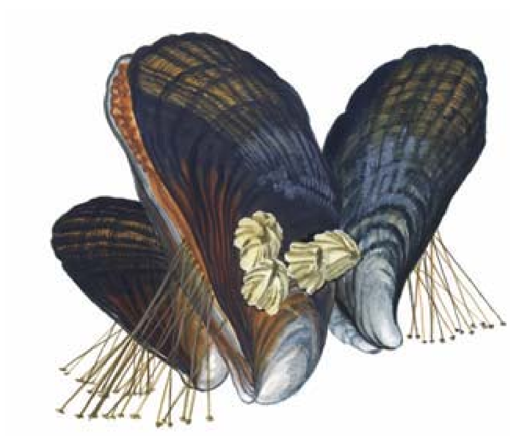
Seafood Watch
Seafood Report

MONTEREY BAY AQUARIUM®

Farmed Mussels



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About Seafood Watch® and the Seafood Reports

Monterey Bay Aquarium's Seafood Watch® program evaluates the ecological sustainability of wild-caught and farmed seafood commonly found in the United States marketplace. Seafood Watch® defines sustainable seafood as originating from sources, whether wild-caught or farmed, which can maintain or increase production in the long-term without jeopardizing the structure or function of affected ecosystems. Seafood Watch® makes its science-based recommendations available to the public in the form of regional pocket guides that can be downloaded from www.seafoodwatch.org. The program's goals are to raise awareness of important ocean conservation issues and empower seafood consumers and businesses to make choices for healthy oceans.

Each sustainability recommendation on the regional pocket guides is supported by a Seafood Report. Each report synthesizes and analyzes the most current ecological, fisheries and ecosystem science on a species, then evaluates this information against the program's conservation ethic to arrive at a recommendation of "Best Choices", "Good Alternatives" or "Avoid". The detailed evaluation methodology is available upon request. In producing the Seafood Reports, Seafood Watch® seeks out research published in academic, peer-reviewed journals whenever possible. Other sources of information include government technical publications, fishery management plans and supporting documents, and other scientific reviews of ecological sustainability. Seafood Watch® Research Analysts also communicate regularly with ecologists, fisheries and aquaculture scientists, and members of industry and conservation organizations when evaluating fisheries and aquaculture practices. Capture fisheries and aquaculture practices are highly dynamic; as the scientific information on each species changes, Seafood Watch® sustainability recommendations and the underlying Seafood Reports will be updated to reflect these changes.

Parties interested in capture fisheries, aquaculture practices and the sustainability of ocean ecosystems are welcome to use Seafood Reports in any way they find useful. For more information about Seafood Watch® and Seafood Reports, please contact the Seafood Watch® program at Monterey Bay Aquarium by calling 1-877-229-9990.

Disclaimer

Seafood Watch® strives to have all Seafood Reports reviewed for accuracy and completeness by external scientists with expertise in ecology, fisheries science and aquaculture. Scientific review, however, does not constitute an endorsement of the Seafood Watch® program or its recommendations on the part of the reviewing scientists. Seafood Watch® is solely responsible for the conclusions reached in this report.

Executive Summary

In 2003, nearly 89% of world mussel production was from aquaculture. Mussels are cultured throughout most of the world, but the major production areas are China, Spain, Italy, Thailand, France, and New Zealand. The United States is a relatively small producer of mussels (~0.1% of global aquaculture production) and relies on imports primarily from Canada and New Zealand.

Mussels can be cultured by on-bottom or off-bottom (suspension) techniques. In on-bottom culture, spat are dredged from natural sites and placed on the seabed at aquaculture sites. Mussels produced by on-bottom techniques must also be harvested by dredging. Spat for off-bottom culture, which is the primary method of production (~85%), normally are captured from the water column with spat collectors.

Dredging bottom culture plots for harvest can have negative impacts on the seabed and cause benthic diversity to decline. Sediment degradation including increased organic matter concentration, lower redox potential, and decreased benthic diversity occurs beneath and around the edges of mussel aquaculture sites. However, sediment degradation is relatively minor, and dredging of natural colonies can cause damage to a much greater area per unit of mussel harvested than dredging of aquaculture sites.

As with other bivalves, mussels do not require any fish meal or fish oil in the form of formulated feeds. Escape of mussels is uncommon, and furthermore, widespread use of exotic mussels is uncommon for species consumed in the United States. Diseases are rare and mussel producers are not affected by outbreaks to the extent that other bivalve producers are. Because there are few disease issues, chemicals in the form of antibiotics typically are not used. Additionally, mussel aquaculture results in a net decline of nutrients in the water column. Mussels imported to the United States are primarily from developed nations with stringent environmental regulations. In all of these countries, Best Management Practices (BMPs) have been developed. As the risk of environmental harm by mussel aquaculture activities is low, Seafood Watch® gives farmed mussels the overall recommendation of Best Choice; though, if possible, consumers and businesses should seek out mussels that have been grown in suspended culture over mussels that have been harvested by dredges, as it is the most sustainable choice.

Table of Sustainability Ranks

	Conservation Concern			
Sustainability Criteria	Low	Moderate	High	Critical
Use of Marine Resources	√			
Risk of Escaped Fish to Wild Stocks	√			
Risk of Disease and Parasite Transfer to Wild Stocks	√			
Risk of Pollution and Habitat Effects	√ suspended culture	√ dredged		
Management Effectiveness	√			

About the Overall Seafood Recommendation

- A seafood product is ranked "**Avoid**" if two or more criteria are of High Conservation Concern (red) OR if one or more criteria are of Critical Conservation Concern (black) in the table above.
- A seafood product is ranked "**Good Alternative**" if the five criteria "average" to yellow (Moderate Conservation Concern) OR if four criteria are of Low Conservation Concern (green) and one criteria is of High Conservation Concern.
- A seafood product is ranked "**Best Choice**" if three or more criteria are of Low Conservation Concern (green) and the remaining criteria are not of High or Critical Conservation Concern.

Overall Seafood Recommendation

Best Choice ☐ Good Alternative ☐ Avoid ☐

Introduction

Most concerns about the possible negative environmental impacts of aquaculture have focused on culture of freshwater and marine fish in cages, flow-through systems, and ponds, and production of marine shrimp in ponds (Goldburg and Triplett 1997; Naylor et al. 2000). There has been much less discussion of the negative effects of the culture of bivalve shellfish as a result of the comparatively low impacts of producing them. Bivalves are filter feeders that obtain their nutrition by removing suspended particles from water. Because it is not necessary to apply feeds to stimulate production, bivalve farming does not increase nutrient inputs to coastal waters. In fact, an increase in abundance of shellfish in an area is usually considered to have a positive benefit on water quality (Shumway et al. 2003).

Bivalve aquaculture includes the production of oysters, clams, mussels, and scallops. The culture of bivalves has a long history dating back for perhaps a millennium. According to Mason (1971), mussel culture was first done by a shipwrecked Irish seaman in 1235. He drove two wooden poles into the seabed and attached a large net to capture birds. Although he failed to capture birds, he discovered that mussels colonized the underwater parts of the poles. This story reveals both the antiquity and the simplicity of mussel culture and bivalve culture in general. It is evident from United Nations (UN) Food and Agricultural Organization (FAO) statistics that bivalves are a popular seafood item and the harvest from the sea cannot meet the demand. The culture of these organisms increased from 1 million metric tons (mt) in 1950 to about 12.3 million mt in 2003 (FAO 2005). About 89% of world mussel production is from aquaculture.

Shumway et al. (2003) discussed the environmental virtues of bivalve culture in comparison to other types of aquaculture. They stated that bivalve aquaculture has great potential for increasing seafood production without causing negative environmental impacts.

Basic biology
The most common culture species in Europe and North America is the blue mussel (*M. edulis*) (Figure 1).

Figure 1. The blue mussel (*Mytilus edulis*). Photo credited to California Biota.

The shell of this species is inequilateral and roughly triangular in outline, although the exact shape varies with environmental conditions. The shell is smooth, sculptured with concentric lines, but without radiating ribs as found in shells of some other species. The ligament is inconspicuous. The shell color usually is purple or blue, but sometimes shells are brown. Shell length normally varies from 5 to 10 cm, although in some populations mussels never attain a length more than 2 to 3 cm, and the largest mussels may reach 15 to 20 cm. Other aquaculture species of *Mytilus* have similar appearance. For example, the Mediterranean mussel (*M. galloprovincialis*) often is mistaken for *M. edulis*, because no single morphological characteristic definitely separates the two species (Gosling 1992; Seed 1992; Seed 1995).

Byssal attachment to ships and high fecundity rates have favored introductions of mussels throughout the world for centuries (Dodgshun and Coutts 2002). Gosling (1992) described the present distribution of blue mussels; they can be found in boreal, temperate waters of both the northern and southern hemispheres. In Europe, the blue mussel can be found in the White Sea, Russia, and Iceland, and as far south as the Atlantic coast of southern France. In North America, the range of the blue mussel extends from the Canadian Maritime Provinces southward to Cape Hatteras, North Carolina in the United States. In the southern hemisphere, these mussels can be found in the waters off the coasts of Argentina, Chile, the Faulkland Islands, and the Kerguelen Islands. The Mediterranean mussel (*M. galloprovincialis*) is found along the Mediterranean coast of Europe and in the Adriatic, Aegean, and Black Seas. It also occurs along the coasts of the western United States, China, Korea, Japan, southwestern Australia, most of Tasmania, northeastern New Zealand, and southwestern South Africa. Another aquaculture species, *M. californianus* occurs along the western coast of the United States and Canada where it is native.

Other major aquaculture mussel species are in the genus *Perna* and include *P. viridis* (Asian green mussel), *P. perna* (brown mussel), and *P. canaliculus* (New Zealand mussel). The Asian green mussel is native to south and Southeast Asia, but it has been introduced into northern Australia as well as the Gulf of Mexico and Caribbean. The natural range of the brown mussel was tropical and subtropical regions of the Atlantic Ocean, but it has been introduced in many other locations. The New Zealand mussel is a native of its namesake.

A brief review of mussel ontogeny will help readers understand production aspects of mussel aquaculture discussed later. The typical life cycle of mussels is illustrated in Figure 2. Mussels can reach sexual maturity in 12 months under normal environmental conditions. First, males release sperm and then females release eggs into the water where external fertilization occurs. About 10,000 spermatozoa are released for each ovum spawned (Thompson 1979). Sperm in the water likely promotes egg release (Newell and Thompson 1984). Fertilization over mussel beds occurs rapidly because of the abundance of spermatozoa. Fertilized eggs develop rapidly, and embryonic development reaches the trocophore stage in 24 hours. The shell gland begins to secrete the first larval shell, and in about 2 days, the trocophore has developed into the planktonic veliger. Veligers have ciliated swimming organs called velum and feed on phytoplankton. After 1 to 4 weeks, veligers develop a foot-like, pedal organ that allows them to crawl along surfaces. These larva are called pediveligers. The foot secretes a liquid protein that will eventually form byssal threads by which mussels attach to the substrate. The secretion of byssal threads and attachment of larvae to substrate is termed settlement. Metamorphosis from larvae to juvenile takes place approximately 24 to 48 hours after settlement. During metamorphosis, the mussel does not feed and relies on stored nutrients. After metamorphosis is completed, juvenile mussels, called spat, begin to feed and grow. In aquaculture, spat are used to seed culture systems, and the term seed often is used instead of spat (Hickman 1992).

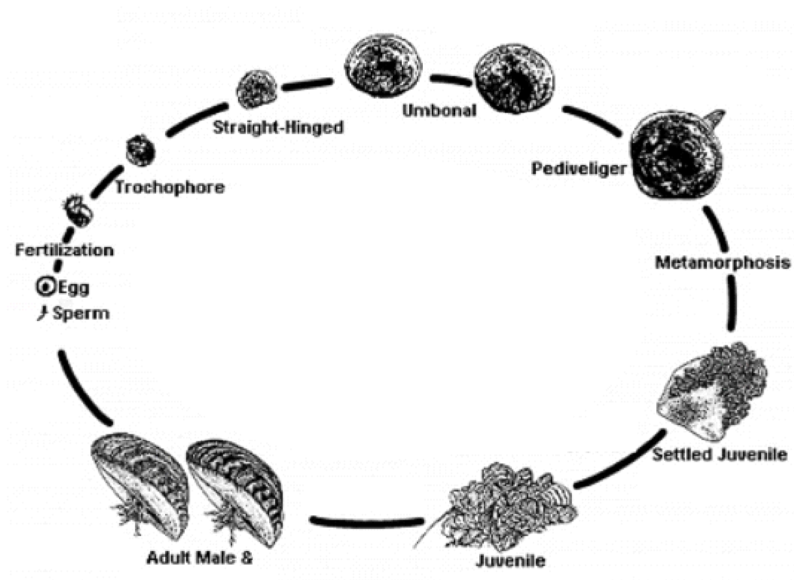

Figure 2. Developmental stages of the mussel. Image credited to the United States Army Corp of Engineers.

Mussels are efficient filter feeders removing particles as small as 2 to 3 µm from water with 80% to 100% efficiency (Møhlenberg and Riisgård 1977). Bacteria, phytoplankton, fine organic detritus, and material of inorganic origin are utilized as food.

Mussels have a number of attributes that contribute to their success as a cultured bivalve. High fecundity and free-swimming larvae ensure wide distribution of offspring, settlement of mussels usually occurs in great numbers, and a high growth rate allows them to out-compete other benthic species. Mussels tolerate crowding well, and they can be found in extremely large numbers on suitable substrates. They are also not as susceptible to parasites and disease organisms as oysters and other cultured bivalve species. Mussels, like other bivalves, are preyed upon by a number of crab, starfish, fish, and bird species.

Aquaculture production

According to Hickman (1992), about 40 countries culture species of *Mytilus, Perna*, or both. Reference to FAO (2005) revealed that the leading producers, in order of increasing importance, were China, Spain, Italy, Thailand, New Zealand, and France (Figure 3). Other countries with significant production are Ireland, the Netherlands, Canada, and the United States.

Development of off-bottom culture technology has extended mussel farming to areas not suitable for natural mussel beds or on-bottom culture because of too little substrate or poor substrate characteristics. However, there must be some natural production of mussels nearby mussel aquaculture sites to provide an adequate supply of spat.

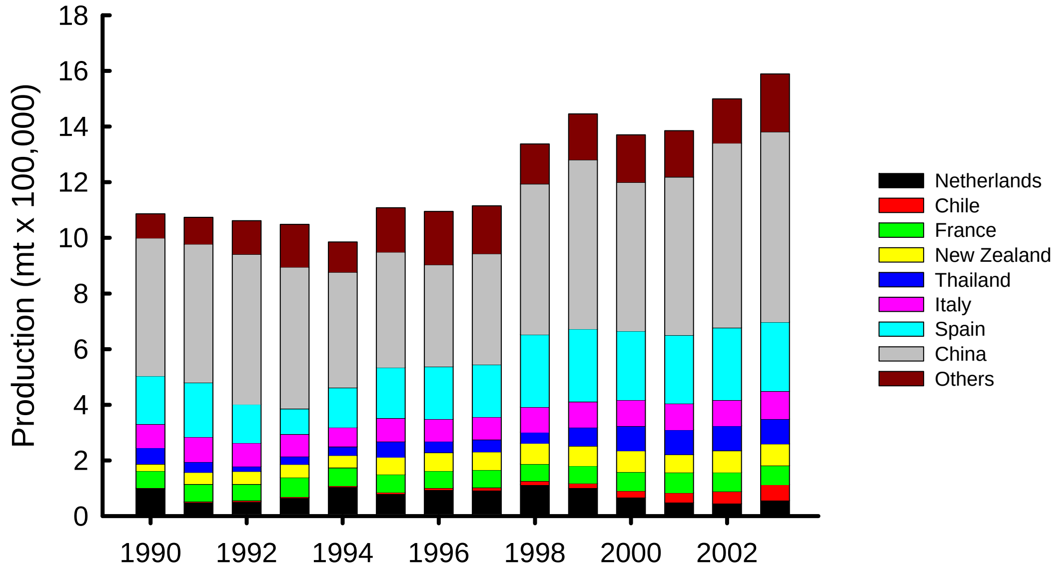

Figure 3. The major countries producing mussels by aquaculture. The U.S. and Canada are included in the "others" category. Source: FAO 2005.

Although China is the leading mussel producer in the world, FAO statistics do not reveal which species are cultured there. Hickman (1992) indicates that *M. edulis* is produced in China by the longline[1] culture technique, but species of *Perna* also are cultured. Thailand also produces *Perna*. Both on-bottom and off-bottom culture may be found in Asia.

In Spain, mussels are farmed mostly off the Galician coast near the border between Spain and Portugal. These waters are deep, productive, and sheltered from extreme weather conditions. The primary culture method involves suspending mussels on ropes hanging from rafts.

The French mussel industry produces around 73,000 mt per year using *M. edulis* on the Atlantic coastline and *M. galloprovincialis* on Mediterranean shores. This production represents half of the yearly demand, and France also imports mussels from Spain, Italy, and other countries. Most imports occur between September and March, when Atlantic production is low and meat quality declines in response to spawning. Although a mussel fishery still exists in France, most of the production is based on aquaculture.

Mussel culture has been rapidly increasing in New Zealand. The major cultured species is *P. canaliculus*, which is unique to New Zealand. It is green to black in color with a distinctive green lip along the inside shell margin.

Mussel culture is a significant activity in other parts of the world including South American countries, Korea, Japan, Thailand, Italy, the Netherlands, Ireland, Canada, and other nations. Thus, mussels truly are cultured worldwide, and there is a large and expanding market in many

[1] Longline culture in aquaculture is not similar to longline fishing, where bycatch is a high conservation concern.

nations. Of course, many of the nations that culture mussels are not self sufficient and still import mussels.

According to FAO (2005), the total world aquaculture production of mussels in 2003 was 1.6 million metric tons (mt), recovering from a slight, downward trend during 1997-1999. In 2003, 264,000 mt of mussels were captured from natural populations, of which about 62% was blue mussel (*M. edulis*) and around 18% was Mediterranean mussel (*M. galloprovincialis*). Green and brown mussels made up the remainder. The catch of mussels from natural populations has been steadily declining, and the production of mussels by aquaculture has been increasing, most dramatically in the past decade. The share of mussel capture fisheries in total world production was 41% in 1970 (FAO 2005). In 1992, the share of capture fisheries in total production was 21%, and by 2003 the capture share declined to 11% (Figure 4).

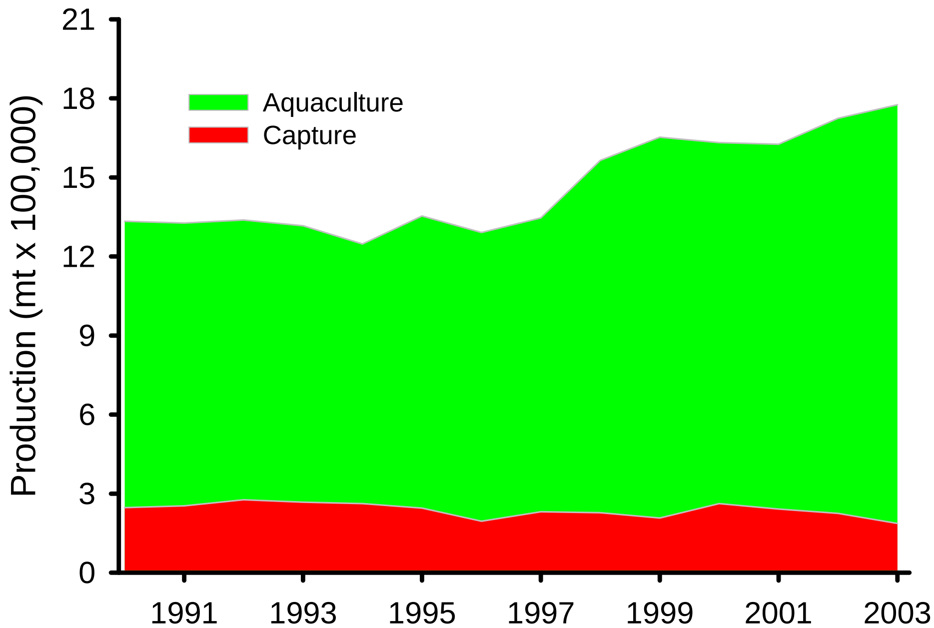

Figure 4. Comparison of mussel aquaculture and wild capture of mussels. Source: FAO 2005.

In 2003 the main culture species were listed by FAO as follows: sea mussel (*Mytilidae*), 683,000 mt; blue mussel (*M. edulis*), 472,000 mt; Mediterranean mussel (*M. galloprovincialis*), 149,000 mt; green mussel (Perna viridis), 113,000 mt; and New Zealand mussel (P. canaliculus), 78,000 mt. The leading producer of mussels by aquaculture was China with 683,000 mt, but the species were not separated. Other major mussel-producing countries (Figure 3) included Spain (249,000 mt), Italy (100,000 mt), Thailand (89,000 mt), New Zealand (78,000 mt), and France (68,000 mt). Spain and France produce mainly *M. edulis* while Italy produces mainly *M. galloprovincialis*. New Zealand produces primarily the New Zealand mussel (*P. canaliculus*).

One of the most important mussel species is the blue mussel. World production of this species peaked in 1998 at 501,300 mt. In 2002, the production was 386,453 mt with a farm gate value of nearly 300 million U.S. dollars. By far the leading producer of blue mussel is Spain and most of the world blue mussel production is in Europe. The decline in global production of *M. edulis* has been influenced mainly by a decrease in European production. The decline in *M. edulis* production also was a major reason for the slight decrease in total mussel production in 2001. The drop in production in Europe was primarily a result of poor spat harvests and stricter regulations in recent years.

In spite of its high production, France is a net importer of mussels, but Spain, the Netherlands, and Ireland are net exporters. The European market for mussels was strong in 2002 even with the decrease in production. In 2002, total French mussel imports fell by 17% to 48,000 mt (Globefish 2003). The United States produced only 1,562 mt of mussels in 2001, and 726 mt of these were exported (Aquaculture Magazine 2004).

The United States is a relatively small producer and consumer of mussels. However, interest and consumption of mussels is growing and the total farm gate value of cultured mussels has been increasing (Figure 5). The main area of mussel aquaculture in the United States is the North Atlantic coast and Washington State. The United States produced 1,545 mt of mussels in 2003 (FAO 2005) and imported 19,100 mt (United States Department of Agriculture Foreign Agriculture Service 2005), thus approximately 93% of mussels consumed in the U.S. are imported, primarily from Canada and New Zealand.

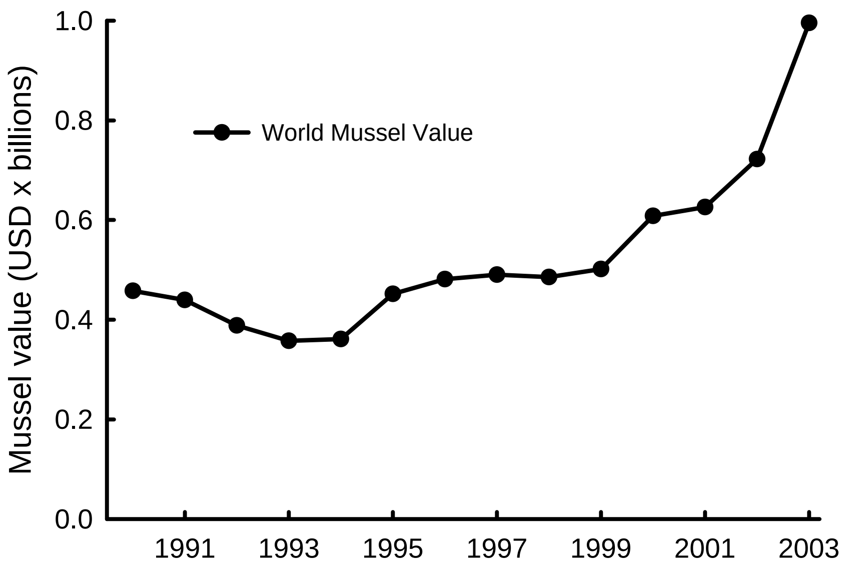

Figure 5. The farm gate value of mussels. Source: FAO 2005

Aquaculture systems

Mussel culture consists of two major activities: spat (seed) collection; and grow-out of spat to marketable size. Spat may be dredged, handpicked, or captured on spat collectors. There are two fundamental types of grow-out: on-bottom culture; and off-bottom culture.

Spat collection

The natural availability of spat is often given as a factor in mussel aquaculture, and references to commercial-scale, hatchery seed production of mussel spat could not be found for this report. Hatchery production of oyster, clam, and scallop seed is common in the United Kingdom and many other nations (Spencer 2002); however, this technology apparently has not been extended to mussels because it is too expensive.

Dredging of spat is usually practiced where the grow-out technique is on-bottom culture. Dredging disrupts the seabed and dislodges both substrate and mussels, which are caught in a basket. Small mussels can be re-laid in waters that are productive and protected from storms and other weather extremes (Hickman 1992). Handpicking of spat is not widely practiced, but where mussel beds are frequently exposed to the air, this method may be used. Mussels release large numbers of propagules into the water by natural reproduction, and the larvae settle on suitable substrate. Artificial substrates suspended in the water for encouraging the settlement of spat for use in aquaculture are called spat collectors. This is the most common method for collecting mussel spat. Spat collectors are especially convenient for capturing spat for off-bottom culture, which represents about 85% of mussel culture.

Dredging
Boats for dredging spat are usually equipped with multiple dredges. Dredging operations typically take place in waters 1 to 20 m deep. In Holland, a typical dredging boat would be 30 m long and employ four dredges (Chalfant et al. 1980). Mussels are mixed with substrate particles and commercially unimportant bivalves. A washer-grader system is employed on the dredging boat to clean and select the mussels. The unwanted substrate and bivalves are separated and discharged back into the water. Mussels ranging from 8 to 13 mm are most desirable for replanting in culture plots (Hurlburt and Hurlburt 1980). Juvenile mussels should be transported as quickly as possible (usually 1 day) to the grow-out culture systems to prevent excessive mortalities (Korringa 1976). Mussel spat harvested from natural beds are transplanted to culture plots at densities of 20 to 35 mt/ha (Korringa 1976).

Spat collectors
Seed collection with spat collectors is the most common method of obtaining juvenile mussels. The technique is simple and requires very little technical proficiency. Nevertheless, the best sites for spat collection are often overlooked. The presence of adult mussel beds is often perceived as a prerequisite for spat collection sites; however, Incze and Lutz (1980) described sites without adult mussel beds in the immediate vicinity that yielded large spatfalls on artificial collectors. Stability of water quality and moderate to strong currents are better criteria for selecting sites for spat collectors because spat may be transported many kilometers from mussel beds by ocean currents. Sites with good water quality and water flow are sometimes even superior to sites near mussel beds. Up-river estuary environments that are prone to excessive wave action and high salinity and temperature fluctuations seldom are good locations for spat collection (Incze and Lutz 1980).

Materials for construction of spat collectors vary widely and depend on local availability, durability, and cost (Spencer 2002). Historically, wooden poles have been used in France, but ropes suspended in the water column now are the dominant method. Ropes used in spat collection are similar to those used to suspend mussels for grow-out culture. Many ropes are suspended to increase surface area and promote higher rates of settlement (Spencer 2002). Dare (1980) found that split-film polypropylene suspended off-bottom was an efficient spat collector.

Grow-out

On-bottom

On-bottom grow-out systems are an extensive and traditional form of mussel culture. Mussels are dredged from natural beds and transferred to culture plots where water depths range from 3 to 6 m. These culture plots are typically leased from the government. Mussel growth varies with food supply and temperature, and many farmers leave mussels on beds for 18 to 24 months or longer before harvesting (Spencer 2002; Dijkema and Stralen 1989). Bottom culture of blue mussels can yield 100 to 125 mt of shell-on mussels per hectare (ha). With a 30% meat yield (Hurlburt and Hurlburt 1980), the harvest results in 33 to 41 mt of mussel meat/ha.

Mussels in on-bottom culture are harvested by dredging, and sediment trapped in mussels must be removed. Mussels are flushed with seawater on harvest boats or cleaned by confining the harvested mussels in a porous container that is dragged behind the boat to create water flow through the container. Mussels also may be re-laid on sandy substrate for several weeks until contaminating sediment is purged naturally.

Off-bottom

Because mussel culture by suspension (off-bottom) techniques is more widely adaptable than bottom culture, it has become more common. Spat collected with artificial collectors are used in off-bottom mussel culture. They are transferred from the spat collectors to the culture substrate by hand. Yakily (1989), Jenkins (1985), and Jamieson (1989) described the numerous types of suspension structures utilized in off-bottom, grow-out of mussels, including raft culture, longlines, and buchots, or pole culture. The suspension structure employed varies greatly by country and is possibly related to tradition more than any other factor.

In raft culture, spat from artificial collectors are attached to raft lines that hang in the water column. Alternatively, seed may be collected from exposed, rocky mussel beds and transplanted to mesh socks that are hung from rafts (Hickman 1992). The seeded lines or socks are reared for 5 to 6 months until the weight of mussels on each line or in each sock is approximately 100 to 200 kg. At this time, mussels are thinned by removing enough from each rope or sock to fill three or four more ropes or bags. They are replaced on the rafts and cultured for an additional 12 to 18 months. Wooden poles are inserted into the ropes at various intervals to prevent mussel clumps from sliding to the end. Harvest is performed using cranes to lift the mussel colonies from the water. Yields are typically 10 kg/m of rope.

Longlines can be suspended by plastic floats on the water surface or they can be weighted down below the surface. Vertical lines containing the mussels attached to the longlines are typically 4 to 6 m long (Spencer 2002). Culture periods can range from 12 to 24 months, and upon harvests, the weight of mussels is 7 to 14 kg/m of rope (Hickman 1992).

Bouchots or pole culture used in France is one of the original culture techniques for blue mussels. Spat are collected on wooden or aluminum poles during May and June. Juveniles are then transferred to mesh socks that are wound around poles for grow-out (Spencer 2002). In the French bouchot system, three to five socks wrapped around each pole yield 25 to 60 kg of mussels.

Availability of Science

There is considerable scientific and grey literature on mussel aquaculture. The FAO provides a wealth of information on aquaculture and capture production, as well as commodity reports. Shellfish producers are quite approachable and are willing to discuss public concerns. Sea Grant also provides an abundance of simple facts regarding mussel culture. For more technical information, the National Shellfisheries Association and the Journal of Shellfish Research encompass a broad spectrum of shellfish species biology, ecology, and aquaculture production. Because the impacts of shellfish farming, in general, are small compared to finfish and shrimp aquaculture, much of the industry promotes the environmental benefits of mussel culture. Thus, the result is a large body of knowledge on production practices. Aside from FAO documents, information on mussel culture in developing countries is not readily available to the public.

Market Availability

Common and market names:
Farmed mussels are sold as “mussels.” When used for sushi or sashimi, mussels are commonly sold as *murugai*.

Seasonal availability:
Farmed mussels are available year-round, but fresh mussel availability may be limited in specific regions for food safety reasons (see Appendix 2).

Product forms:
Mussels are typically served cooked in or out of the shell, but are also available smoked and canned, or frozen.

Import and export sources and statistics:
The majority of mussel imports are in their shell, fresh or chilled, and from Canada and New Zealand (Figure 6). The market for mussels in the United States is small when compared to Europe and Asia; however, the United States is purchasing an increasing amount of mussels especially for sale in Italian restaurants.

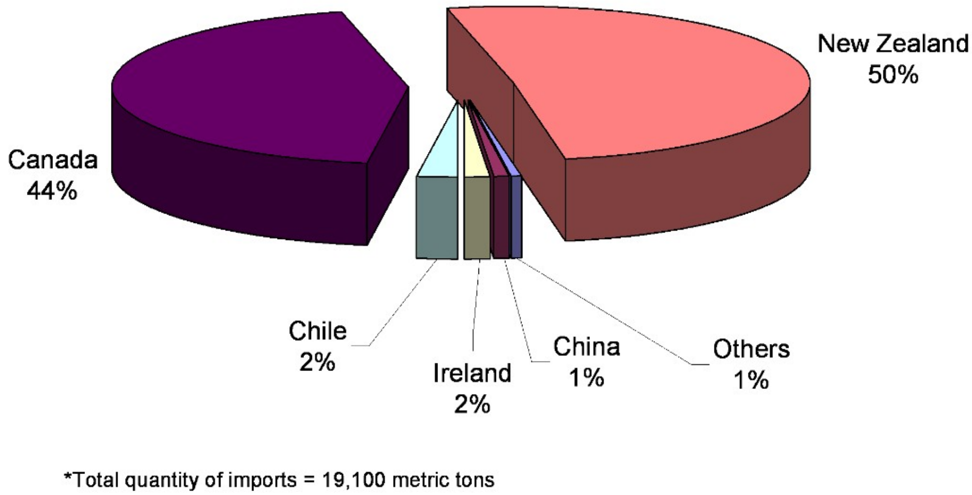

Figure 6. Proportion of mussel imports to the United States by country. Source: United States Department of Agriculture Foreign Agriculture Service 2005.

Analysis of Seafood Watch® Sustainability Criteria for Farmed Species

Criterion 1: Use of Marine Resources

Mussels require no wild fish in the form of fishmeal or fish oil in aquaculture production or natural production, thus there is no direct effect on wild fish populations by this aquaculture activity. Because mussels rely on natural production of food organisms in grow-out, there will be a reduction of nutrients, phytoplankton, zooplankton, and bacteria in the water column as a result of the aquaculture activity. There is little information to suggest that this has a detrimental effect on larval fish and natural bivalves that rely on this source of food, or that they limit primary productivity because most coastal systems are eutrophic (Boesch and Brinsfield 2000).

There is little evidence to suggest that capture of wild mussel spat and brood stock for aquaculture lessens the abundance of mussels in coastal ecosystems. Mussel farms are sited where conditions are good for growth, and mussel survival and growth no doubt are better than at many other sites where the spat would have otherwise settled naturally. When spat are collected with spat collectors, there is no bycatch of fish and shrimp. Spat for some mussel culture may be dredged; thus, this method of spat collection will cause some benthic damage in areas with sensitive habitat (see Criterion 4).

Synthesis
Formulated feed is not used in grow-out of mussels, thus fishmeal and fish oil are not used. In few cases mussels are produced in hatcheries, and cultured algae are used as food for mussels. Mussels rely on natural organisms and other non-living organic matter in the grow-out stage,

thus removing nutrients from the water column. The use of marine resources, therefore, ranks low for cultured mussels.

Use of Marine Resources Rank:

Low	Moderate	High	Critical

Criterion 2: Risk of Escapes to Wild Stocks and Ecosystems

Mussels undergo a planktonic larval stage and can be introduced to other areas of the world with relative ease. For example, many different larval bivalves and other organisms are discharged when cargo ships dispose ballast water into the local environment (Carlton 2001).

Although biosecurity has increased in much of the world, there are still areas where laws are not in place to control the importation of non-established or non-native species. However, U.S. imports of mussels are from countries where the species consumed are native.

Synthesis
Mussels consumed in the United States are native to the regions in which they are cultured. Because the majority of mussels imported into the U.S. are from countries using longline or raft culture techniques (suspended), the area under culture is relatively small and the activity is concentrated. Thus, the impact on wild mussels is small. Furthermore, because spat are harvested from the wild and not genetically manipulated, any escapes that do occur would not cause the genetic integrity of wild stocks to be compromised. Thus, as with all other forms of bivalve culture the risk of wild stock detriment by escape of culture species ranks low.

Risk of Escaped Fish to Wild Stocks Rank:

Low	Moderate	High	Critical

Criterion 3: Risk of Disease and Parasite Transfer to Wild Stocks

High mortalities caused by parasites or infectious diseases have not been encountered in mussels (Bower 1992). One disease that could become commercially important, however, is hemic neoplasia. The geographic range of this disease is the Pacific coast of North America, British Columbia, Wales, Denmark, Finland, and the southeast coast of England (Elston 1990). There is no treatment for this disease; however, outbreaks are uncommon at normal culture densities.

Mussels are hosts to a large number of parasites, and several ciliate species are commonly found on the gills and in the digestive tract of mussels. None of these are considered to be harmful to the mussel or to consumers. There is evidence (Lutz and Hidu 1978) that a parasitic nematode, *Gymnophallus bursicola*, is associated with pearl production in mussels. Pearls are undesirable and can prove hazardous for consumers, but pearl development in mussels less than four years old is rare, thus this is not a serious concern because mussels are typically harvested before they reach 2 years of age.

Synthesis
There are few incidences of disease outbreaks among mussels (Bower 1992), and little evidence of cultured mussels threatening native stocks. Thus, the risk of disease transfer from cultured mussels to wild mussels ranks low.

Risk of Disease and Parasite Transfer to Wild Stocks Rank:

Low	Moderate	High	Critical

Criterion 4: Risk of Pollution and Habitat Effects

Unlike other forms of aquaculture, bivalves cause a net reduction of nutrients in the water column. However, dredging and other benthic changes may negatively impact the culture environment.

Pelagic effects
Mussels feed by filtering particulate organic matter from the water column, and this organic matter includes both phytoplankton and nutrients on which the phytoplankton feed. In this way mussel aquaculture can reduce the abundance of phytoplankton in the water, and subsequently reduce the abundance of zooplankton, which feed on the phytoplankton. There are concerns that such a reduction in plankton could lessen benthic and fish production; however, unless mussel culture is highly intensive in an embayment with restricted water circulation, mussel culture would not be expected to cause great changes in plankton or fish production. This is not a common problem though as such sites are not optimal for aquaculture activities, especially for shellfish. Additionally, eutrophication is a common problem in coastal waters in most parts of the world; thus, the removal of organic matter and nutrients by cultured mussels can be a positive factor. Mussel aquaculture sites can remove excess nutrients from the ecosystem, improving water quality in coastal areas.

Sediment effects
Mussels and other bivalves cannot convert all of the food that they filter from the water into harvestable biomass; thus, they excrete wastes into the environment. Soluble or fine wastes will be carried away from the culture site in water currents, but larger, solid wastes will settle to the bottom under and near culture areas.

The most serious environmental effects of mussel culture have been recorded in two Spanish embayments where there has been intensive mussel culture for 40 years (Tenore et al. 1982). The impacts have resulted primarily from increased sedimentation under mussel culture rafts. This has caused changes in benthic structure and organic matter enrichment of sediment beneath the culture rafts. However, this appears to be a rare incidence and not common throughout the mussel aquaculture industry.

There is no uniform impact that mussel culture has on the habitats they are raised in, and site selection is of primary interest, as the negative effects of a mussel grow-out facility will be determined by this factor. However, there are few cases where mussel culture has caused serious environmental impacts.

Fouling control

There have been many attempts to control predators and fouling organisms in bivalve culture through the use of chemicals such as Victoria Blue B, copper sulfate, quicklime, saturated salt solutions, chlorinated hydrocarbon insecticides, and other pesticides (Loosanoff 1960; MacKenzie 1977; MacKenzie 1979; Shumway et al. 1988; Brooks 1993). A review of predator controls in bivalve culture conducted by Jory et al. (1984) revealed that the installation of exclusionary devices such as netting was more successful than chemical treatment for control of predators and fouling organisms. Also, monitoring of mussel growth and survival is necessary, and physical cleaning to prevent fouling can be incorporated into a monitoring program. Additionally, the majority of chemicals used in shellfish culture are to prevent predation or parasitism at on-bottom culture locations. Suspended culture techniques that are used in Canada and New Zealand negate the use of seabed chemical sterilization procedures.

Dredging

Spat for seed stock in on-bottom culture are dredged and transferred to culture areas. Harvest of on-bottom culture plots is also done by dredging. The influence of mussel dredging was discussed by Dolmer et al. (2001), who found impacts to include changes in seabed topography and sediment structure, re-suspension of sediment, and reduction in diversity of macrofauna. Dolmer et al. (2001) found the influence of dredging on sediment topography to be insignificant in sandy sediment, but observed furrows up to 5 cm deep in more stable sediment. However, Dolmer et al. (2001) also found sediment texture and organic matter content to be unaffected by dredging. After dredging, sediment was found to have a lower number of species, especially of polychaetes, than undredged areas; however, this effect only lasted for a few weeks.

Dredging for wild mussels has impacts similar to those of dredging for cultured mussels (Shumway et al. 2003). The density of mussels in culture plots, however, is usually much greater than in natural mussel beds. Thus, the area dredged per unit weight of mussels harvested is typically less for aquacultural production than for mussel fishing. However, this is dependant on natural spatfalls and varies seasonally. If there is good recruitment, less area is dredged for collection of wild seed, yet if recruitment is low, large tracks of seabed may be dredged.

Water quality

Mussels are filter feeders, and they remove particulate organic matter including phytoplankton, detritus, zooplankton, bacteria, and suspended soil particles, from the water. They digest the particulate matter and release feces, pseudofeces[2], and ammonium, phosphate, silicate, and other nutrients back into the water (Dame et al. 1991; Gosling 1992). The growth rate of mussels depends on the stocking density and the availability of particulate organic matter. About 42% of the nitrogen, 58% of the carbon, and presumably similar percentages of other nutrients contained in particulate organic matter and removed by mussels are excreted directly back into the water

[2] Pseudofeces is material that has not been ingested but rather collected around the mantle. This material is often released into the water column by spasmodic contractions.

through the protonephridium and gills (Rodhouse et al. 1985). The remainder of the nutrients in particles filtered from the water are excreted as feces or harvested in the mussels.

According to Shumway et al. (2003), the average concentrations of nitrogen and phosphorus in shellfish are 1.4% and 0.14%, respectively. Thus, the harvest of 1 mt of mussels would contain 14 kg of nitrogen and 1.4 kg of phosphorus. McKinnon et al. (2003) reported annual yields of mussels of as little as 7 mt/ha in Australia to as much as 1,500 mt/ha in Spain. Thus, the harvest from a 1-ha production area could remove from 98 to 21,000 kg of nitrogen and 9.8 to 2,100 kg of phosphorus. The volume of water filtered by mussels on a 1-ha culture area would be much greater than the volume of water in a 1-ha natural area, and the removal of nutrients could have a significant effect on slowing the rate of nutrient loading in an ecosystem in which mussel culture is superimposed.

Synthesis

The grow-out of mussels is accomplished in the natural environment, thus there is typically a beneficial effect on water quality in the culture area. However, some localized effects have been observed when mussels have been at very high biomass densities. Additionally, dredging of mussel plots may cause moderate harm to benthic organisms and habitat.

If achieved by dredging, harvesting presents a moderate risk of disturbing habitat, and the activity allows for temporary declines in biodiversity. However, harvesting of culture plots is less destructive than harvesting wild mussels because harvest is restricted to relatively small plots. This contrasts with dredging of long expansive mussel reefs for spat collection or capture fishery harvests. Presently, the risk of pollution and habitat effects is therefore ranked low for off-bottom cultured mussels, while it is ranked of moderate concern for mussels grown on-bottom and harvested by dredging.

There are few reports of disease outbreaks at mussel culture sites (Bower 1992), thus there is little need for antimicrobials.

Risk of Pollution and Habitat Effects Rank:

Suspended culture:	**Low**	Moderate	High	Critical
Dredged mussels:	Low	**Moderate**	High	Critical

Criterion 5: Effectiveness of the Management Regime

Review of grey and scientific literature suggests that great care is taken to preserve the environment surrounding mussel farms. The health of cultured bivalves depends on habitat quality more so than other species produced by aquaculture because they can quickly bioaccumulate contaminants in their tissues (see Appendix 2); thus, in the United States and in the major countries the U.S. imports mussels from, there are strict regulations governing water quality and habitat change. Furthermore, according to Shumway et al. (2003), New Zealand and Canada have environmental codes with Best Management Practices (BMPs) for mussel culture.

Furthermore, many states and industry organizations in the United States have produced or are producing BMPs. Some of these BMPs address issues such as pest and predator control, biofouling control, vehicle and vessel practices, visual impacts, noise and odor impacts, and seed and broodstock collection. Awareness in the industry that the farming practices of mussels are of lower impact than other forms of aquaculture has prompted many producers to go above and beyond normal recommendations and regulations for monitoring and averting environmental and social impacts.

In the United States, the Pacific Coast Shellfish Growers Association (PCSGA) has developed BMPs for shellfish production on the west coast. The East Coast Shellfish Growers Association (ECSGA) submitted a pre-proposal to the Northeast Regional Aquaculture Center at the U.S. Department of Agriculture (USDA) for funding the development of shellfish Best Management Practices, but has yet to get funding approved. BMPs also have been developed for the state of Massachusetts. Additionally, the use of therapeutics in U.S. aquaculture is overseen by the U.S. Food and Drug Administration (FDA) and regulations are quite stringent regarding use of unapproved chemicals. The U.S. Environmental Protection Agency (EPA) regulates the use of non-pharmaceutical chemicals used in shellfish culture as well. Laws are strict and shellfish producers typically do not use unapproved chemicals.

Mussel producers in the United States, Canada, and New Zealand are held to strict food safety and environmental regulations. As shellfish producers promote their industry as environmentally friendly, it is understandable that they attempt to go above and beyond recommendations and regulations for food safety and environmental health. At this time the management regime is deemed highly effective.

Effectiveness of Management Rank:

Highly Effective Moderately Effective Ineffective Critical

Overall Evaluation and Seafood Recommendation

Mussels are a delicacy and obtain a high price in a growing U.S. market. Mussels can be raised through a variety of methods, which, in relation to environmental impacts, typically fit into two categories: on-bottom culture; and off-bottom culture. On-bottom practices rely on dredging and physical disturbance of the benthos; whereas off-bottom practices generally have milder impacts. At the present, disease transfer is not a major risk. Mussels do not consume marine fish in the form of fishmeal or fish oil, and they typically make waters less eutrophic by filtering out nutrients. Most introductions of non-native mussel species to U.S. waters have occurred before laws were in place to ban such practices. Farmed mussels present few threats to biodiversity and ecological integrity and thus Seafood Watch® gives them the overall recommendation of Best Choice, though, if possible, consumers should seek out mussels farmed using off-bottom, suspended culture techniques as it is the more sustainable culture method.

Table of Sustainability Ranks

	Conservation Concern			
Sustainability Criteria	Low	Moderate	High	Critical
Use of Marine Resources	√			
Risk of Escaped Fish to Wild Stocks	√			
Risk of Disease and Parasite Transfer to Wild Stocks	√			
Risk of Pollution and Habitat Effects	√ suspended culture	√ dredged		
Management Effectiveness	√			

Overall Seafood Recommendation

Best Choice ▮   Good Alternative ▯   Avoid ▮

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Scientific review does not constitute an endorsement of Seafood Watch® on the part of the reviewing scientists; Seafood Watch® is solely responsible for the conclusions reached in this report.

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Appendix 1: Rankings of individual criteria

Factor	Ranking
Estimated wild fish used to produce farmed fish (ton/ton) Green: Low use (WI:FO=0-1.1), Yellow: Moderate use (WI:FO=1.1-2), Red: Extensive use (WI:FO>2)	NA
Stock status of the reduction fishery used for feed for the farmed species Green: Underexploited, Yellow: Close to BMSY, Red: Substantially below BMSY	NA
Source of stock for the farmed species Green: Hatchery or no impact from wild collection, Yellow: Potential impact from wild collection, Red: Wild collection results in depletion	■
Conservation Concern: Use of marine Resources	■

Factor	Ranking
Evidence that farmed fish regularly escape to the surrounding environment Green: Rarely or never escapes, Yellow: Infrequent or unknown escapes, Red: Regularly and often escapes	■
Status of escaping farmed fish to the surrounding environment Green: Native and genetically and ecologically similar, Yellow: Non-native but widely established or unknown, Red: Non-native and not established or native and genetically and ecologically distinct from wild stocks	■
Where escaping fish is non-native-Evidence of the establishment of self-sustaining feral stocks	■
Where escaping fish is native-Evidence of genetic introgression through successful crossbreeding Green: No evidence of introgression, Yellow: Introgressions likely or unknown, Red: Empirical evidence of introgression	■
Evidence of spawning disruption of wild fish	■
Evidence of competition with wild fish for limiting resources or habitats	■
Stock status of affected wild fish	■
Conservation Concern: Risk of Escaped Fish to Wild Stocks	■

Factor	Ranking
Risk of amplification and retransmission of disease or parasites to wild stocks	■
Risk of species introductions or translocations of novel disease/parasites to wild stocks	■
Bio-safety risks inherent in operations	■
Stock status of potentially affected wild fish	■
Conservation Concern: Risk of Disease Transfer to Wild Stocks	■

Factor	Ranking
Effluent water treatment	■
Evidence of substantial local effluent effects	■

Evidence of regional effluent effects	
Extent of local or regional effluent effects	
Potential to impact habitats: Location	
Potential to impact habitats: Extent of Operations	
Conservation Concern: Risk of Pollution and Habitat Effects	

Factor	**Ranking**
Demonstrated application of existing federal, state and local laws to current aquaculture operation	
Use of licensing to control the location (siting), number, size and stocking density of farms	
Existence and effectiveness of "better management practices" for aquaculture operations, especially to reduce escaped fish	
Existence and effectiveness of measure to prevent disease and to treat those outbreaks that do occur	
Existence of regulations for therapeutants, including their release into the environment, such as antibiotics, biocides, and herbicides	
Use and effect of predator controls in farming operations	
Existence and effectiveness of policies and incentives utilizing a precautionary approach against irreversible risks to guide expansion of the aquaculture industry	
Conservation Concern: Effectiveness of the Management Regime	

Appendix 2: Public health

Mussels filter large volumes of water to remove food particles. Because they are efficient at capturing food particles, they are also efficient at accumulating potentially toxic or pathogenic organisms that may occur in water. Moreover, heavy metals, pesticides, dioxins, polyphenol bichlorides, dibutyltin, and other potentially toxic substances in water may be absorbed by and accumulated in mussels. Thus, mussels should not be reared in areas where waters receive significant levels of pollution or where potentially toxic dinoflagellates are abundant. Mussels from polluted waters can contain high enough levels of biological or chemical contaminants to represent a health risk to consumers.

Improved detection methods and inspection technology, monitoring programs, and laws and regulations imposed on the shellfish industry have resulted in a decline in illnesses related to shellfish consumption (Shumway 1992). Nevertheless, Shumway (1992) emphasized that outbreaks of shellfish-borne illnesses still occur. More outbreaks of shellfish illnesses result from private collection and consumption of shellfish than from commercial suppliers of shellfish. Regulations have little effect on protecting the public from non-commercial sources of shellfish. The human health risk of consuming raw shellfish is much greater than for consuming cooked shellfish. Nevertheless, Shumway (1992) stressed that cooking will not always deactivate infectious particles in shellfish.

"Mussel watch" or "shellfish watch" programs are common throughout the world. In these programs, bivalves, and particularly mussels, are used as sentinel organisms in environmental monitoring programs. According to Widdows and Donkin (1992), the following attributes of mussels make them excellent sentinel organisms:

- They are dominant components of the fauna of most coastal ecosystems and have large, stable populations.

- They are suspension feeders that pump large volumes of water and concentrate many chemicals in their tissues at factors of 10 to 100,000 times seawater concentrations.

- They are tolerant to a wide range of conditions including relatively high concentrations of contaminants in the water.

- They metabolize or excrete contaminants at a low rate compared to fish.

- They can be transplanted in the location desired and they are sessile; thus, they are a better indicator organism of local conditions than fish or other mobile species.

- They are important as seafood, and measurement of contamination is important in protecting public health.

The shellfish watch programs can provide useful information on contaminants and their concentrations in coastal waters and evaluate changes in contaminant concentrations over time. In addition, results of these programs may be used to assess the contaminant concentrations in shellfish and assess the health risk of consuming shellfish from a specific location. Shellfish harvest may be prohibited during periods when microbiological quality is poor or organisms contain high concentrations of potentially toxic compounds.

Microbial quality
Shumway (1992) provided a list of bacterial and viral contaminants identified in mussels. The list includes many dangerous pathogens including hepatitis and polio viruses, fecal coliforms, fecal streptococci, and *Vibrio*. The source of these contaminants is sewage discharges into coastal waters, and mussels and other shellfish concentrate the pathogens to much greater concentrations than found in the water.

Because mussels and other shellfish can cause public health concerns, most nations have imposed standards for microbial quality of mussels. For example, in the United States, the total aerobic viable bacterial count must be $\leq 5 \times 10^5$ cells/mL of shucked meat and the fecal coliform count must be ≤ 230 cells/100 mL of shucked meat (Slabyj 1980). In the United Kingdom, mussels containing < 230 fecal coliforms/100 mL of meat in all samples are suitable for human consumption. Those containing > 230 but < 4,600 coliforms/100 mL can be consumed by humans if depurated, heated, or re-laid for a short period to reduce coliform loads. If coliforms are between 4,600 and 60,000/100 mL, mussels must be re-laid at least 2 months. Mussels with > 60,000 coliforms/100 mL flesh cannot be offered for human consumption.

In the United States, waters for capture or culture of shellfish are monitored. The total coliform median or geometric mean must not exceed 70/100 mL and the estimated 90^{th} percentile must not exceed 230/100 mL. Shellfish from areas not meeting these standards cannot be offered for human consumption. However, shellfish from water containing 71-700 coliforms/100 mL (90^{th} percentile < 2,300/mL) can be eaten following depuration.

The European Union (EU) requires countries to have shellfish monitoring programs and national regulations that are developed using EU regulations as guidelines. Shellfish harvesting (including aquaculture) is classified into three types of waters:

Classification	Status
A	Shellfish grown in these waters can be used for direct sale without any treatment.
B	Shellfish grown in these waters must be purified (depurated) or re-laid before sale.
C	Shellfish grown in these waters must be re-laid in appropriate waters of A or B classification for at least 2 months to allow them time to reach an acceptable bacterial standard.

Algal toxins
Several coastal waters around the world have sporadic increases in the abundance of dinoflagellates and other toxic algae (Shumway 1990). Dinoflagellates of the genus *Gonyaulax* are capable of producing compounds which are highly toxic to humans (Yentsch and Incze 1992). Shellfish are relatively tolerant to algal toxins, but they can concentrate algal toxins and constitute a threat to public health. A number of algal toxins have been identified to include amnesic shellfish poisoning (ASP), paralytic shellfish poisoning (PSP), and diarrhetic shellfish poisoning (DSP). These intoxications can be quite serious or lethal. The symptoms follow:

ASP – Symptoms of ASP include vomiting and diarrhea, and in some cases, this can be followed by confusion, loss of memory, disorientation, and even coma. Chronic effects of ASP may include permanent loss of short-term memory.

PSP – Symptoms of PSP can begin within 5 to 30 minutes after consumption. Initially there is slight perioral tingling progressing to numbness that spreads to the face and neck in moderate cases. Headache, dizziness, nausea and vomiting are also common in the early stages of poisoning. In severe cases, the numb sensation spreads to the extremities. This is followed by incoordination and respiratory difficulty. Acute intoxication can lead to medullary disturbances, which are evidenced by difficulty swallowing, sense of throat constriction, speech incoherence or complete loss of speech, as well as brain stem dysfunction. In very severe cases, complete paralysis can occur in 2-12 hours, followed by death from respiratory failure.

DSP – Symptoms of DSP include diarrhea, nausea, and vomiting and abdominal pain. Onset occurs from 30 minutes to a few hours after eating. The duration is usually short with a maximum of a few days in severe cases. The disease is not usually life threatening. Complete clinical recovery is usually seen within 3 days even in severe cases. The illness is often mistaken as gastro-enteritis and therefore is probably under-reported.

Algal toxins can affect shellfish from both fishing and aquaculture operations. Although it is well known that dinoflagellate blooms are the cause of the algal toxin problem in shellfish, it is difficult to predict when and where these blooms will occur. Of course, some waters have a history of developing dinoflagellate blooms during a particular season, but blooms may sometimes not follow the usual pattern. They also may occur at other places where dinoflagellate blooms have not been reported previously. Thus, the most reliable procedure for protecting public health is the implementation of "shellfish watch" programs in which the abundance of *Alexandium* is monitored, and when blooms begin to develop, mussels and other shellfish are monitored for concentrations of algal toxins. Shellfish fisheries and aquaculture sites are closed when public health authorities conclude that it is potentially dangerous to consume the shellfish.

Chemical contamination
The chemical compounds that may contaminate shellfish originate in pollution and include pesticides, heavy metals, and industrial chemicals. The substances measured in the Mussel

Water Program in the United States include trace metals (arsenic, cadmium, copper, lead, nickel, mercury, selenium, and zinc) and organic compounds (DDT, chlordane, dieldrin, polychlorinated biphenyls, polyeyclic aromatic hydrocarbons, and butyltin).

Shumway (1992) provided a list of action levels for concentrations of several undesirable substances in seafood (Table A1).

Table A1. Action levels, tolerances and other values for poisonous or deleterious substances in seafood. Source: Shumway (1992).

Deleterious substances	Level	Food commodity
Aldrin/Dieldrin	0.30 ppm	Fish and shellfish
Chlordane	0.30 ppm	Fish only
DDT, DDE, TDE	5.00 ppm	Fish only
Endrin	0.30 ppm	Fish and shellfish
Heptachlor/Heptachlor Epoxide	0.30 ppm	Fish and shellfish
Kepone	0.30 ppm 0.40 ppm	Fish and shellfish; crabmeat
Mercury	1.00 ppm	Fish and shellfish
Mirex	0.10 ppm	Fish only
Paralytic shellfish poison	80 μg/100 g of meat	Fresh, frozen, and canned clams, mussels, and oysters
Polychlorinated biphenyls (PCBs)	20 ppm	Fish and shellfish
Ptychodiscus brevis toxins	20 Mouse units/100 g	Shellfish
Toxaphene	5.00 ppm	Fish only