furnace coil. The impurities are driven forward in the liquid phase with the zone of melting. The purified metal resolidifies at the trailing edge of the melting zone. This technique has been used to reduce impurities to the parts per billion level.

Remediation of the Mine Site

Once mining has taken place both the mine site and any processing site must be remediated (**Figure** 7). Considerable scientific work took place in the 1980s and 1990s looking at the rate that the ocean bottom recovers after being scraped in a mining operation. While it is clear that recovery does take place and is slow, it is still unclear how many years are involved. A period of several years to several decades appears likely for natural recolonization of an underwater mined site. It also appears that relatively little can be done to enhance this process. Once all mining equipment is removed from the site, nature is best left to her own processes.

An independent yet perhaps even more important issue is the way the waste products are handled after mineral processing. There are both liquid and solid wastes. The most advanced of a number of clean-up scenarios for the discharged liquids is to use some form of artificial ponds or wetlands, most often involving cattails (*Typha*) and peat moss (*Sphagnum*), the two species shown to be most adept at wastewater clean-up. Typically the wastewater will circulate over several limestone beds and through various artificial wetlands rich with these and related species. At the end of the circulation a certain amount of cleaned water is lost to ground water and the rest is usually sufficiently cleaned to dispose in a natural stream, lake, river, or ocean.

The larger and as yet less satisfactorily engineered problem is with solid waste. In fact, recent environmental work on manganese crusts has shown that 75% of the environmental problems associated with marine ferromanganese operations will be with the processing phase of the operation, particularly tailings disposal. Traditionally, mine tailings are dumped in a tailings pond and left. Current work with manganese tailings has shown them to be a resource of considerable value in their own right. Tailings have applications in a range of building materials as well as in agriculture. Manganese tailings have been shown to be a useful additive as a fine-grained aggregate in concrete, to which they impart higher compressive strength, greater density, and reduced porosity. These tailings serve as an excellent filler for certain classes of resin-cast solid surfaces, tiles, asphalt, rubber, and plastics, as well as having applications in coatings and ceramics. Agricultural experiments extending over 2 years have documented that tailings mixed into the soil can significantly stimulate the growth of commercial hardwood trees and at least half a dozen other plant species. Finding beneficial uses for tailings is an important new direction in the sustainable environmental management of mineral waste.

See also

Authigenic Deposits. Hydrothermal Vent Deposits. Manganese Nodules. Mid-Ocean Ridge Geochemistry and Petrology. Remotely Operated Vehicles (ROVs).

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MOLLUSKAN FISHERIES

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Introduction

The Phylum Molluska, the second largest phylum in the animal kingdom with about 100 000 named species, includes commercially important gastropods, bivalves, and cephalopods. All are soft-bodied invertebrates and most have a calcareous shell secreted by a phylum-specific sheet of tissue called the mantle. The shell is usually external (most gastropods, all bivalves), but it can be internal (most cephalopods). Gastropods live in salt water, fresh water, and on land; bivalves live in salt water and fresh water; cephalopods are marine. Gastropods include land and sea slugs (these have a reduced or no internal shell and are rarely exploited by humans) and snails (including edible periwinkles, limpets, whelks, conchs, and abalone). Bivalves include those that cement to hard substrates (oysters); that attach to hard substrates by strong, beard-like byssus threads (marine mussels, some pearl oysters); that burrow into hard or soft substrates (clams, cockles); or that live on the sea bottom but can move into the water column if disturbed (scallops). Cephalopods are mobile and include squid, cuttlefish, octopus, and the chambered nautilus (uniquely among cephalopods, the nautilus has a commercially valuable external shell). Most gastropods are either carnivores or grazers on algae, most commercial bivalves 'filter' suspended food particles from the surrounding water, and cephalopods are carnivores.

Humans have exploited aquatic molluscs for thousands of years, as shown worldwide by shell mounds or middens produced by hunter-gatherers on sea coasts, lake margins, and riverbanks. Some mounds are enormous. In the USA, Turtle Mound in Florida's Canaveral National Seashore occupies about a hectare of land along about 180 m of shoreline, contains nearly 27 000 m^3 of oyster shell, and was once an estimated 23 m high (humans have mined such mounds worldwide for the shells, which serve as a source of agricultural and building lime, as a base for roads, and for crumbling into chicken grit). A group of oystershell middens near Damariscotta, Maine, USA stretches along 2 km of shoreline. One mound was about 150 m long, 70 m wide, and 9 m high before it was mined; a smaller mound was estimated to contain about 340 million individual shells. Studies by anthropologists have shown that many middens were started thousands of years ago (e.g. 4000 years ago in Japan, 5000 years ago in Maine, 12 000 years ago in Chile, and perhaps up to 30 000 years ago in eastern Australia; sea level rise may have inundated even older sites).

Mollusks have been exploited for uses other than food. More than 3500 years ago, Phoenicians extracted 'royal Tyrian purple' dye from marine whelks in the genus *Murex* to color fabrics reserved for royalty, and other whelks in the Family Muricidae have long been used in Central and South America to produce textile dyes. From Roman times until the early 1900s, the golden byssus threads of the Mediterranean pen shell *Pinna nobilis* were woven into fine, exceedingly lightweight veils, gloves, stockings, and shawls. Wealth has been displayed worldwide on clothing or objects festooned with cowry (snail) shells. Cowries, especially the money cowry *Cypraea moneta*, have been widely used as currency, perhaps as early as 700 BC in northern China and the first century AD in India. Their use spread to Africa and North America. Also in North America, East Coast Indians made disk-shaped beads, or wampum, from the shells of hard clams *Mercenaria mercenaria* for use as currency.

Mollusk shells have been used as fishhooks and octopus lures (the latter often made of cowry shells), household utensils (bowls, cups, spoons, scrapers, knives, boring devices, adzes, chisels, oil lamps), weapons (knives, axes), signaling devices (trumpets made from large conch shells), and decorative objects (beads, lampshades made of windowpane oyster shell, items made from iridescent 'mother-of-pearl' shell of abalone). Many species of mollusks produce 'pearls' when they cover debris that is irritating their mantle with layers of nacre (mother-of-pearl; an aragonite form of calcium carbonate). The pearl oyster (not a true oyster) and some freshwater mussels (not true mussels) use an especially iridescent nacre that results in commercially valuable pearls. Some religious practices involve shells, including scallop shells used as symbols by pilgrims trekking to Santiago de Compostela in Spain to honor St James (the French name for the scallop is Coquille St-Jacques).

As human populations and the demand for animal protein have grown, harvests of wild mollusks have expanded. However, overharvesting and pollution of mollusk habitat have depleted many wild populations. To meet the demand for protein and to combat these losses, aquaculture has increased to supplement wild harvests. Unfortunately, some harvesting and aquaculture practices can have detrimental effects on the environment (see below).

Harvesting Natural Populations

Historical exploitation of mollusks occurred worldwide in shallow coastal and freshwater systems, and artisanal fishing still takes place there. The simplest fisheries involve harvesting by hand or with simple tools. Thus marine mussels and various snails exposed on rocky shores at low tides are harvested by hand, with oysters, limpets, and abalone pried from the rocks. Low tide on soft-substrate shores allows digging by hand to capture many shallow-dwelling species of burrowing clams. Some burrowing clams live more deeply or can burrow quickly when disturbed. Harvesting these requires a shovel, or a modified rake with long tines that can penetrate sediment quickly and be rotated so the tines retain the clam as the rake is pulled to the surface.

Mollusks living below low tide are usually captured by some sort of tool, the simplest being rakes and tongs. For example, oyster tongs in Chesapeake Bay (**Figure 1**) have two wooden shafts, each with a half-cylinder, toothed, metal-rod basket bolted at one end and with a metal pin or rivet holding the shafts together like scissors. A harvester standing on the side of a shallow-draft boat lets the shafts slip through his hands (almost all harvesters are male) until the baskets reach the bottom and then moves the upper ends of the shafts back and forth to scrape oysters and shells into a pile. He closes the baskets on the pile and hoists the contents to the surface manually or by a winch, opening the baskets to dump the scraped material onto a sorting platform on the boat (see **Figure 1**). Harvesters use hand tongs at depths up to about 10 m. Also in Chesapeake Bay, harvesters exploiting oysters living deeper than 10 m deploy much larger, heavier, and more efficient tongs from their boat's boom, using a hydraulic system to raise and lower the tongs and to close them on the bottom. In addition to capturing bivalves, rakes and hand tongs are used worldwide to harvest gastropods like whelks, conchs, and abalone (carnivorous gastropods like whelks and conchs can also be captured in pots baited with dead fish and other animals).

Mollusks can be captured by dredges towed over the bottom by boats, some powered by sail (**Figure 2**) and others by engines (**Figure 3**). Dredges harvest attached mollusks like oysters and marine mussels, as well as buried clams, scallops lying on or swimming just above the sea bottom, and some gastropods (whelks, conchs). Dredges are built of metal and usually have teeth on the leading edge that moves over the bottom. Captured material is retained in a sturdy mesh bag made of wear-resistant heavy metal rings linked together and attached to the dredge frame. Mesh size is usually regulated so that small molluscs can fall out of the bag and back onto the sea bottom.

Some dredges use powerful water jets to blow buried molluscs out of soft sediment and into a metal-mesh bag. Where the water is shallow enough, subtidal clams (and oysters in some regions) are harvested by such water jets, but instead of being captured in a mesh bag the clams are blown onto a wire-mesh conveyor belt that carries them to the surface alongside the boat. Harvesters pick legal-sized clams off the mesh as they move past on the belt. Mesh size is such that under-sized clams and small debris fall through the belt and return to the bottom while everything else continues up the belt and falls back into the water if not removed by the harvester.

Commercial harvesting of freshwater mussels in the USA since the late 1800s has taken advantage of the propensity of bivalves to close their shells tightly when disturbed. Harvest vessels tow 'brails' over the bottom. Brails are long metal rods or galvanized pipe with eyebolts at regular intervals. Wire lines are attached to the eyebolts by snap-swivels. Each line holds a number of 'crowfoot' hooks of various sizes and numbers of prongs, depending on the species being harvested. Small balls are formed on the end of each prong so that, when the prong tip enters between the partially opened valves of the mussel, the valves close on the prong and the ball keeps the prong from pulling free of the shell. When the brails are brought on deck the clinging mussels are removed. This method works best in river systems with few snags (tree stumps, rocks, trash) that would catch and hold the hooks.

Cephalopods are captured by trawls, drift nets, seines, scoop and cast nets, pots and traps, and hook and line. A traditional gear is the squid jig, which takes various shapes but which has an array of barbless hooks attached. Jigs are moved up and down in the water to attract squid, which grab the jig and ensnare their tentacles, allowing them to be hauled into the boat. In oceanic waters, large vessels using automated systems to oscillate the jig in the water may deploy over 100 jig lines, each bearing 25 jigs. Such vessels fish at night, with lights used to attract squid to the fishing boat. A typical vessel may carry 150 metal-halide, incandescent lamps that together produce 300 kW of light. Lights from concentrations of vessels in the global light-fishing fleet off China and south-east Asia, New Zealand, the Peruvian coast, and southern Argentina can be detected by satellites. With a crew of 20, a vessel as described above may catch 25–30 metric tons of squid per night.

Some harvesters dive for mollusks, especially solitary organisms of high market value such as pearl oysters and abalone. Breath-hold diving has been used for centuries, but most divers now use SCUBA or air-delivery (hooka) systems. Diving is efficient because divers can see their prey, whereas most other capture methods fish 'blind'. Unfortunately, although diving allows for harvesting with minimal damage to the habitat, it has led to the depletion or extinction of some mollusk populations such as those of abalone.

Figure 1 Post-harvest activities on shallow-draft tonging boats in Chesapeake Bay, Maryland, USA. Note the array of tongs, and the sorting or culling platform in the boat in the left foreground. (Photograph by Skip Brown, courtesy of Maryland Sea Grant.)

Figure 2 Oyster dredge coming on board a sailboat ('skipjack') in Chesapeake Bay, Maryland, USA. Note the small 'push-boat' or yawl hoisted on the stern on this sailing day. (Photograph by Michael Fincham, courtesy of Maryland Sea Grant.)

Figure 3 Harvesting vessel *Mytilus* with blue mussel dredges in Conwy Bay, Wales. (Photograph courtesy of Dr Eric Edwards.)

A variety of measures are in place around the world to regulate mollusk fisheries. A common regulation involves setting a minimum size for captured animals that is larger than the size at which individuals of the species become capable of reproducing. This regulation ensures that most individuals can spawn at least once before being captured. Size selection is often accomplished by use of a regulated mesh size in dredge bags or conveyor-belts as described earlier. If the animals are harvested by a method that is not size selective, such as tonging for oysters or brailing for freshwater mussels, then the harvester is usually required to cull undersized individuals from the accumulated catch (see **Figure 1** for the culling platform used by oyster tongers) and return them to the water, usually onto the bed from which they were taken. Oysters are measured with a metal ruler; freshwater mussels are culled by attempting to pass them through metal rings of legal diameter and keeping those that cannot pass through.

Other regulatory mechanisms include limitations as to the number of harvesters allowed to participate in the fishery, the season when harvesting can occur, the type of harvest gear that can be used, or the total catch that the fishery is allowed to harvest. There may be areas of a species' range that are closed to harvest, perhaps when the region has many undersized juveniles or when beds of large adults are thought to be in need of protection so that they can serve as a source of spawn for the surrounding region. Restrictions may spread the capture effort over a harvest season to prevent most of the harvest from occurring at the start of the season, with a corresponding market glut that depresses prices. Finally, managers may protect a fishery by regulations mandating inefficiencies in harvest methods. Thus, in Maryland's Chesapeake Bay, diving for oysters has been strictly regulated because of its efficiency. Similarly, the use of a small boat (**Figure 2**) to push sailboat dredgers ('power dredging') is allowed only on 2 days per week (the days chosen – usually days without wind – are at the captain's discretion). Dredging must be done under sail on the remaining days of the week (harvesting is not allowed on Sunday). Around the world, inspectors ('marine police') are empowered to ensure that regulations are followed, either by boarding vessels at sea or when they dock with their catch.

A great hindrance to informed management of molluskan (and other) fisheries is the lack of data on the quantity of organisms taken by noncommercial (recreational) harvesters. For example, in Maryland's Chesapeake Bay one can gather a bushel (around 45 l) of oysters per day in season without needing a license if the oysters are for personal use. Clearly it is impossible to determine how many of these bushels are harvested during a season in a sizeable body of water. If such harvests are large, the total fishing mortality for the species can be greatly underestimated, complicating efforts to use fishery models to manage the fishery.

Processing mollusks involves mainly shore-based facilities, except for deep-sea cephalopod (mostly squid) fisheries where processing, including freezing, is done on board, and for some scallop species (the large muscle that holds scallop shells shut is usually cut from the shell at sea, with the shell and remaining soft body parts generally discarded overboard). Thus the catch may be landed on the same day it is taken (oysters, freshwater and marine mussels, many clams and gastropods) or within a few days (some scallop and clam fisheries). If the catch is not frozen, ice is used to prevent spoilage at sea.

Suspension-feeding mollusks (mostly bivalves) can concentrate toxins from pollutants or poisonous algae and thereby become a threat to human health. If such mollusks are harvested, they have to be held in clean water for a period of time to purge themselves of the toxin (if that is possible). Thus they may be relaid on clean bottom or held in shore-based systems ('depuration facilities') that use ozone or UV light to sterilize the water that circulates over the mollusks. Relaying and reharvesting the mollusks or maintaining the land-based systems adds to labor, energy, and capital costs.

Aquaculture

Aquaculture involves using either natural 'seed' (small specimens or juveniles that will be moved to suitable habitat for further growth) that is harvested from the wild and reared in specialized facilities, or producing such seed in hatcheries. Most commercial bivalves and abalone can be spawned artificially in hatcheries. The techniques involve either taking adults ripe with eggs or sperm (gametes) from nature or assisting adults to ripen by providing algal food in abundance at temperatures warm enough to support gamete production. Most ripe adults will spawn when provided with a stimulus such as an increase in temperature or food or both, or by the addition to the ambient water of gametes dissected from sacrificed adults. The spawned material is washed through a series of screens to separate the gametes from debris. Eggs are washed into a container and their numbers are estimated by counting samples, then the appropriate density of sperm is added to fertilize the eggs. Depending on the species of mollusk, an adult female may produce millions of eggs in one spawning event, so hundreds of millions of larvae produced by a relatively small number of females may be available for subsequent rearing.

Larvae are reared in specialized containers that allow culture water to be changed every few days and the growing larvae to be captured on screens, counted, and replaced into clean water until they become ready to settle. As they grow, larvae are fed cultured algae at appropriate concentrations (this requires extremely large quantities of algae to support the heavily feeding larvae). Depending on the species, after 2 or more weeks many larvae are ready to settle ('set') onto a solid surface (e.g., oysters, marine mussels, scallops, pearl oysters, abalone) or onto sediment into which they will burrow (e.g. clams). The solid material on which setting occurs is called 'cultch'. Settled larvae are called 'spat'.

Spat can be reared in the hatchery if sufficient algal food is available (usually an expensive proposition given the large quantity of food required). Thus most production facilities move spat (or seed) into nature soon after they have settled. However, this exposes the seed to diverse natural predators – including flatworms, boring sponges, snails, crabs, fish, and birds. Consequently, the seed may need to be protected (e.g. by removing predators by hand, poisoning them, and providing barriers to keep them from the seed), which is labor-intensive and expensive. Mortalities of larvae, spat, and seed are high at all stages of aquaculture operations.

The energy and monetary costs of maintaining hatchery water at suitable temperatures and of rearing enormous quantities of algae means that molluskan hatcheries are expensive to operate profitably. Thus only 'high-value' mollusks are cultured in hatcheries. One option for those who cannot afford to maintain a hatchery is to purchase larvae that are ready to settle. In the supply hatchery, larvae are screened from the culture water onto fine mesh fabric in enormous densities. The densely packed larvae withdraw their soft body parts into their shells, closing them. The larvae can then be shipped by an express delivery service in an insulated container that keeps them cool and moist until they reach the purchaser, who gently rinses the larvae off the fabric into clean water of the appropriate temperature and salinity in a setting tank. Also in the tank is the cultch that the larvae will attach to or the sediment into which they will burrow. This procedure of setting purchased larvae is called remote setting.

Among bivalves, oyster larvae settle on hard surfaces, preferably the shell of adults of the species, but also on cement materials, wood, and discarded trash. The larva cements itself in place and is immobile for the rest of its life. Thus oysters have traditionally been cultured by allowing larvae to cement to cultch like wooden, bamboo, or concrete stakes; stones and cement blocks; or shells (such as those of oysters and scallops) strung on longlines hanging from moored rafts (**Figure 4C**). As noted above, the settling larvae may be either those produced in a hatchery or those living in nature. The spat may be allowed to remain where they settle, or the cultch may be moved to regions where algal production is high and spat growth can accelerate. Scallop, marine mussel, and pearl oyster larvae do not cement to a substrate, but secrete byssus threads for attachment. For these species, fibrous material like hemp rope is provided in hatcheries or is deployed in nature where larvae are abundant. As these settled spat grow, they may be transferred to containers such as single- or multi-compartment nets (**Figure 4A, B**) or to flexible mesh tubes (used for marine mussels). Most clams are burrowers and will settle onto sediment. This may be provided in ponds, sometimes including those used to grow shrimp and other crustaceans (simultaneous culture of various species is called polyculture). Abalone settle on hard surfaces to which their algal food is attached, so they are usually cultured initially on corrugated plastic plates coated with diatoms. As they grow, they may be moved to well-flushed raceways or held suspended in nature (**Figure 4C**) in net cages.

There are risks associated with aquaculture, just as with harvesting natural populations. A major problem is the one that affects many agricultural monocultures and that is the increased susceptibility to disease outbreaks among densely farmed organisms. Such diseases now affect cultured abalone and scallops in China. Another problem involves the reliance on a relatively few animals for spawning purposes, which can lead to genetic deficiencies and inbreeding, further endangering a culture program. The coastal location of aquaculture facilities makes them susceptible to damage by storms, and if such storms increase or intensify with global warming, aquaculturists risk losing their animals, facilities, and investment. Ice can cause damage in cold-winter regions, although this is more predictable than are intense storms and preventative steps can be taken (not always successfully).

Extensive use of rafts and other systems for suspension culture (**Figure 4C**) may interfere with shipping and recreational uses of the water, and in some regions, laws against navigational hazards prevent water-based culture systems. If land contiguous to the water is too expensive because of development or other land-use practices, land-based culture systems may not be economically feasible. Finally, coastal residents may consider rafts to be an eyesore that lowers the value of their property and they may seek to have them banned from the region.

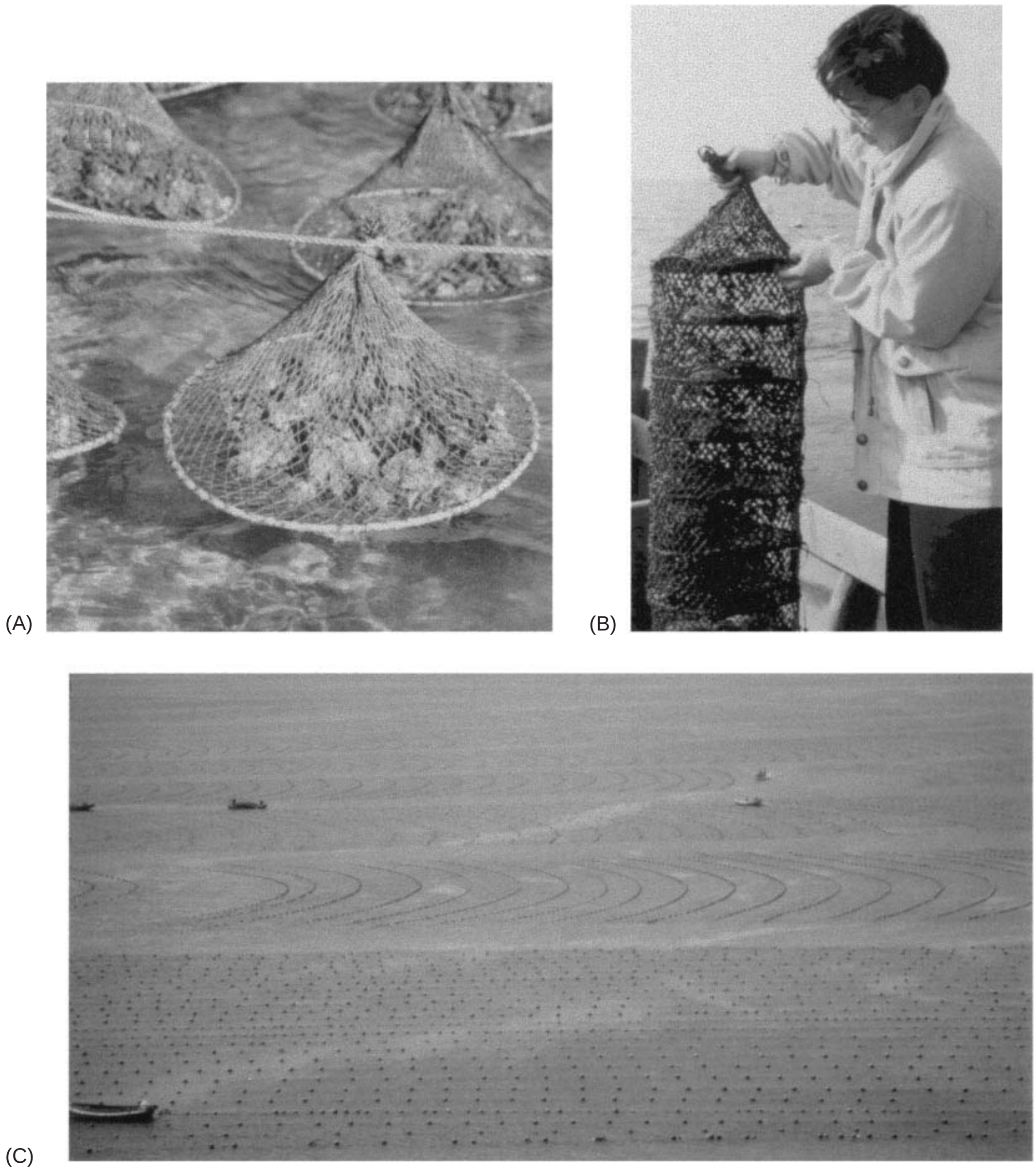

Figure 4 (A) Single-compartment pearl oyster cages attached to intertidal longlines. (B) Multi-compartment lantern net used to culture scallops. (C) Suspended longlines for growing Pacific oyster, scallops, and abalone off Rongchen, China. (Photographs courtesy of Dr Ximing Guo; reproduced with permission from Guo *et al.* (1999) *Journal of Shellfish Research* 18: 19–31.)

Comparisons of Wild and Cultured Production

Of the 86–93 million metric tons of aquatic species harvested from wild stocks in 1996–1998 (capture landings), fish comprised 86%, mollusks 8%, and crustaceans (shrimp, lobsters, crabs) 6% (**Table 1**). Among the mollusks, the average relative proportions over the 3 years were cephalopods, 44%; bivalves, 32%; gastropods, 2%; and miscellaneous, 21%. Within the bivalves, the relative proportions over the 3 years were clams, 38% of all bivalves; freshwater mussels, 25%; scallops, 22%; marine mussels, 9%; and oysters, 6%.

Aquaculture had a greater effect on total landings (wild harvest plus aquaculture production) of mollusks than of fish and crustaceans. Of FAO's estimated 27–31 million metric tons of aquatic animals cultured worldwide from 1996 to 1998, fish comprised 64% and crustaceans comprised 5% by weight, declines from their proportions of the wild harvest (**Table 1**). In contrast, mollusks comprised

Table 1 Worldwide capture landings (wild harvest) and aquaculture production and value of fish, mollusks, and crustaceans from 1996 to 1998

Category	*1996 (%)*	*1997 (%)*	*1998 (%)*	*Average percentage*
Capture landings (million metric tons)				
Fish	80.9 (87)	79.7 (86)	72.7 (85)	86
Mollusks	6.6 (7)	7.3 (8)	6.6 (8)	8
Crustaceans	5.5 (6)	5.9 (6)	6.4 (7)	6
Total	93.0	92.9	85.7	
Aquaculture production (million metric tons)				
Fish	17.0 (63)	18.8 (65)	20.0 (65)	64
Mollusks	8.6 (32)	8.7 (30)	9.2 (30)	31
Crustaceans	1.2 (4)	1.4 (5)	1.6 (5)	5
Total	26.8	28.9	30.8	
Aquaculture value (billion $US)				
Fish	26.5 (62)	28.3 (62)	27.8 (61)	62
Mollusks	8.6 (20)	8.7 (19)	8.5 (19)	19
Crustaceans	7.8 (18)	8.5 (19)	9.2 (20)	19

From UN Food and Agriculture Organization statistics as at 21 March 2000.

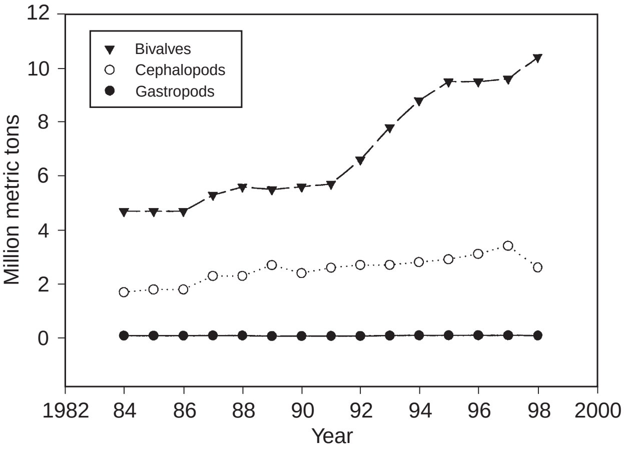

Figure 5 Worldwide production of bivalve, cephalopod, and gastropod mollusks from wild fisheries plus aquaculture activities in the period from 1984 to 1998. (From UN Food and Agriculture Organization statistics as at 21 March 2000.)

31% of culture production, about four times their proportion of the wild harvest. In addition, 20–40% more mollusks by weight were produced by aquaculture than were harvested from nature; by contrast, the quantities of cultured fish and crustaceans were a small fraction of quantities harvested in nature (**Table 1**). Of the cultured mollusks produced from 1996 to 1998, bivalves represented 87% by weight, followed by miscellaneous mollusks at 13%; cultured gastropods and cephalopods represented fractions of a percent of produced weight. When the FAO's harvest values of the wild fisheries and aquaculture production from 1984 to 1998 are combined for bivalves, cephalopods, and gastropods (**Figure 5**), the production of bivalves is seen to have risen greatly in the 1990s, with cephalopod production having increased modestly and gastropod production not at all. The differences can be attributed to the relatively greater yield of cultured bivalves compared with the other two molluskan groups.

The economic value of cultured animals ranged from 43 to 46 billion US dollars over the period 1996–1998, with fish comprising an average of 62%, mollusks 19%, and crustaceans 19% of this amount (**Table 1**). Thus, although production (weight) of cultured mollusks was six to seven times that of cultured crustaceans, their value just equaled that of crustaceans (this was a result of the premium value of cultured shrimps and prawns). Of the cultured mollusks, bivalves represented 93% by economic value followed by miscellaneous mollusks at 6%; cultured gastropods and cephalopods represented fractions of a percent of overall economic value.

Among cultured bivalves, the relative proportions by weight and by economic value were: Oysters, 42% and 42% respectively; clams, 26% and 32%; scallops, 15% and 20%; marine mussels, 17% and 6%; and freshwater mussels, < 1% in both categories. Thus, although oysters were the least important bivalve in terms of wild harvests (6% of bivalve landings, see above), they were the most important cultured bivalve. On the other hand, freshwater mussels represented 25% of wild harvests but were relatively insignificant as a cultured item.

China provides an excellent example of increased efforts in aquaculture, with its industry producing about 50% of the world's aquacultural output in the early 1990s, rising to about 67% by 1997 and 1998. Oyster and clam culture has been practiced in China for about two millennia, but growth of aquaculture accelerated in the early 1950s, with production outstripping wild fishery harvests by 1988 (**Figure 6A**). Mollusk culture was a substantial factor in this growth (**Figure 6B**). The intensified culture involved new species beyond the traditional oysters and clams, beginning with marine mussels, then scallops, then abalone. Over 30 species of marine mollusks are farmed along China's coasts, including 3 species of oysters, 14 of clams, 4 of marine mussels, 4 of scallops, 2 of abalone, 2 of snails, and 1 of pearl oyster. Marine mussel production has declined since 1992 (**Figure 6C**), apparently because of increased production of 'high-value' species (oysters, scallops, abalone).

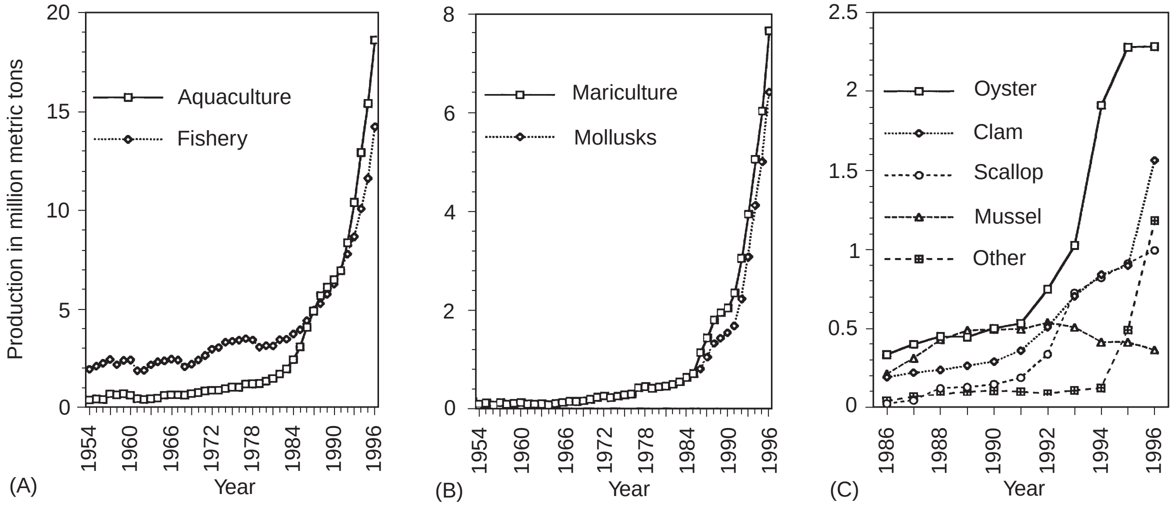

Figure 6 Production (wet, whole-body weight) in the natural fishery and in aquaculture in China. (A) Natural fishery and aquaculture. (B) Total mariculture (marine aquaculture) production and the molluskan component. (C) Comparative production among molluskan groups. (Adapted with permission from Guo *et al.* (1999) *Journal of Shellfish Research* 18: 19–31.)

Detrimental Effects of Molluskan Fisheries

Harvesting Natural Populations

Harvesting can have direct and indirect effects on local habitats. Direct effects include damage caused by harvest activities, such as when humans trample rocky shore organisms while harvesting edible mollusks. Similarly, heavy dredges with strong teeth can damage and kill undersized bivalves as well as associated inedible species. Dredges that use high-pressure water jets churn up bottom sediments and displace undersized clams and nontarget organisms that may not be able to rebury before predators find them exposed on the surface. When commercial shellfish are concentrated within beds of aquatic grasses, dredging can uproot the plants.

On the other hand, some harvesting techniques are relatively benign. For example, lures like squid jigs attract the target species with little or no 'by-catch' of nontarget species. Size selectivity can be attained by using different sizes of jigs. However, as with most fishing methods, overharvesting of the target species can still occur.

From the perspective of population dynamics, intense harvesting pressure commonly results in smaller average sizes of individual organisms and eventually most survivors may be juveniles. Care must be taken to ensure that a suitable proportion of individuals remains to reproduce before they are harvested, thus the widespread regulations on minimal sizes of individuals that can be harvested.

In terms of indirect effects, if some molluskan species are overharvested, inedible associated organisms that depend on the harvested species in some way can be affected. For example, oysters are 'ecosystem engineers' (like corals) and produce large structures (beds, reefs) that are exploited by numerous other organisms. Oyster shells provide attachment surfaces for large numbers of barnacles, mussels, sponges, sea squirts, and other invertebrates, as well as for the eggs of some species of fish and snails. Waterborne sediments as well as feces from all the reef organisms settle in interstices among the shells and become habitat for worms and other burrowing invertebrates. The presence of these organisms attracts predators, including crustaceans and fish. Consequently, the diversity of species on and around oyster reefs is higher than it is for adjacent soft-bottom systems. The same is true for marine mussel beds. Harvesting these bivalves can result in lowered biomass and perhaps lowered diversity of associated organisms.

Depleted populations of commercial bivalves may have other ecological consequences. These bivalves are 'suspension feeders' and pump water inside their shell and over their gills to extract oxygen and remove suspended food particles. When Europeans sailed into Chesapeake Bay in the 1600s, oyster reefs broke the Bay's surface and were a navigational hazard. Today, many oyster beds have been scraped almost level with the Bay bottom and annual harvests in Maryland have dropped from an estimated 14 million bushels of oysters in the 1880s to a few hundred thousand bushels today. Knowing the pumping capacity of individual oysters and the estimated abundances of pre-exploitation and present-day populations, scientists can calculate the filtering ability of those populations. Estimates are that a quantity of water equivalent to the total amount contained in the Bay could have been filtered in about a week in the early eighteenth century; today's depleted populations are thought to require nearly a year to filter the same amount of water.

This diminished filtering capacity has implications for food web dynamics. A feeding oyster ingests and digests food particles and expels feces as packets of material larger than the original food particles. Nonfood particles are trapped in mucous strings and expelled into the surrounding water as pseudofeces. Thus, oysters take slowly sinking microscopic particles from the water and expel larger packets of feces and pseudofeces that sink more rapidly to the Bay bottom. When oyster numbers are greatly diminished, this filtering and packaging activity is also diminished and more particles remain suspended in the water column. Thus ecological changes in Chesapeake Bay over the last century may have been enormous. Many scientists believe the Bay has shifted from a 'bottom-dominated' system in which oyster reefs were ubiquitous and the water was clearer than now to one dominated by water-column organisms (plankton) in which light levels are diminished. Smaller plankton serve as food for larger plankton, including jellyfish, and some scientists believe that the large populations of jellyfish present in the Bay in warmer months may be a result of overharvesting of oysters over the past century.

The reverse of this phenomenon is seen in the North American Great Lakes, where huge populations of zebra mussels *Dreissena polymorpha* and quagga mussels *Dreissena bugensis* have developed from invaders inadvertently introduced from Europe in ships' ballast water. The mussels filter the lake water so efficiently that the affected lakes are clearer than they have been for decades – they have become 'bottom-dominated' and plankton populations have decreased in abundance. Unintended consequences resulting from overharvesting other mollusk populations remain to be elucidated.

Aquaculture Practices

A number of environmental problems affect molluskan aquaculture. For one, heavy suspension feeding by densely farmed mollusks in coastal bays may outstrip the ability of the environment to supply algae, so the mollusks may starve or cease to grow. Another problem is that large concentrations of cultured organisms produce fecal and other wastes in quantities that can overwhelm the environment's ability to recycle these wastes. When this happens, eutrophication occurs, inedible species of algae may appear, and abundances of algal species that support molluskan growth may be reduced. To counter these problems, countries like Australia are using Geographic Information System technology to pinpoint suitable and unsuitable locations for aquaculture.

Introductions of exotic species of shellfish for aquaculture purposes have sometimes been counterproductive. A variety of diseases that have depleted native mollusk stocks have been associated with some introductions (e.g. MSX disease in the eastern oyster *Crassostrea virginica* in Chesapeake Bay is thought to be linked to attempts to import the Pacific oyster *Crassostrea gigas* to the bay). 'Hitchhiking' associates that are carried to the new environment by imported mollusks have sometimes caused problems. For example, the gastropod *Crepidula fornicata* that accompanied oysters of the genus *Crassostrea* that were brought to Europe from Asia has become so abundant that it competes with the European oyster *Ostrea edulis* and blue mussel *Mytilus edulis* for food and may foul oyster and mussel beds with its wastes. Recently, the veined rapa whelk *Rapana venosa* has appeared in lower Chesapeake Bay, apparently arriving from the Black Sea or from Japan in some unknown fashion. It is a carnivore and may pose a threat to the indigenous oyster and hard clam fisheries (although it might prove to be a commercial species itself if a market can be found). As a result of these and other problems, many countries have developed stringent rules to govern movement of mollusks locally and worldwide.

See also

Cephalopods. Coral Reef and Other Tropical Fisheries. Corals and Human Disturbance. Dynamics of Exploited Marine Fish Populations. Ecosystem Effects of Fishing. Exotic Species, Introduction of. Fisheries and Climate. Fishery Management, Human Dimension. Fishery Manipulation through Stock Enhancement or Restoration. Fishing Methods and Fishing Fleets. Marine Fishery Resources, Global State of. Rocky Shores.

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MONSOONS, HISTORY OF

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Introduction

The difference in specific heat capacity between continents and oceans (and specifically between the large Asian Continent and the Indian Ocean) induces the monsoons, strong seasonal fluctuations in wind direction and precipitation over oceans and continents. Over the Indian Ocean, strong winds blow from the south-west during boreal summer, whereas weaker winds from the north-east blow during boreal winter. The monsoons are strongest over the western part of the Indian Ocean and the Arabian Sea (**Figure 1**). The high seasonal variability affects various fluctuations in the environment and its biota which are reflected in marine sediments. Marine sedimentary sequences from the continental margins thus contain a record of the history of monsoonal occurrence and intensity, which may be deciphered to obtain insight in the history of the monsoon system. Such insight is important not only to understand the mechanisms that cause monsoons, but also to understand the influence of monsoons on the global climate system including the Walker circulation, the large-scale, west–east circulation over the tropical ocean associated with convection. The summer monsoons may influence the Southern Oscillation because of interactions between the monsoons and the Pacific trade wind systems.

Geologic Records of the Monsoons

Sedimentary sequences record the effects of the monsoons. One such effect is the upwelling of deeper waters to the surface, induced by the strong southwesterly winds in boreal summer in the Arabian Sea, and the associated high productivity of planktonic organisms. Continents supply sediments to the continental margin through the discharge of rivers, as the result of coastal erosion, and carried by winds (eolian sediments). Monsoon-driven wind direction and strength and precipitation therefore control the sediment-supply to the continental margin.

Monsoonal precipitation supplies a large volume of fresh water, discharged by rivers from the conti-