), water chemical alterations, discoloration of seawater	Egypt (Mediterranean Sea)	Northern Europe, Azores, Australia
	Gymnodinium catenatum	Toxins production (PSP), water chemical alterations	Mexico	Australia
	Ostreopsis cf. *ovata*	Toxins production (PlTX), water chemical alterations, mucous barrier	Thailand	Mediterranean Sea and NE Atlantic
	Prorocentrum minimum	Discoloration of seawater, reduced transparency	Gulf of Lion (NW Mediterranean Sea)	Baltic Sea
Marine diatoms	*Coscinodiscus wailesii*	Gelatinous secretion	NE Pacific, Sea of China and Japan	Europe

(continued)

Table 14.1 (continued)

Taxa		Impact	Native area	Introduced area
Marine bivalves	*Ruditapes philippinarum*	Accumulation of contaminants, nutrient recycling, decrease in turbidity and phytoplankton concentrations, sediment organic enrichment and sedimentation increase	Indo-Pacific	North East Pacific, North East Atlantic, and Mediterranean Sea
	Crassostrea gigas		NW Pacific	North East Pacific, North and South Atlantic, Mediterranean Sea, and Indo-Pacific
Freshwater bivalves	*Corbicula fluminea*	Accumulation of contaminants, nutrient recycling, decrease in turbidity and phytoplankton concentrations, sediment organic enrichment and sedimentation increase, biofouling	SW Asia	Europe, America,
	Dreissena polymorpha		Black, Caspian, Aral, and Azov Seas	Asia, Europe, North America

CYN cylindrospermopsin, *PSP* paralytic shellfish poisoning toxins, *PlTX* palytoxins

ovalisporum are invasive filamentous cyanobacteria that were first assigned to tropical environments, but which, in the past two decades, have spread to subtropical and temperate zones. Both species have the ability to form dormant cells (akinetes) and to fix atmospheric nitrogen, supporting their establishment and proliferation in new environments. *Cylindrospermopsis raciborskii* was first described in Indonesia (Java) in 1912, but in recent years its distribution has spread to almost all continents. It is suggested to have originated in America and then subsequently spread into Africa, followed by movement into Asia and Australia, with Europe being the last continent that it has invaded (Moreira et al. 2015). *Chrysosporum ovalisporum*, previously known as *Aphanizomenon ovalisporum* (Zapomělová et al. 2012), first appeared in Lake Kinneret (Israel) in 1994 as a bloom-forming species and was subsequently described in Australia, Asia, and occasionally in different ecosystems of southern Europe, such as in the Iberian Peninsula (Sukenik et al. 2012).

In marine ecosystems, several diatom and dinoflagellate species have been categorized as invasive. *Coscinodiscus wailesii* is a classic example of an invasive bloom-forming species with harmful effects. This species was originally known from two regions, namely, the northeast Pacific, from California to British Columbia, and the Sea of China and Japanese coastal waters. Extensive detrimental blooms were identified in Europe during the 1970s (Boalch and Harbour 1977), and it has become well established in the North Sea since then. The dinoflagellate *Prorocentrum minimum*, first described in the English Channel, has been increasing in abundance and has spread over large areas. It is now considered the principal invasive phytoplankton species of the Baltic Sea (Olenina et al. 2010). The role of the resting cysts of the toxic marine dinoflagellates *Gymnodinium catenatum* and *Alexandrium* spp. has been pointed out as responsible for their introductions in distinct regions. Although the occurrence of *G. catenatum* on the West Coast of the Iberian Peninsula could result from expansion of its natural range, most likely from northwest Africa (Ribeiro et al. 2012), the presence of *G. catenatum* in Australia suggests a pathway of introduction via ship ballast water, possibly from Japan (Hallegraeff et al. 2012). Finally, it is important to highlight the spread of the tropical and subtropical dinoflagellate genus, *Ostreopsis*, during the past decades throughout the Mediterranean Sea.

14.2.1 Bloom Formation and Collapse

A phytoplankton bloom is intrinsically associated with a significant proliferation of algae cell abundance, often concurrent with a high increase of biomass. Intense blooms commonly result in water discolouration, foul odours and tastes, oxygen depletion, a decrease in water transparency, and other changes in the physical, chemical, and biological parameters of the water bodies.

The most recognised aspect of algal blooms is their propensity to change the water colour. The water of lakes and other freshwater bodies whose surfaces are fully or partially covered by cyanobacteria turns green or greenish. In the marine environment colours of algal blooms are more diverse depending on the type and density of bloom species. Notable changes in water colour and a decline in water transparency were observed after intense blooms (3.5×10^8 cells l^{-1}) of *Prorocentrum minimum* in the Baltic Sea (Olenina et al. 2010). Such high and extensive biomass blooms limit light penetration into the water column, thereby preventing growth of beneficial algae and submerged aquatic vegetation.

The massive blooms of *Ostreopsis* cf. *ovata* in the Mediterranean Sea have been associated with mortality events of benthic communities, including gastropods, bivalve mollusks, cirripeds, cephalopods, echinoderms, and fishes. Morphological anomalies, loss of substrate-adhering capacity, and other damage were also registered in the affected organism. *Ostreopsis* are aggregated in mucilage that increases during cell proliferation, giving *Ostreopsis* the ability to rapidly colonize benthic substrates. It has been pointed out that the mucilage matrix plays a role in bloom toxicity by actively disseminating the toxins, as affected benthic organisms are often covered by it (Giussani et al. 2015). Extensive mucilage production is also associated with blooms of the giant diatom *Coscinodiscus wailesii* (Boalch and

Harbour 1977). The grayish mucilage is described as a highly sticky material, containing plankton remains and other solid particles, which impairs fishing nets and trawling activities. The mucilage formation seems to be related to cell lysis and bloom senescence, which may influence the biogeochemical cycles of regions where intensive blooms occur. In oligotrophic systems, *Didymosphenia geminata* often forms nuisance blooms consisting of thick mats that cover great extents of the bottom of streams and rivers. These mats may lead to changes in the composition and abundance of benthic invertebrates that can occur as a result of alterations in several mechanisms, including physical habitat and water chemistry. The presence of *D. geminata* mats promotes changes in hydrodynamic conditions by covering exposed sediment and increasing diurnal fluctuations in pH and dissolved oxygen (Larned and Kilroy 2014).

Extensive blooms consume nutrients, and thus may affect the water nutrient pools and dynamics. Algal blooms may occur at both extremes of the nutrient gradient, either in oligotrophic or nutrient-enhanced habitats. The nutrient uptake kinetics of phytoplankton species are affected by many processes, such as luxury consumption, local inputs, and transient nutrient pulses, which means that patterns between algal bloom development and external nutrient concentration are not generally clear and may be interpreted in different ways (Vila et al. 2005). When high biomass blooms exceed the assimilative capacity of the system, anoxia occurs. Oxygen depletion in the water column may result from intense algal respiration and incomplete phytoplankton decomposition at the bottom.

14.2.2 Toxin Production

One of the most significant impacts posed by bloom-forming invasive phytoplankton species on water quality is their potential for the production of toxic secondary metabolites, which leads to adverse health effects on plants and animals. These compounds vary from small to complex molecules (mol. wt. > 2600 Da). Their mode of action in mammals (the main organism models studied) includes inhibition of sodium channels, blocking neuromuscular transmission, and inhibition of protein phosphatases, leading to neuro- and hepatotoxic effects. The toxins can be released into the water or incorporated by the biota via food web transfer, resulting in different routes of exposure: drinking water, seafood contamination, aerosols, etc.

The marine dinoflagellates *Gymnodinium catenatum* and *Alexandrium* spp. are responsible for paralytic shellfish poisoning (PSP) outbreaks reported throughout the world's coastal regions. PSP is considered the most widespread of the algal blooms-related shellfish poisoning syndromes, as PSP toxins are potent neurotoxins that may cause human fatalities. The impacts of these toxin-producing dinoflagellates can be devastating for shellfish industry because of long-term closures of harvesting, and increasing geographic distribution and frequency of blooms of toxic *Alexandrium* populations have been reported. A recent example is the first report of a massive bloom (1.3×10^7 cells l^{-1}) of *A. minutum* in a remote coastal lagoon in São

Fig. 14.2 The first bloom of *Alexandrium minutum* in the Azores (Santo Cristo Lagoon, S. Jorge Island, Portugal) in September 2013 (Photograph by Rui Sequeira)

Jorge Island in the Azores in late 2013 (Santos et al. 2014). This island, located in the middle of the North Atlantic Ocean at a distance of 1500 km from the African/European coast, is surrounded by oligotrophic waters with low phytoplankton biomass. The bloom caused an orange-brown water discolouration (Fig. 14.2), culminating with the death of small pelagic fish, toxification of shellfish resources, and human poisonings after consumption of shellfish. Extremely high levels of PSP toxins that exceeded the Regulatory Limit (800 μg STX equiv. kg^{-1}) by more than 30 fold were determined in shellfish, which lead the local authorities to ban shellfish harvesting for more than 6 months.

The Mediterranean Sea marine region has the most non-native species in Europe (Vilà et al. 2010). Of increased concern is the impact of the benthic and epiphytic dinoflagellate genus, *Ostreopsis*, particularly *O.* cf. *ovata*, which produces palytoxin or palytoxin-like compounds (ovatoxins). Acute symptoms, including high fever, watery rhinorrhea, pharyngeal pain, bronchoconstriction with mild dyspnea and wheezes, conjunctivitis, and dermatitis, were observed in people exposed to seawater on Mediterranean beaches. The symptoms were severe at the peak of the bloom and dissipated with their senescence. This coincidence suggested that *Ostreopsis* cells or their toxins were transferred into the air through a mechanism similar to that previously observed with brevetoxins and microcystins in the Gulf of Mexico and in Californian lakes, respectively. However, it was only recently that the presence of ovatoxins was successfully determined in marine aerosols by high resolution mass spectrometry (Ciminiello et al. 2014). Figure 14.3 illustrates the spread of *Ostreopsis* throughout the Mediterranean Sea since its first toxic outbreak in 1998 until its detection on the Atlantic coast of Morocco, the Canary Islands and Portugal. Some countries (e.g., Italy and France) that frequently experience *Ostreopsis*-related outbreaks have developed close collaborations between policy makers and scientists to take management actions against these algal blooms.

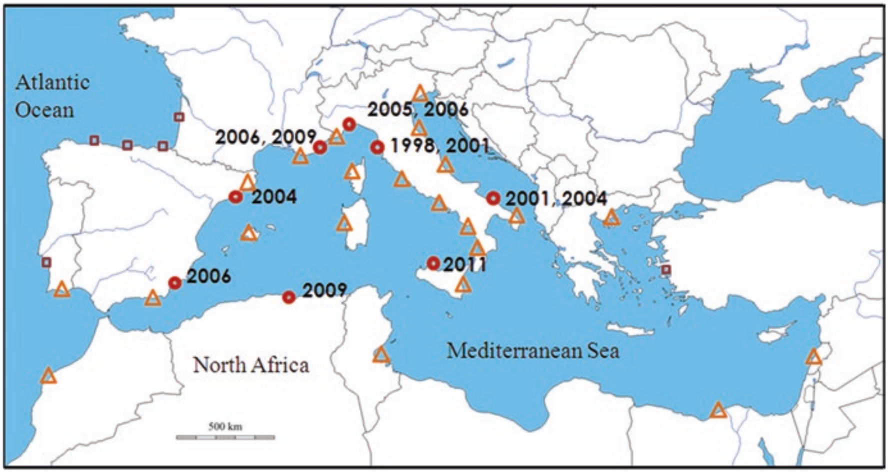

Fig. 14.3 Spread of *Ostreopsis* spp. in the Mediterranean Sea and the Atlantic coast. *Circles* indicate where and when human health outbreaks associated with *Ostreopsis* blooms occurred; *triangles* indicate where blooms have been detected; *small rectangles* indicate locations where *Ostreopsis* cells have been observed (Adapted from Ciminiello et al. 2014)

The invasive filamentous diazotrophic cyanobacteria *Cylindrospermopsis raciborskii* and *Chrysosporum ovalisporum* are a major concern regarding freshwater water quality. Some *C. raciborskii* toxic strains in South America have been reported to produce PSP toxins. However, many of the toxic strains of *C. raciborskii* and *C. ovalisporum* have been found to produce cylindrospermopsin (CYN). This alkaloid is a cytotoxin that can cause human poisoning. An outbreak of hepatoenteritis affecting 148 people, mostly children, was first reported in 1979 on Palm Island (Queensland, Australia) as a result of the consumption of water contaminated with CYN produced by *C. raciborskii* (Griffiths and Saker 2003). In addition to the human diseases reported here, aquatic toxins also cause devastating effects on benthic and pelagic communities. Bioaccumulation of toxins produced by freshwater cyanobacteria, such as CYN, has been documented in a range of aquatic vertebrates and invertebrates potentially affecting higher trophic levels. Bottom-up effects may also result from domination of nuisance cyanobacteria through alteration of the zooplankton community. The presence of toxin-producing *C. raciborskii* in the St. Johns River System (Florida) promoted a decrease in the size structure of the zooplankton community, pointing to an inevitable decline in the carbon and energy transfer efficiency to higher consumers (i.e., fish) (Leonard and Paerl 2005). Mass development of *G. catenatum* and *Alexandrium* spp. blooms and trophic transfer of PSP toxins has resulted in mass mortality of fish and other marine organisms, including top predators such as seabirds and sea mammals (Costa 2016).

14.3 Impacts of Invasive Freshwater and Marine Filter Feeders on Water Quality

Filter-feeding bivalves play a relevant role in ecosystems functioning by influencing the primary productivity through strong top-down control on phytoplankton. By filtering suspended particles from the water column and sinking these into the sediment surface as faeces and pseudofaeces, bivalves also have a role in nutrients dynamics. Additionally, bivalves are an important food source for higher trophic levels, which makes them an entry point for toxins through the food webs. All these processes may be exacerbated by invasive bivalve species leading to significant impacts on water quality.

Tremendous ecological and economic impacts have been promoted by invasive freshwater bivalve species (Gutierrez 2017). The zebra mussel, *Dreissena polymorpha*, and the Asian clam, *Corbicula fluminea*, have been responsible for the highest number of documented cases (Sousa et al. 2014). *Corbicula fluminea* is a freshwater clam native to Asia, which, over the past century, has spread its distribution to several continents including America (North and South) and Europe. *Dreissena polymorpha* is native to fresh and brackish waters of the Ponto-Caspian basins, revealing its strong invasive character first in Europe and later in North America.

The Manila clam, *Ruditapes philippinarum*, is native to the Indo-Pacific region. It has been introduced worldwide, mostly for cultivation purposes. It was accidentally introduced during the 1930s to the Pacific Coast of North America along with the Pacific oyster, *Crassostrea gigas*, seed imports, and has naturally spread to the Pacific Coast from California to British Columbia. It was also introduced into France in the early 1980s and since then in several other European countries to compensate for the irregular yields of the native European congeneric species *Ruditapes decussatus* (Bidegain and Juanes 2013). Other important species that have been introduced for cultivation purposes worldwide include the oysters *C. gigas*, *C. ariakensis*, *C. virginica*, and *Ostrea edulis*; the hard clam, *Mercenaria mercenaria*; and the softshell clam, *Mya arenaria.*

14.3.1 Water Clearance Effects

Invasive bivalves, such as the zebra mussel, the Asian clam, and the Manila clam, may significantly increase the grazing pressure in aquatic systems with consequent top-down control effects. A classical example is that of the massive decline in phytoplankton biomass (85 %) concurrent with the invasion of zebra mussels in the Hudson River Estuary (Caraco et al. 1997). In addition to the grazing pressure promoted by the invasive bivalve species, selective ingestion of particles dictated by the characteristics of the bivalve mantle cavity, selective digestion of phytoplankton, and selective removal of less buoyant and slower growing phytoplankton species may lead to drastic changes in phytoplankton composition. For these reasons, the presence of invasive bivalves (e.g., *D. polymorpha*) has been often associated with changes in cyanobacteria dominance and the promotion of toxic groups, namely *Microcystis* (Vanderploeg et al. 2001).

Under turbid conditions, some of these invasive species increase the rate of particle removal, improving water clarity and thereby enhancing benthic macroalgal or eelgrass production. The establishment of a *Dreissena polymorpha* community in Lough Sheelin, Ireland, and its increased population in the following years resulted in shellfish populations capable of filtering the total volume of the lake (82×10^6 m^3) within 13 days (Millane et al. 2008). The macrobenthic filtration capacity in the Venice lagoon more than doubled with the introduction of *R. philippinarum* (the Manila clam) (Pranovi et al. 2006). The increase in water clarity through the active filter-feeding behaviour of invasive bivalves might be used as support for a misconception that bivalve introductions lead to significant improvements in water quality. Nevertheless, high clearance rates also alter nutrient cycling (i.e., increase concentrations of ammonia, nitrates, and phosphates) and increase deposition of ingested particles as faeces and pseudofaeces adding organic matter to sediments (Sousa et al. 2014).

Invasive bivalves, such as *C. fluminea*, trap metal contaminants and accumulate them. This trait might be considered as an ecosystem service when these bivalves are used for bioremediation of metal-bearing effluents (Rosa et al. 2014). However, metal accumulation by invasive bivalves is likely to become biomagnified along the food chain with important impacts on higher trophic levels, as was verified in San Francisco Bay, where *Corbula amurensis* was observed to trap selenium and the effects of this metal were biomagnified along the food chain (Stewart et al. 2004).

14.4 Ecological Side Effects of Bivalve Mollusk Culture and Harvesting

Many non-native bivalve species have been deliberately introduced for aquaculture purposes or to improve fisheries yield. Harvesting devices vary in their design and implementation, but mechanical and hydraulic shellfish dredges are some of those most used for species with high economic value (Fig. 14.4). The action of mechanical and hydraulic shellfish dredges physically disrupts the benthic substrate and may suspend sediment, increase turbidity, alter substrate composition, and cause sediment plumes. The resuspension process of contaminated sediments (e.g., metals, tributyltins, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and pesticides) releases contaminants into the surrounding water column that may then become biologically available (Eggleton and Thomas 2004).

Other faunal activities of introduced non-native species include burrowing, ingestion and defecation of sediment grains, and consumption of the vegetation. In special circumstances, the benthic infauna influences the distribution of oxygen in sediments through active mixing of sediment particles (i.e., bioturbation). These

Fig. 14.4 Harvesting of the Manila clam, *Ruditapes philippinarum*, with shellfish dredges in the Tagus estuary, Portugal (Photograph by Paula Chainho)

activities also intensify the benthic–pelagic coupling because benthic infauna can profoundly influence N cycling through their feeding, metabolic, burrow construction, bioturbation, and sediment ventilation activities (Welsh 2003).

14.5 Conclusions

Many phytoplankton species are transported by ship ballast waters. Some of these species, when introduced, form phytoplankton blooms with severe impacts on water quality. The occurrence of harmful algae species in regions where they were not previously observed has lead to a vast array of different impacts, including the production of an uncharacterised suite of toxic compounds, depletion of oxygen, production of mucilage covering benthic communities, decreased water transparency, water discolouration, and foul odours and taste. Filter-feeding bivalve mollusks have a key role controlling the proliferations of these harmful algae. The filtering capability by native and non-native bivalve species may cause massive declines in phytoplankton biomass, mitigating the effects of algal proliferations. The high abundance of invasive bivalves can also promote the filtration of large volumes of water, removing suspended particles and thus increasing the transparency of certain aquatic systems. Nevertheless, the high densities and high biomass achieved by invasive bivalve species can cause considerable ecological problems and physical environment modifications via selective grazing of phytoplankton species that induce the dominance of toxic groups, altering nutrient dynamics, increasing sedimentation, biofouling, changing biotic interactions, and enabling the accumulation and transfer of contaminants. Understanding the impacts of invasive species on water quality is crucial for supporting further legal water framework directives and environmental management decisions.

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