# Chapter 14

# Marine invaders and bivalve aquaculture: sources, impacts, and consequences

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## Introduction

Since the earliest times of human travel, people have transported species beyond their native ranges. Some introductions have been deliberate for food and trade, while others have been an unintentional consequence of species being transported with the movement of humans and goods. Historically, this was in large part due to a lack of knowledge or understanding of the potential dangers of such introductions, especially the ecological and economic damage that can occur when species are transported to areas outside of communities and systems with which they share a long-term evolutionary history. For example, starlings were deliberately introduced to Central Park in 1890 as homage to Shakespeare, but are now a major pest, causing $800 million in agricultural damages annually (Pimentel et al. 2005). The eastern gray squirrel (*Sciurus carolinensis*) was first introduced to Britain in 1876 as a living garden ornament, and became major pests both in Britain and Europe. This introduction is now responsible for economic losses and extensive ecological damage across Britain and Europe (Gurnell et al. 2004).

With globalization and increased trade, there has been an increase in the spread and impacts of species that have been introduced outside of their native range. As these introductions begin to have major impacts on ecosystem services on which we depend, such as species cultivated in aquaculture, greater

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interest has been generated on controlling the spread and impacts of nonnative species. The heightened awareness of the problems associated with nonnative introductions has resulted in more care and often regulations to prevent the unintentional spread of macrospecies beyond their native ranges.

The introduction and spread of nonnative species has garnered much recent attention from scientists, managers, and industry on virtually every continent, as it is one of the most pressing environmental issues around the globe. The environmental and economic costs of introductions of nonnative species introductions are enormous and increasing daily. A recent estimate of the total annual cost of nonnative species introductions in the United States, in terms of losses and damages as well as control costs, exceeds $120 billion (Pimentel et al. 2005). In spite of awareness and regulations, new species introductions and the spread of existing pest species continue.

Several terms have been used to describe such species of concern. They have been variously described as exotic species, alien species, introduced species, and invasive species (Colautti and Richardson 2009). Some authors have tried to make distinctions between species that are known to have economic impacts or those that behave differently in new areas as compared with their native habitats (Valéry et al. 2008). The economic and environmental impacts of most species have not, however, been assessed, and there are often long lag times between initial introductions and spread and the measured impacts for many species (e.g., Klinger et al. 2006; Blanchard 2009; Karatayev et al. 2009). Here were are considering all species that are out of place in time and space relative to their natural distribution, and will refer to them as introduced species or invaders. These species have been transported beyond their native range by human activities, rather than through natural dispersal.

In marine waters, aquaculture has a long history, dating back to oyster cultivation by the Romans (Gunther 1897; Chew 1990). Oysters and other marine species have been transported for aquaculture since at least the 1700s (reviewed in Food and Agriculture Organization (FAO) 1997; Chew 1990; Ruesink et al. 2005; McKindsey et al. 2007). Along with the transport of species for aquaculture there has been the unintentional transport of associated species (e.g., commensals, attached organisms, parasites, and diseases) to new waters. Charles Elton (1958) noted that aquaculture, especially oyster aquaculture, was particularly important for the spread of nonnative species. He states that, "But the greatest agency of all that spreads marine animals to new quarters of the world must be the business of oyster culture." He goes on to say that, "The moving about, without particularly stringent precautions, of masses of oysters was bound to spread other species as well."

Why should we care about introduced species? As mentioned above, these species can cause considerable direct economic and environmental damage. They can impact human activities or structures (e.g., fouling human-made and human-used structures), impact species of concern to humans (e.g., commercial species), or disrupt natural communities and the ecosystem services they provide. The spread of nonnative species can also have indirect effects. They can facilitate the spread of harmful algae or disease agents that are toxic or harmful to humans or other important species (e.g., Lilly et al. 2002; Cohen and Zabin 2009; Hégaret et al. 2009; Shumway, unpublished data; see also Chapter 13 in this book). For example, the shellfish disease caused by the protozoan *Bonamia* has been introduced to different shores with the transport of shellfish (Friedman and Perkins 1994; Cigarría and Elston 1997; Bishop et al. 2006), and this disease can have devastating impacts on local native fisheries where it is introduced (McArdle et al. 1991).

Presently, shipping, ballast water, and hull fouling are the primary sources of new species introductions and the spread of introduced species in aquatic habitats (Cohen and Carlton 1998). Many species introduced through shipping activities have large impacts on aquaculture species and activities associated with aquaculture. Shipping is not, however, the only source of introduced pests. Aquaculture is the second leading source of introduced species (Ruiz et al. 1997). In many cases, other species are transported outside of their native range with aquaculture species (Mann 1979; Critchley and Dijkema 1984; Blanchard 1997; Cohen and Zabin 2009). In other cases, the aquaculture species themselves can escape culture and spread from where they are initially introduced (reviewed in McKindsey et al. 2007).

Rather than providing a comprehensive history of species introductions, this chapter is intended to provide an overview of the practices surrounding introductions and the impacts of introductions on shellfish aquaculture. This chapter will also keep an eye toward improved management decisions and aquaculture practices that will reduce the likelihood of unwanted species introductions and their cascading negative impacts. Here we present information on shellfish aquaculture species and species transported in association with aquaculture activities that have become introduced outside of their native range, as well as introduced species that impact shellfish aquaculture. We also address management and policy strategies and needs to minimize the role of aquaculture as a source of nonnative introductions, as well as strategies that will help the aquaculture industry by reducing the introduction and spread of species that impact shellfish aquaculture.

## Introduced shellfish from aquaculture

The "Blue Revolution" of shellfish aquaculture is widely recognized as an important source of food and an important tool for protecting wild populations of commercial species, which often fall victim to overharvest (Muir 2005; Costa-Pierce 2010). Many authors have reviewed the history of the development of aquaculture (e.g., Shatkin et al. 1997, and references therein; Kurlansky 2006). Initially, the majority of shellfish introductions were deliberate, for replacement fisheries for a collapsed native species fishery or to develop a new industry, such as the introduction of *Argopecten irradians* to China (see Chew 1990). Shellfish represent one-quarter of all aquaculture production worldwide (FAO 1997; USDA 2009). In the U.S. Department of Agriculture (USDA) census of aquaculture, $203 million of the $1.1 billion aquaculture industry was associated with molluscan shellfish aquaculture (USDA 2009). By far, the fastest growing sector of the aquaculture industry is the culture of molluscs, including primarily oysters, clams, and scallops, which increased ~130% from 1998 to 2005 (USDA 2009). As the shellfish industry has grown and hatchery and husbandry techniques have been developed, aquaculture has spread, and the number of species cultured and places where aquaculture has developed has grown accordingly.

The species most widely introduced around the world for shellfish aquaculture is the Pacific oyster, *Crassostrea gigas* (Kurlansky 2006; McKindsey et al. 2007). This species was initially introduced to the Pacific coast of North America from Japan in 1903 to replace the fishery for the native Olympic oyster, *Ostrea lurida*, which was depleted by the late 1800s (Chew 1990; see also the *Journal of Shellfish Research* 28[1] and reviews therein). Olympic oysters form reefs, but are small bodied. They are slow growing, and have relatively low fecundity and limited dispersal potential (Baker 1995). Commercial harvesting rapidly decimated local populations and a replacement oyster was sought to maintain the growing oyster industry, and to supply oysters to the U.S. East Coast where populations of the native *Crassostrea virginica* were suffering from overharvest (Mann 1979; Quayle 1988). Similar stories have played out around the world as populations of native shellfish are overharvested and the demand for shellfish has increased. With growing demand, there has been a steady increase in efforts to indentify new shellfish species for commercial cultures.

At present, there are at least 63 species of bivalves in aquaculture somewhere in the world. Table 14.1 provides a list of bivalve species grown in aquaculture, their native range, and the countries or continents in which they are presently grown in culture. Of the 63 bivalve species cultured, 15 (24%) are grown on continents outside of their native range (Table 14.1). Many of the species that are grown only on their native continent are grown in areas outside of their native range, where natural dispersal would never carry them. Of the 15 species grown on continents outside of their native range, 33% (5 of 15) have been documented to have established feral populations and are having negative impacts on the systems where they have invaded (Table 14.2).

Activities associated with shellfish aquaculture have been responsible for the introduction of 48 additional noncultured species to new regions of the world (Table 14.3). Once species are introduced outside of their native range, they may continue to spread via the dispersal of adults or larvae. The new feral populations that are created may then serve as source populations for introductions through other vectors. For example, although *Crassostrea gigas* was deliberately introduced for culture to many areas in Europe, it appears also to have spread to some areas in Europe via fouled ship hulls (Fletcher and Manfredi 1995; Eno et al. 1997; Eno 1998).

Many of the bivalve species grown in aquaculture are important ecosystem engineers, capable of having large impacts on communities and ecosystems where they are found by modifying the physical habitat or ecosystem processes in a way that changes the habitat for other species (Jones et al. 1994; Cuddington et al. 2007). Oysters are especially important ecosystem engineers and, when in high density, have the ability to modify ecosystems dramatically and alter habitat suitability for other species (see Chapter 9 in this book)

Among the aquaculture species that have become introduced outside of their native range, bivalves are by far the most studied. In some cases, these species have been deliberately introduced to establish feral populations for seeding aquaculture, such as *Crassostrea gigas* in British Columbia, Canada (Quayle 1988), which is frequently considered among the 100 worst invaders worldwide (DAISIE 2008). In other cases, species have escaped aquaculture operations and are now spreading through larval transport, such as *Perna viridis* (Rajagopal et al. 2006). In the Wadden Sea and in France, recent warming of local waters is believed to be facilitating the spread of *Crassostrea gigas* (Diederich et al. 2005; Schmidt et al. 2008; Thieltges et al. 2009) and increased invasion, especially through larval transport, is expected with continued climatic change. These feral populations can have large impacts on the systems they invade and can impact other ecologically and commercially important species (e.g., Dubois et al. 2006; Nehls et al. 2006; Rajagopal et al. 2006; Kochmann et al. 2008; Markert et al. 2010). These invasions can also impact marine reserves, a major tool for the protection of marine biodiversity and wild-caught fisheries. Klinger et al. (2006) found that invading *Crassostrea gigas* in the San Juan Archipelago in Washington State was more abundant in marine reserves than paired control areas outside of reserves. This invasion appears to be impacting biodiversity, especially when oysters are dense (D.K. Padilla, pers. obs.). Surprisingly, few quantitative or experimental studies have examined the impacts of aquaculture escapees on the systems they invade (Table 14.2). This is clearly an area where more research is needed before we can draw

**Table 14.1** Bivalve species in aquaculture.

| Family | Species | Common name | Native range | Nonnative | Escaped |
|---|---|---|---|---|---|
| Arcidae | *Anadara granosa* | Blood cockle | Asia | | |
| | *Scapharca broughtonii* | Inflated ark | Asia | | |
| | *Scapharca subcrenata* | Half-crenate ark | Asia | | |
| Cardiidae | *Cerastoderma edule* | Common edible cockle | Africa, Europe, Former USSR | | |
| Hiatellidae | *Panopea abrupta* | Pacific geoduck | North America | | |
| Mactridae | *Mactra glabrata* | Smooth mactra | Africa | | |
| | *Mactra veneriformis* | Globose clam | Asia | | |
| | *Spisula solidissima* | Atlantic surf clam | North America | | |
| Myidae | *Mya arenaria* | Sand gaper | North America, Asia, Europe, Former USSR | North America | Yes |
| Mytilidae | *Aulacomya ater* | Cholga mussel | Africa, South America, Oceania | | |
| | *Choromytilus chorus* | Choro mussel | South America | | |
| | *Mytilus californianus* | Californian mussel | North America | | |
| | *Mytilus chilensis* | Chilean mussel | South America | | |
| | *Mytilus coruscus* | Korean mussel | Asia, Former USSR | | |
| | *Mytilus edulis* | Blue mussel | Africa, North America, South America, Asia, Europe | | |
| | *Mytilus galloprovincialis* | Mediterranean mussel | Africa, Asia, Europe, Former USSR | Africa, North America, Asia | Yes |
| | *Mytilus planulatus* | Australian mussel | Oceania | | |
| | *Perna canaliculus* | New Zealand mussel | Oceania | | |
| | *Perna indica* | Indian brown mussel | Asia | | |
| | *Perna perna* | South American rock mussel | Africa, South America | North America | |
| | *Perna viridis* | Green mussel | Asia, Oceania | North America, Oceania | Yes |

**Table 14.1** (*Continued*)

| Family | Species | Common name | Native range | Nonnative | Escaped |
|---|---|---|---|---|---|
| Pectinidae | *Aequipecten opercularis* | Queen scallop | Africa, Europe | | |
| | *Argopecten irradians* | Atlantic bay scallop | North America, South America | Asia | |
| | *Argopecten purpuratus* | Peruvian calico scallop | North America, South America | | |
| | *Argopecten ventricosus* | Pacific calico scallop | North America, South America | | |
| | *Chlamys farreri* | Farrer's scallop | Asia, Former USSR | | |
| | *Chlamys islandica* | Iceland scallop | North America, Europe, Former USSR | | |
| | *Chlamys nobilis* | Noble scallop | Asia | | |
| | *Patinopecten yessoensis* | Yesso scallop | Asia, Former USSR | North America | |
| | *Pecten fumatus* | Australian southern scallop | Oceania | | |
| | *Pecten maximus* | Great Atlantic scallop | Africa, Europe | | |
| | *Pecten novaezelandiae* | New Zealand scallop | Oceania | | |
| | *Placopecten magellanicus* | Sea scallop | North America | | |
| Pteriidae | *Pinctada fucata* | Japanese pearl oyster | Africa, Asia, Oceania | | |
| | *Pinctada margaritifera* | Black-lip pearl oyster | Africa, North America, Asia, Oceania | | |
| | *Pinctada maxima* | Silver-lip pearl oyster | Asia, Oceania | | |
| | *Pteria penguin* | Penguin wing oyster | Asia | Oceania | |
| Ostreidae | *Crassostrea belcheri* | Lugubrious cupped oyster | Asia | | |
| | *Crassostrea corteziensis* | Cortez oyster | North America, South America | | |
| | *Crassostrea gigas* | Pacific oyster | Asia | Africa, North America, South America, Europe, Oceania | Yes |
| | *Crassostrea iredalei* | Slipper cupped oyster | Asia | | |
| | *Crassostrea madrasensis* | Indian backwater oyster | Asia | | |

**Table 14.1** (*Continued*)

| Family | Species | Common name | Native range | Nonnative | Escaped |
|---|---|---|---|---|---|
| | *Crassostrea rhizophorae* | Mangrove cupped oyster | North America, South America | Oceania | |
| | *Crassostrea rivularis* | Suminoe oyster | Asia | North America | |
| | *Crassostrea virginica* | Eastern oyster | North America, South America | North America | Yes |
| | *Ostrea chilensis* | Chilean flat oyster | South America | | |
| | *Ostrea edulis* | European flat oyster | Europe | North America | |
| | *Ostrea lurida* | Edible (flat) oyster | North America | | |
| | *Saccostrea commercialis* | Sidney rock oyster | Oceania | | |
| | *Saccostrea cuccullata* | Hooded oyster | Africa, Asia | Europe | |
| | *Saccostrea echinata* | Spiny oyster | Asia, Oceania | | |
| Solecurtidae | *Sinonovacula constricta* | Constricted tagelus | Asia | | |
| Tridacnidae | *Tridacna derasa* | Smooth giant clam | Asia, Oceania | | |
| | *Tridacna gigas* | Giant clam | Asia, Oceania | | |
| Veneridae | *Mercenaria mercenaria* | Northern quahog | North America | Europe | |
| | *Meretrix lusoria* | Japanese hard clam | Asia | | |
| | *Meretrix meretrix* | Asiatic hard clam | Asia | | |
| | *Paphia undulata* | Undulate venus | Asia | | |
| | *Protothaca staminea* | Pacific littleneck clam | North America | | |
| | *Venerupis decussatus* | Grooved carpet shell | Africa, Asia, Europe | | |
| | *Venerupis philippinarum* (*Ruditapes philippinarum*) | Japanese littleneck | North America, Asia | Europe | |
| | *Saxidomus giganteus* | Butter clam | North America | | |
| | *Venerupis pullastra* | Pullet carpet shell | Africa, Asia, Europe | | |

Species are grouped by family. Columns include the continents where each species is naturally found and grown in aquaculture ("Native range") and where it has been introduced for aquaculture outside of that native range ("Nonnative"). For both the native range and where they are grown, species are not always found or grown in all areas within each geographic area. "Escaped" designates those species that have been documented to spread beyond where they are grown for aquaculture or have established feral populations. Information on all species from FAO (1996). Information on *Mya arenaria, Mytilus galloprovincialis, Perna viridis* and *Crassostrea gigas* also from the U.S. Geological Survey (USGS 2009) and data for *Crassostrea virginica* also from Coles et al. (1999).

**Table 14.2** Bivalve aquaculture species that have escaped in regions outside of their native range, and documented impacts of feral populations.

| Scientific name | Common name | Impact | Species/systems impacted | Reference |
|---|---|---|---|---|
| *Crassostrea gigas* | Pacific oyster | Ecosystem engineer, change substrate available for other species, competition for space with benthic species, competition for food with suspension-feeders, overgrowth of benthic species, affect suspended particle concentrations and quality, decrease turbidity and increase light penetration, provide refuge for invertebrates from predators, affect flow and sedimentation, foul water systems | Soft sediment communities, fouling community (ascidians, bryozoans, sponges, hydrozoans, algae), native intertidal mussels, cultivated *Crassostrea gigas*, other engineering and reef building species including honeycomb worm (*Sabellaria alveolata*) | Diederich et al. (2005); Cognie et al. (2006); Decottignies et al. (2007a, 2007b); Rodriguez and Ibarra-Obando (2008); Sousa et al. (2009; reviewed in Ruesink et al. 2005) |
| *Crassostrea virginica* | Eastern oyster | Ecosystem engineer, affect phytoplankton species composition, biodeposition of waste materials, affect flow and sedimentation, decrease turbidity, increase light penetration, provide refuge for invertebrates from predators, foul water systems | Phytoplankton, benthic invertebrate communities | Mugg Pietros and Rice (2003); Sousa et al. (2009; reviewed in Ruesink et al. 2005) |
| *Mytilus galloprovincialis* | Mediterranean mussel | Ecosystem engineer, increase habitat for infaunal species, provide hard substrate, provide refuge for invertebrates, increase recruitment and species richness in some habitats, affect flow and sedimentation, empty shells block soft-sediment burrowing organisms, increase food supply for intertidal predators, competitive displacement of native species, hybridize with native mussels | *Mytilus trossulus,* soft-sediment burrowers, tube-building polychaete *Gunnarea capensis,* limpet *Soutellastra granularis,* limpet *Soutellastra argenwillei*, other benthic invertebrates, African black oystercatchers *Haematopus moquini* | Branch and Steffani (2004); Wonham (2004); Steffani and Branch (2005); Robinson et al. (2005, 2007); Coleman and Hockey (2008); Sousa et al. (2009); Branch et al. (2010) |

**Table 14.2** (*Continued*)

| Scientific name | Common name | Impact | Species/systems impacted | Reference |
|---|---|---|---|---|
| *Ostrea edulis* | Edible (flat) oyster | Ecosystem engineer, provide refuge for invertebrates from predators, spread disease | Other populations of *Ostrea edulis* | da Silva et al. (2005); Sousa et al. (2009); reviewed in Ruesink et al. 2005) |
| *Perna perna* | Brown mussel | Ecosystem engineer, provide hard substrate in soft-sediment habitats, provide refuge for invertebrates from predators, affect flow and sedimentation, foul navigation buoys, foul water systems | Benthic invertebrate communities | Rajagopal et al. (2003); Sousa et al. (2009) |
| *Perna viridis* | Green mussel | Ecosystem engineer, provide hard substrate, affect water flow and sedimentation, foul power plant heat interchangers, foul water systems, clog crab traps and clam culture bags, foul vessels | Algae, hydroids, tubiculous polychaetes, barnacles, and ascidians, free-living polychaetes, and amphipods | Masilamoni et al. (2003, 2002); Rajagopal et al. (2003); Sousa et al. (2009; reviewed in Rajagopal et al. 2006) |
| *Venerupis philippinarum* | Japanese littleneck | Ecosystem engineer, provide refuge from predators, provide hard substrate, affect flow and sedimentation, enhancement of oxygen and solute penetration because of burrowing, increase filtration capacity of bivalves in ecosystem, increase food supply for intertidal predators | Eurasian oystercatcher, *Haematopus ostralegus ostralegus*, *Polydora* spp., other benthic invertebrates | Gosling (2003); Pranovi et al. (2006); Caldow et al. (2007); Sousa et al. (2009) |

generalizations. Thus far, the majority of impacts appear to be due to the ecosystem engineering effects of these invaders (Padilla 2010). The types of impacts of invasion by feral aquaculture species that have been documented include fouling, overgrowth, or displacement of native benthic species (Reise et al. 2005; Diederich 2006; Nehls et al. 2006; Buttger et al. 2008; Kochmann et al. 2008; Krassoi et al. 2008; Markert et al. 2010) and reduced recruitment of native species and negative impacts on populations of other

**Table 14.3** Taxa that have been introduced through bivalve aquaculture, either intentionally or accidentally.

| Group | Scientific name | Common name | Introduction | Reference |
|---|---|---|---|---|
| Alga (brown) | *Rugulopteryx okamurae* | | Accidental | Verlaque et al. (2009) |
| | *Sargassum muticum* | | Accidental | Critchley and Dijkema (1984); FAO (2005) |
| | *Undaria pinnatifida* | Asian kelp | Intentional and accidental | Fletcher and Manfredi (1995); Curiel et al. (2001); Global Invasive Species Database (GISD) (2005) |
| Alga (diatom) | *Coscinodiscus wailesii* | | Accidental | Laing and Gollasch (2002) |
| Alga (dinoflagellate) | *Alexandrium catenella* | | Accidental | Lilly et al. (2002) |
| | *Alexandrium minutum* | Red tide dinoflagellate | Accidental | GISD (2005) |
| | *Gonyaulax excavata* | | Accidental | Langeland et al. (1984) |
| | *Gymnodinium catenatum* | Chain-forming dinoflagellate | Accidental | GISD (2005) |
| | *Procentrum minimum* | | Accidental | Langeland et al. (1984) |
| Alga (green) | *Codium fragile tomentosoides* | Dead man's fingers | Accidental | GISD (2005) |
| Alga (red) | *Heterosiphonia japonica* | | Accidental | Sjøtun et al. (2008); Moore and Harries (2009) |
| Annelid | *Boccardia proboscidea* | | Accidental | Bailey-Brock (2000) |
| | *Polydora* sp. | | Accidental | FAO (2007) |
| | *Polydora nuchalis* | | Accidental | Bailey-Brock (1990) |
| Bacteria | *Vibrio cholerae* | Asiatic cholera | Accidental | GISD (2005) |
| Bryozoan | *Bugula neritina* | Brown bryozoan | Accidental | GISD (2005) |
| | *Schizoporella errata* | Branching bryozoan | Accidental | GISD (2005) |
| | *Schizoporella unicornis* | Single-horn bryozoan | Accidental | GISD (2005) |
| Crustacean | *Mytilicola orientalis* | Parasitic copepod | Accidental | McKindsey et al. (2007) |
| | *Rhithropanopeus harrisii* | Estuarine mud crab | Accidental | GISD (2005) |
| Echinoderm | *Asterias amurensis* | Flatbottom sea star | Accidental | GISD (2005) |

**Table 14.3** (*Continued*)

| Group | Scientific name | Common name | Introduction | Reference |
|---|---|---|---|---|
| Mollusc | *Batillaria attramentaria* | Asian hornsnail | Accidental | |
| | *Boonea bisuturalis* | Two-groove odostome | Accidental | GISD (2005) |
| | *Crassostrea gigas* | Pacific oyster | Intentional | GISD (2005) |
| | *Crassostrea virginica* | Eastern oyster | Intentional | McKindsey et al. (2007) |
| | *Crepidula fornicata* | Common Atlantic slippersnail | Accidental | Minchin et al. (1995); Blanchard (1997); GISD (2005) |
| | *Cyclope neritea* | | Accidental | Le Duff et al. (2009) |
| | *Fusinus rostratus* | | Accidental | Le Duff et al. (2009) |
| | *Gemma gemma* | Amethyst gem clam | Accidental | GISD (2005) |
| | *Gibbula albida* | | Accidental | Le Duff et al. 2009 |
| | *Mercenaria mercenaria* | Northern quahog | Intentional | FAO (2005); Le Duff et al. 2009 |
| | *Musculista senhousia* | Senhouse mussel | Accidental | Bachelet et al. (2009); GISD (2005) |
| | *Mya arenaria* | Eastern soft-shell clam | Accidental | GISD (2005); Le Duff et al. 2009 |
| | *Mytilopsis sallei* | Black-striped mussel | Accidental | GISD (2005) |
| | *Mytilus galloprovincialis* | Mediterranean mussel | Accidental | GISD (2005) |
| | *Ocinebrellus inornatus* | Japanese oyster drill | Accidental | Faasse and Ligthart (2009); Le Duff et al. (2009) |
| | *Ostrea edulis* | Edible (flat) oyster | Intentional | GISD (2005) |
| | *Perna perna* | Brown mussel | Intentional and accidental | FAO (2005) |
| | *Perna viridis* | Green mussel | Intentional and accidental | GISD (2005) |
| | *Rangia cuneata* | Atlantic rangia | Accidental | GISD (2005) |
| | *Rapana venosa* | Asian rapa whelk | Accidental | GISD (2005); Le Duff et al. (2009) |
| | *Urosalpinx cinerea* | Eastern oyster drill | Accidental | Faasse and Ligthart (2009); GISD (2005) |
| | *Venerupis philippinarum* | Manila clam | Accidental | Cloern (1982); FAO (2005); Le Duff et al. (2009) |
| Plant | *Spartina alterniflora* | Smooth cordgrass | Accidental | Chew (1998); Civille et al. (2005) |
| Protozoan | *Perkinsus marinus* | Dermo | Accidental | Cohen and Zabin (2009) |
| Tunicate | *Ascidiella aspersa* | European sea squirt | Accidental | GISD (2005) |
| | *Styela clava* | Asian tunicate | Accidental | GISD (2005) |
| | *Styela plicata* | Leathery tunicate | Accidental | GISD (2005) |

important native ecosystem engineers (Dubois et al. 2006; Kelly and Volpe 2007; Kelly et al. 2008). Feral populations of aquaculture species have also been found to function as an ecological trap for important native species (Trimble et al. 2009) or to hybridize with native species, disrupting local populations and aquaculture (e.g., Rawson et al. 1999; Wonham 2004; Dias et al. 2009; Shields et al. 2010).

## Species moved with aquaculture

The movement of species for aquaculture has also resulted in the introduction of a wide range of additional species associated with the target species (Mann 1979; Carlton 1989, 1996, 1999). This has included all types of organisms, from macro animal and algal species to microparasites, including disease agents (Chapter 13), and harmful microalgae (Table 14.3). Over 40 species of bivalves, gastropods, arthropods, echinoderms, crustaceans, and algae have been introduced through activities associated with bivalve shellfish aquaculture. In some cases, these organisms were introduced historically, when the aquaculture industry was in its infancy, and when the ecological and economic dangers of transporting nonnative species to new environments were not known or considered unimportant (Elton 1958). For example, in the early days of oyster aquaculture, large quantities of oysters were collected from natural environments and sent by train or ship to new parts of the world (Mann 1979). As ecosystem engineers, oysters provide habitat for a wide range of both sessile and mobile species. Thus, when oysters were placed in new habitats with the hopes that they would grow and thrive, all of their associates were also moved and introduced. In some cases, the species that were transferred became significant pests of the aquaculture industry that was established. Smooth cordgrass, *Spartina alterniflora*, is the primary salt marsh grass on the Atlantic coast of North America. However, this species was accidentally introduced on the West Coast, most likely with oysters transferred from the Atlantic seaboard (Civille et al. 2005). The spread of this invader greatly reduces essential habitat for shellfish and aquaculture, and thus, although it is a protected species in much of its native habitat, it has become a major pest where introduced, especially when it hybridizes with native congeners (Brusati and Grosholz 2008).

The Atlantic slipper snail, *Crepidula fornicata*, is another such species. This snail is a suspension feeder that occurs in very high population densities. It was carried to Europe with the transfer of the eastern oyster, *Crassostrea virginica*, which was imported as a replacement for the severely overharvested European flat oyster, *Ostrea edulis*. Although the eastern oyster did not prove to be a good species for aquaculture in Europe, and was replaced by importation of the Pacific oyster, *Crassostrea gigas*, introduced populations of *Crepidula fornicata* have flourished (Minchin et al. 1995; Blanchard 1997). This snail is currently a major problem for shellfish aquaculture in many areas of Europe, where it competes with aquaculture species for suspended food. The Japanese littleneck (=Manila clam), *Venerupis* (*Ruditapes*) *philippinarum*, is another species accidentally introduced with the Pacific oyster. Rather than becoming a pest like *Crepidula fornicata*, the Japanese littleneck has become an important commercial species (Chew 1990). Japanese littlenecks have primarily supported a wild-caught fishery on the U.S. West Coast and Canada, but there has been a recent expansion of aquaculture for this species in North America and Europe (Flassch and Leborgne 1990; Zhu et al. 1999; Ferreira et al. 2009).

With the development of hatchery techniques, the movement of wild-caught animals for aquaculture has been greatly reduced as growers are able to reliably produce seed for transplant in the lab, and no longer need to rely on reproduction in the wild or constant restocking from native regions (Quayle 1988). In some cases, live animals or their shells are still moved for aquaculture and restoration purposes (Luckenbach et al. 1999; Hégaret et al. 2008; Cohen and Zabin 2009). Awareness of the problems associated with nonnative introductions has resulted in more care, and in some cases, regulations to prevent the unintentional spread of macrospecies. Microspecies, including harmful algae (see Hégaret et al. 2008), protozoans, and viruses, including some that cause disease, remain a challenge, especially when species are moved within a country with the transfer of aquaculture species. This was the case with the spread of the oyster parasite *Perkinsus marinus* (dermo), which was spread to Delaware Bay with oysters from the Chesapeake (Ford 1996).

Advances are being made to determine best practices to minimize the likelihood of unintentional transfers of species (e.g., Mineur et al. 2007; Hégaret et al. 2008; see section below). Illicit trade in some species continues, and it continues to introduce species to new areas (Verlaque and Latala 1996).

## Introduced species that impact aquaculture

Many nonnative species that have been introduced in marine and estuarine waters around the world have deleterious impacts on shellfish aquaculture (e.g., Anon 2005; Castilla et al. 2005; Bullard et al. 2007; Lambert 2007) (Table 14.4). Ironically, as mentioned above, some of these species are those that were introduced via aquaculture (Table 14.3). As mentioned above, *Crepidula fornicata* is very abundant now in its introduced range and competes with native blue mussels, as well as *Crassostrea gigas*, which is now the major shellfish grown in aquaculture in Europe (Beninger et al. 2007; Blanchard et al. 2008; Blanchard 2009). The oyster drill, *Urosalpinx cinerea*, was introduced with shellfish aquaculture from the Atlantic coast of North America to the Pacific coast and now is an important predator for *Crassostrea gigas* aquaculture and is impacting restoration efforts for the native Olympia oyster, *Ostrea lurida*, in Washington State (Buhle and Ruesink 2009). The green crab, *Carcinus maenas*, a European native that was introduced to the North American Atlantic coast over 100 years ago, was recently introduced to the Pacific coast of North America in 1995. This invader spread north with warm waters during an El Niño Southern Oscillation (ENSO) event, and populations have persisted as far north as British Columbia, Canada (Behrens Yamada et al. 2005, 2008a). Research is under way to determine the impacts of this invader on shellfish and aquaculture (Behrens Yamada et al. 2008a, 2008b; Behrens Yamada and Kosro 2010).

A large number of marine invaders that impact shellfish aquaculture are fouling species (Table 14.4). They include a variety of macroalgae, ascidians (both colonial and solitary), and bryozoans. Ascidians are of special concern as they are increasing in abundance globally and can spread very quickly once introduced (Anon 2005; Bullard et al. 2007; Lambert 2007). They are large bodied and foul cages and other gear, reducing water flow necessary for healthy shellfish (Bullard et al. 2005; Ramsay et al. 2008). They also are very effective suspension-feeders, can directly compete with bivalves for suspended food (Currie et al. 1998), and may serve as a vector for transfer of harmful algal species (Shumway, unpublished). In a recent survey assessing the impacts of fouling species on the economics of aqaculture, Adams et al. (2011) found that efforts to control biofouling cost ~15% of the total operating costs for individual aquaculture businesses and over 40% of businesses feel that fouling decreases the marketability of their product. With the increased number of

**Table 14.4** Introduced species that have been documented to impact bivalve aquaculture, and which aquaculture species or industry they are known to impact.

| Group | Scientific name | Common name | Species impacted | Impact | Reference |
|---|---|---|---|---|---|
| Alga (brown) | *Sargassum muticum* | | *Ostrea edulis*; mussel long line | Foul organisms, may foul gear | Critchley and Dijkema (1984); Harries et al. (2007) |
| Alga (dinoflagellate) | *Alexandrium minutum* | | Mussels | Toxic, PSP | Hallegraeff et al. (1988); Delgado et al. (1990) |
| | *Gonyaulax excayata* | | Mussels | Toxic, PSP | Langeland et al. (1984) |
| | *Gymnodinium catenatum* | | *Mytilus galloprovincialis* | Toxic, PSP | Hallegraeff et al. (1988); Laiño (1991) |
| | *Procentrum lima* | | Mussels | Toxic, PSP | Levasseur et al. (2003) |
| | *Procentrum mexicanum* | | Mussels | Toxic, PSP | Levasseur et al. (2003) |
| | *Procentrum minimum* | | Mussels | Toxic, PSP | Langeland et al. (1984) |
| Alga (green) | *Codium fragile* | Dead man's fingers | *Mytilus galloprovincialis*; oysters | Increase recruitment and survival, overgrowth, decrease abundance | Trowbridge (1999); Bulleri et al. (2006) |
| Annelid | *Imogine mcgrathi* | | *Pincta imbricata* | Predation | O'Connor and Newman (2001) |
| | *Boccardia proboscidea* | | Oysters | Bore into shell, cause blisters, increase parasitism risk | Bailey-Brock (2000); National Introduced Marine Pest Information System (NIMPIS) (2002) |
| | *Polydora* spp. | Mudworm | *Ostrea angasi*, *Patinopecten yessoensis*, *Saccostrea commercialis*, *Saccostrea glomerata* | Bore into shell | FAO (2007); Ogburn et al. (2007) |
| | *Polydora ciliata* | | *Mytilus edulis* | Bore into shell | FAO (2007) |
| | *Polydora nuchalis* | | | Accumulate in culture ponds | Bailey-Brock (1990) |
| | *Polydora websteri* | | *Crassostrea gigas*, *Mytilus galloprovincialis*, *Ostrea angasi*, *Pecten fumatus* | Bore into shell | Bailey-Brock (1990); Nell (2007) |

**Table 14.4** (*Continued*)

| Group | Scientific name | Common name | Species impacted | Impact | Reference |
|---|---|---|---|---|---|
| Bacteria | *Nocardia crassostreae* | | *Crassostrea gigas* | Disease | Friedman et al. (1998) |
| | Proteobacteria | Juvenile oyster disease | *Crassostrea angulata, Crassostrea virginica* | Disease | Renault et al. (2002); Renault and Novoa (2004) |
| | *Vibrio cholerae* | Asiatic cholera | Shellfish | Disease | Dalsgaard (1998) |
| Bryozoan | *Bugula neritina* | | Scallop pearl nets | Foul gear | Dumont et al. (2009) |
| | *Schizoporella errata* | Branching bryozoan | | Foul gear | GISD (2005) |
| | *Schizoporella unicornis* | Single-horn bryozoan | | Foul gear | GISD (2005) |
| Cnidarian | *Tubularia crocea* | | *Pecten maximus* | Foul gear | Ross et al. (2004) |
| Crustacean | *Carcinus maenus* | European green crab | *Crassostrea gigas, Mya arenaria, Mytilus edulis* | Predation | Behrens Yamada et al. (2008a,b); Glude (1955); Dare et al. (1983); Floyd and Williams (2004); Murray et al. (2007); Behrens Yamada and Kosro (2010) |
| | *Mytilicola orientalis* | Parasitic copepod | *Mytilus edulis*, other mussels, *Ostrea gigas, Ostrea lurida, Paphia staminea* | Parasitism | Odlaug (1946); Cole and Savage (1951); Gee et al. (1977) |
| | *Pilumnus spinifer* | | *Crassostrea gigas* | Foul gear | Sala and Lucchetti (2008) |
| Echinoderm | *Asterias amurensis* | Flatbottom sea star | *Fulvia tenuicostata*, oysters | Predation | NIMPIS (2002); Ross et al. (2002) |
| Mollusc | *Anadara demirii* | Arcid clam | *Crassostrea gigas* | Foul gear, foul organisms | Morello et al. (2004); Sala and Lucchetti (2008) |
| | *Crepidula fornicata* | Common Atlantic slippersnail | *Crassostrea gigas, Mytilus edulis*, and other oysters and mussels | Competition for food, interference competition, exclude other species, foul organisms | Blanchard (1997); Barton and Heard (2005); Decottignies et al. (2007a, 2007b); Thieltges (2005) |

**Table 14.4** (*Continued*)

| Group | Scientific name | Common name | Species impacted | Impact | Reference |
|---|---|---|---|---|---|
| | *Mytilopsis adamsi* | False mussel | | Exclude other species, foul organisms, foul gear | Wangkulangkul and Lheknim (2008) |
| | *Mytilopsis sallei* | Black-stripped mussel | | Decrease species richness | NIMPIS (2002) |
| | *Mytilus galloprovincialis* | Mediterranean mussel | *Crassostrea gigas*, *Mytilus californianus*, *Mytilus edulis* | Decrease species richness, foul gear, overgrowth | Harger (1968); Geller (1999); Sala and Lucchetti (2008) |
| | *Ocinebrellus inornatus* | Japanese oyster drill | Mussels, *Ostrea lurida* | Predation | Buhle and Ruesink (2009); Faasse and Ligthart (2009) |
| | *Rapana venosa* | Asian rapa whelk | *Anadara inaequivalvis*, *Crassostrea gigas*, *Mytilus edulis*, *Mytilus galloprovincialis*, *Tapes philippinarum* | Predation | Kerckhof et al. (2006); Savini and Occhipinti-Ambrogi (2006) |
| | *Urosalpinx cinerea* | Eastern oyster drill | Mussels, *Ostrea lurida*, other oysters | Predation | Barton and Heard (2005); Buhle and Ruesink (2009); Faasse and Ligthart (2009) |
| Plant | *Spartina alterniflora* | Smooth cordgrass | Oysters | Habitat alteration, hybridization with native species | Chew (1998); Brusati and Grosholz (2008) |
| Protozoan | *Bonamia exitiosa* | | *Tiostrea chilensis* | Disease | Ruesink et al. (2005) |
| | *Bonamia osteae* | | *Crassostrea sikamea*, *Ostrea angasi*, *Ostrea edulis*, *Tiostrea chilensis* | Disease | Ruesink et al. (2005) |
| | *Haplosporidium nelsoni* | MSX | *Crassostrea virginica* | Disease | Ruesink et al. (2005) |
| | *Marteilia refringens* | | *Ostrea angasi*, *Ostrea edulis*, *Tiostrea chilensis* | Disease | Ruesink et al. (2005) |
| | *Marteilia sydneyi* | QX | *Saccostrea commercialis* | Disease | Ruesink et al. (2005) |

**Table 14.4** (*Continued*)

| Group | Scientific name | Common name | Species impacted | Impact | Reference |
|---|---|---|---|---|---|
| | *Perkinsus marinus* | Dermo | *Crassostrea ariakensis*, *Crassostrea gigas*, *Crassostrea virginica* | Disease | Ruesink et al. (2005) |
| Tunicate | *Ascidiella aspersa* | European sea squirt | Mussels, oysters, scallops | Competition for food, foul gear | Braithwaite et al. (2006); Currie et al. (1998) |
| | *Asterocarpa humilis* | | Scallop ropes | Foul gear | Castilla et al. (2005) |
| | *Botrylloides violaceus* | Orange sheath tunicate | *Mytilus edulis* | Foul organisms | Ramsay et al. (2008) |
| | *Botryllus schlosseri* | Golden star tunicate | *Crassostrea gigas*, *Mytilus edulis* | Foul gear, foul organisms | Ramsay et al. (2008); Sala and Lucchetti (2008) |
| | *Ciona intestinalis* | Vase tunicate | *Mytilus edulis*, other mussels, scallop pearl nets | Foul gear, foul organisms | Bullard et al. (2005); Castilla et al. (2005); Braithwaite et al. (2006); Blum et al. (2007); Ramsay et al. (2008); Dumont et al. (2009) |
| | *Didemnum* sp. | Carpet tunicate | Mussels, mussel cages, oyster farms, scallops | Foul gear, overgrowth | Bullard et al. (2007) |
| | *Diplosoma listerianum* | | | Foul gear | Bullard et al. (2005) |
| | *Molgula ficus* | | Scallop ropes | Foul gear | Castilla et al. (2005) |
| | *Molgula manhattensis* | Sea grape | | Foul gear | |
| | *Styela clava* | Asian tunicate | *Mytilus edulis* | Foul organisms, overgrowth | Bullard et al. (2005); LeBlanc et al. (2007); Ramsay et al. (2008) |
| | *Styela plicata* | Leathery tunicate | | Decrease species richness, competition for space, foul organisms, slough off and remove other species | Sutherland (1978) |

**Table 14.4** (*Continued*)

| Group | Scientific name | Common name | Species impacted | Impact | Reference |
|---|---|---|---|---|---|
| Virus | Iridolike viruses | | *Crassostrea angulata*, *Crassostrea gigas* | Disease | Ruesink et al. (2005) |
| | Oyster herpesvirus | | *Crassostrea gigas*, *Crassostrea sikamea*, *Ostrea edulis*, | Disease | Ruesink et al. (2005) |
| | Oyster virus velar disease | | *Crassostrea gigas* | Disease | Ruesink et al. (2005) |

Many of these species are likely to have additional ecological or economic impacts. PSP, paralytic shellfish poisoning.

introduced fouling species, especially ascidians, these costs are expected to escalate.

The risk of human-mediated spread of shellfish diseases is also of concern. Increasingly, diseases and parasites are spread to new areas that can have large impacts on native shellfisheries as well as aquaculture (Renault et al. 2002; Renault and Novoa 2004; reviewed in Ruesink et al. 2005). We are also seeing increased spread of bloom-forming harmful algae (HABs). These algae can be spread with transported shellfish. Many HABs can have devastating impacts on shellfish populations (Matsuyama and Shumway 2009). In some cases, HABs cause shellfish mortality, while in others, they result in shellfish closures. Hégaret et al. (2008) examined the potential for bivalve aquaculture to spread harmful algal species and developed methods to minimize the likely transport of HAB species by holding the shellfish either in filtered seawater, free of algae, for 48 h or out of the water for the same time period.

## Recommendations for minimizing spread and impacts of introductions

It is clear that reducing the introduction and spread of nonnative species will be in the best interest of aquaculturists as well as natural resource managers, and will simultaneously protect biodiversity and help conservation efforts. The large economic costs of unwanted species introductions are being faced by aquaculture facilities and shellfish farmers on a daily basis. Many nonnative species including those introduced by aquaculture itself (Table 14.3) have well-documented impacts on aquaculture (Table 14.4). The documented impacts of unwanted nonnative species are often on aquaculture species and include predation and competition, as well as disease and toxic algae. For others, the costs are seen through fouling of gear, all of which increases the costs to aquaculture, and reduces production (Watson et al. 2009; Adams et al. 2011).

The large economic costs and environmental impacts associated with introductions of species outside of their native range has also put international pressure on scientists and managers to develop methodologies and policies that will minimize the spread of these species (Firestone and Corbett 2005), including reducing the likelihood of aquaculture species themselves becoming pests (Read and Fernandes 2003; ICES 2005) (Table 14.2). New laws are being implemented to reduce the transfer of species via shipping ballast (Firestone and Corbett 2005; Gregg et al. 2009; Vander Zanden et al. 2010) as well as deliberate introductions of species known to be harmful elsewhere or potentially harmful in the proposed site (Lacey Act 1900). Because it is difficult, if not impossible, to predict which species will become future problem invaders and because the potential costs of invasion are high, in most cases, risk-averse strategies are used that ban or minimize the transfer of any nonnative species.

Natural resource managers should be concerned and careful about allowing introductions of nonnative species to new areas, even if those species are grown in other regions of the same country or state. Small differences in local environmental conditions can be the difference between a species that is locally contained and one that is spreading and impacting other species or systems of economic or environmental interest, as has been seen with the spread of *Crassostrea gigas* in France and the Netherlands (Diederich et al. 2005; Nehls et al. 2006; Kochmann et al. 2008; Schmidt et al. 2008; Thieltges et al. 2009; Markert et al. 2010). This is an important challenge for the introduction of all species with larvae that disperse or those that can readily be moved with gear or boats. In marine systems, although humans recognize political and geographic boundaries, other species do not. Species with long-distance dispersal larvae can travel hundreds of kilometers and readily cross political boundaries.

This issue came into sharp focus for states surrounding the Chesapeake Bay with regard to the proposed wide-scale introduction of the nonnative oyster, *Crassostrea ariakensis* (Committee on Nonnative Oysters in the Chesapeake Bay, National Research Council 2004; Kingsley-Smith et al. 2009). Ultimately, the decision was made to not allow this large-scale introduction. The potential gains were seen as too few and the potential costs due to the introduction of a nonnative too high. In addition, it was determined that the proposed economic gains of this introduction would not be realized.

Any policy (or lack of policy) in one state or country will affect its neighbors. Such awareness has led to new European Union standards of conformity among member states, recognizing the need to protect aquaculture from unwanted introductions, as well as public resources and private industry from the spread of species introduced through aquaculture activities. Council Regulation (EC) No. 708/2007 of 11 June 2007 created a framework governing aquacultural practices to protect aquatic environments from risks associated with the use of nonnative species of animals and plants (including microscopic species) in aquaculture. It controls the movement of any species that is locally absent for use in all types of aquaculture. It also requires all member states to take all appropriate measures to avoid risk to native species and communities resulting from the movement of nonnative species for aquaculture. The regulation requires that neighboring states are informed when any permits for nonnative aquaculture species are granted. Within the United States, similar types of issues are of concern. The regulation of aquaculture permitting is determined within states, and there is no uniform means by which states allow, or do not allow, establishment of new species for aquaculture. In addition, there is no requirement for cooperation between adjacent states that share waterways on decisions regarding allowing, or disallowing, the introduction of new species for aquaculture.

To address these issues, large-scale national and international efforts have begun to develop best management practices (Chapter 3 in this book), standards, and certification for the development of sustainable aquaculture and to minimize the social and environmental issues associated with bivalve farming. One clear example is the leadership taken by the World Wildlife Fund (WWF) in developing the Bivalve Dialogue (WWF 2011), initiated in 2004, which focuses on oysters, mussels, clams, and scallops. Since 2004, there have been meetings in North America, Europe, New Zealand, and China, with more than 300 participants, with the goal of providing a framework for the development of criteria, indicators, and standards for responsible molluscan shellfish farming.

The WWF dialogue has identified several environmental and social issues related to molluscan production, which include several related to the introduction of nonnative species. These include concerns regarding gene transfer to wild populations and the consequences of escapes and deliberate or inadvertent introduction of new nonnative species, including pests and pathogens. This dialogue has produced a list of principles, which includes those that will reduce the transfer and risk of nonnative species introductions. These include as follows: (1) obey the law and comply with all national and local regulations; (2) conserve natural habitat and local biodiversity; (3) protect the health and genetic integrity of wild populations; (4) manage disease and pests in an environmentally responsible manner; (5) use resources efficiently; (6) be a good neighbor and conscientious coastal citizen; (7) continually improve practices over time; and (8) develop and operate farms in a socially responsible manner.

The WWF dialogues have led to the development of an international Aquaculture Stewardship Council (ASC) with the aim of developing independent third-party accreditation and certification of aquaculture operations of species for which standards have been developed. The ASC will provide a consumer label that can be used by processors and distributors that certify that shellfish products were grown in ways that meet a set of standards.

Individual countries are now starting to develop aquaculture codes of practice that include minimizing the risks and impacts of the spread of introduced species and reducing the likelihood of aquaculture escapees. For example, Ireland is developing such a code that includes examples of actions individual farmers can take, especially for dealing with fouling organisms (www.invasivespeciesireland.com/cops/aquaculture). The Irish codes are based on those developed by the International Council for the Exploration of the Sea (ICES) Code of Practice on the Introductions and Transfers of Marine Organisms developed in 2005 (ICES 2005) and other international working groups developed to stop the spread of unwanted invaders. The goal of the ICES code is to reduce the ecological, environmental, economic, and genetic impacts associated with the transfer of species associated with aquaculture activities. It includes things such as cleaning all boats and equipment that comes in contact with the water, removing all living matter, detritus, and sediment from equipment, and the removal of all water trapped in equipment, including rinse water used to clean boats and gear, in order to prevent accidental transfers of unwanted species. They also focus on preventing the movement of fouled vessels or equipment from one area to another and the use of anitfouling technologies. Another important part of reducing the spread of unwanted invaders is reporting all suspicious organisms found, which can greatly help identify new invaders and allow rapid response efforts to eliminate new invasions.

There are clear economic incentives for the aquaculture sector to continue to develop management and industry practices that reduce the impacts of nonnative species on products and equipment. These practices will also insure long-term sustainability of the industry. Such actions include selecting sites for aquaculture and methods that will minimize potential fouling, regular boiling (i.e., cleaning) of gear or cycling gear to reduce the abundance of nonnative species in an area, and disposing of unwanted animals and cleaning water in a way that prevents further spread of these nuisance species. Another effort to help reduce the spread and impacts of unwanted nonnatives is a project by the Collective Research on Aquaculture Biofouling (CRAB; www.crabproject.com). Because of the great cost of gear and animal fouling, especially the growing impact of nonnatives, this is a case where it is clearly in the best interest of farmers to take measures to stop the spread invaders. This project is a particularly good example of how to get education and outreach to farmers, and provide them with recommendations that will reduce their costs and reduce the spread of invaders. In general, gear cycling, as recommended by the USDA (www.mrc.state.va.us/CRD/VA_706ajs.pdf) is one mechanism for reducing the impacts and spread biofouling while keeping costs minimal for farmers.

## Future needs

There are many parallels between aquaculture and agriculture. Both are important industries that provide essential food resources; however, agriculture relies on domesticated species. These species have been bred for characteristics that enhance production and have been transformed through breeding, often for thousands of years, making them very different than their wild ancestors. Their success is generally dependent on the humans that grow them. Aquaculture, on the other hand, relies on the captive culture of essentially wild species, and like many natural species, when transplanted to new environments these animals can reproduce and spread, often with unintended and harmful results. Continued efforts to develop regulations and oversight will simultaneously allow the benefits of aquaculture to be realized and protect both natural marine systems and shellfish aquaculture from the unwanted impacts of nonnative species introductions.

In addition, we need to focus attention to practices that can result in shellfish aquaculture species themselves from becoming unwanted invaders. The development of best management practices that prevent the release of unwanted or unneeded individuals to the environment are necessary. The release of larvae or gametes and leaving leftover individuals in the environment after desirable individuals are harvested can lead to the establishment of feral populations that can spread and cause unwanted environmental damage. Similarly, regulations that prevent deliberate attempts to establish populations of nonnative species for harvest or allow nonnative species in aquaculture to reproduce where they can spread are greatly needed. We also need mechanisms that will minimize the risks of the spread of nonnative species and the escape of aquaculture species. This is especially important when there is consideration of introducing new species for aquaculture outside of their native range.

One factor that will influence the spread and impacts of species introductions is climatic change. Species that were once contained in a region, with temperature-driven physiological limits or limits on reproduction, are able to reproduce now that waters are warmer. As a consequence of climatic change, more species may spread to areas thought to be safe from these species (Diederich et al. 2005; Klinger et al. 2006; Kochmann et al. 2008; Thieltges et al. 2009). Planning and consideration of new aquaculture species or the transport of species also needs to include a consideration of projected changes in climate (Chapter 17 in this book) and the potential for the spread of nonnatives when considering the risks of species introductions.

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