Catch of the day, Chile.

Part Four
Humans and the Sea

CHAPTER 17

Resources from the Sea

People have used the many resources that the oceans offer ever since the first humans ventured to the shore. Evidence of the use of marine life as food goes back to prehistoric times and includes fishhooks, seashell artifacts, and mounds of empty mollusc shells. Our exploitation of marine resources is now much more sophisticated (Fig. 17.1), but, unfortunately, it has also become more destructive. Fishers cross the oceans assisted by satellites, marine chemists extract wonder drugs from marine organisms, genetic engineers develop faster-growing fish, and ocean engineers investigate better ways of harvesting energy from waves and tides.

Chapter 17 examines the resources of the sea and their use, and misuse, by humans. In discussing them we will draw on our knowledge of the sea floor and the chemical and physical features of the ocean (discussed in Part One of the book) and of the types and distribution of marine life (discussed in Parts Two and Three). Many other disciplines, ranging from technology development to the marketing of new products, are also involved.

THE LIVING RESOURCES OF THE SEA

The oceans, which cover most of the surface of the earth, are the planet's largest factory of organic matter. Humans take advantage of this productivity and harvest many different kinds of marine organisms. Most are harvested for food, but they also provide many other products and materials. Millions of people also use the living resources of the sea in recreational fishing, sport diving, or even by keeping an aquarium at home.

Food from the Sea

The oceans provide food as well as employment for millions of people. Many different types of marine organisms are harvested. Seaweeds and creatures as diverse as jellyfishes, sea cucumbers, and even polychaete worms are part of the diet in many cultures. The vast majority of the harvest, however, consists of fishes, which are known in fisheries terminology as **finfish.** Finfish constitute nearly 90% of the total world marine catch. Molluscs and crustaceans, which together are called **shellfish,** are less important than finfish in the size of their catch but the value of the catch is very significant.

Most of the world's food is grown on land, and food from the sea represents only about 1% of all the food eaten. Still, seafood is one of the world's most important foods. It is rich in protein, which is essential for normal growth. Finfish, ocean catches and aquaculture figures combined, provides around 30.4% of the animal protein consumed by people around the world. Dependence on seafood for protein is much higher in most coastal nations, especially poor ones. The world's population is still growing (Fig. 17.2), and it is increasing much faster in the places where it hurts the most: the poor, already crowded countries of the developing world.

The groups of marine organisms that are most widely used as food are fishes, molluscs, and crustaceans. Seafood is important to the world's population because it is a good source of protein.

Marine fisheries provide much-needed employment and profit. As we shall see, however, the world's most important fisheries are already overexploited, and some are exhausted. Worldwide catches had stabilized despite increasing effort by the late 1980s (Table 17.1) after increasing almost fivefold since 1950. Neither the world fish catch nor the world grain output may be able to catch up with global population growth. The amount of grain and fish per person has already started to decrease. The Food and Agriculture Organization (FAO) of the United Nations has estimated that by 2010 world demand for fish will be 10 to 40 million tons above production. The world's oceans have been running out of fish mostly because of overfishing.

FIGURE 17.1 Northern bluefin tuna (*Thunnus thynnus*) being unloaded from a freezer ship to a modern cannery. The valuable catch is canned for human consumption and the by-products processed into pet food, fertilizer, and chicken feed for sale around the world.

Fishing is one of the oldest human endeavors. Small-scale fisheries that involve simple gear and methods are still practiced around the world, especially in developing countries. These fisheries, in fact, employ most of the world's fishing people. They also provide animal protein to people whose diets are often protein-deficient.

The increased demand for seafood in affluent countries and the expansion of the world's population have steadily increased the pressure on the food resources of the sea (Fig. 17.3). The application of technology, from the development of more effective gear to the use of satellites to find fish, has greatly increased the efficiency with which we harvest these resources. Nations like China, Japan, South Korea, and the United States have developed high-tech fishing fleets that can remain on the fishing grounds away from the home port for long periods. Factory, or mother, ships process and store the fish taken by smaller fishing boats. The catch is processed, marketed,

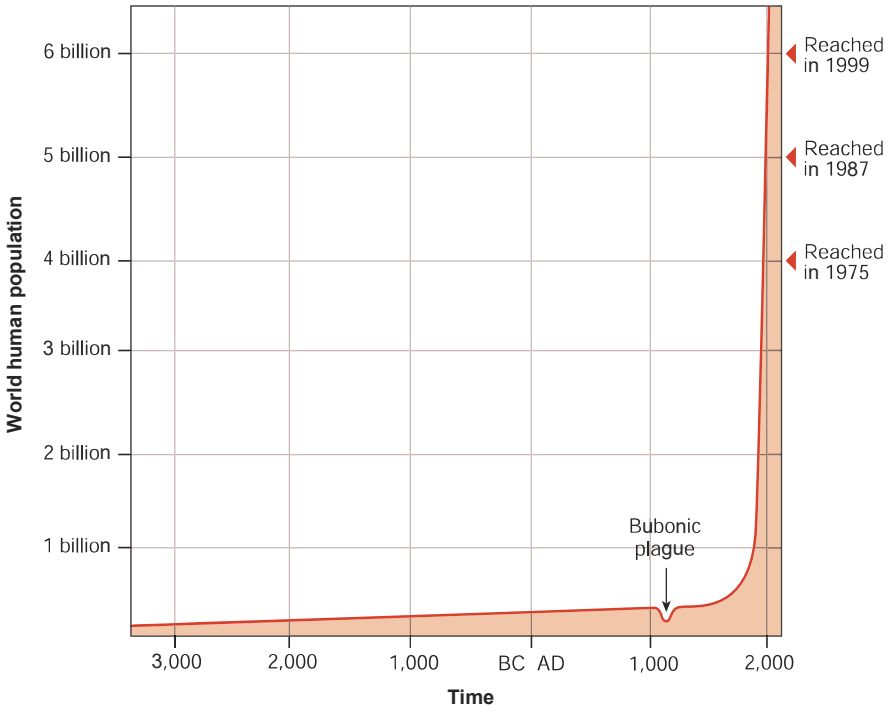


FIGURE 17.2 The curve that represents the growth of the world human population over the centuries looks like a giant J: Very slow, almost non-existent population growth is followed by a sudden explosion of very fast growth. This J-shaped curve indicates that the more people there are, the faster the population grows, as was the case with the dinoflagellates shown in Figure 10.2. Growth was slow for millennia because of food shortages and disease. The domestication of plants and animals helped provide more food, but periodic famines and plagues, like the bubonic plague in Europe during the 1300s, kept the population in check. Better sanitation, advances in medicine, and more efficient agriculture eventually helped sharply reduce the death rate, and within a few centuries the population began to increase rapidly. A decrease in the birth rate of many countries, however, has slowed down global population growth. In addition, AIDS has significantly increased mortality in many countries. In 2005 the United Nations projected a world population of 9.1 billion by 2050. The population of the United States continues to grow, reaching 300 million in 2006.

Table 17.1 World Commercial Catches of Selected Fishes, Molluscs, and Crustaceans in Millions of Metric Tons

Catch	1975	1980	1985	1990	1995	2000	2004
Herrings, sardines, etc.	13.43	16.14	21.10	22.32	22.01	24.90	23.26
Miscellaneous pelagic fishes	not listed	not listed	not listed	not listed	13.93	10.64	11.17
Cods, haddocks, hakes, pollocks	11.85	10.75	12.46	11.58	10.74	8.68	9.43
Tunas, bonitos, billfishes	2.06	2.55	3.18	4.43	4.89	5.82	6.02
Salmon, smelts	0.55	0.80	1.17	1.51	1.15	0.80	0.88
Flounders and other flatfishes	1.16	1.08	1.35	1.23	0.92	1.01	0.87
Sharks, rays	0.59	0.60	0.62	0.69	0.76	0.87	0.81
Total marine fishes	**51.93**	**55.73**	**64.40**	**69.36**	**72.00**	**71.84**	**71.55**
Freshwater fishes	5.96	6.17	8.74	12.23	5.80	6.80	7.85
Squids, octopuses	1.18	1.53	1.79	2.36	2.94	3.66	3.77
Clams, cockles	0.94	1.20	1.51	1.53	0.96	0.80	0.85
Scallops	0.29	0.37	0.60	0.87	0.54	0.66	0.80
Mussels	0.53	0.62	0.97	1.34	0.24	0.26	0.19
Oysters	0.85	0.97	1.09	1.00	0.19	0.25	0.15
Total marine molluscs	**4.03**	**4.91**	**6.18**	**7.73**	**6.38**	**7.25**	**6.89**
Shrimps	1.33	1.70	2.12	2.63	2.44	3.08	3.60
Crabs	0.75	0.82	0.89	0.89	0.95	1.09	1.36
Lobsters	0.10	0.10	0.20	0.21	0.22	0.23	0.23
Krill	0.04	0.48	0.19	0.37	0.12	0.11	0.12
Total marine crustaceans	**2.35**	**3.20**	**3.42**	**4.50**	**4.77**	**5.91**	**5.70**
World total catch in marine fishing areas	**61.22**	**64.46**	**75.68**	**82.25**	**85.04**	**86.80**	**85.79**

Note: Catches tabulated in groups defined by the Food and Agriculture Organization of the United Nations; only selected groups are listed and, when added, will not equal totals.

and sold in a multitude of ways: fresh, frozen, canned, dried and salted, smoked, marinated, as fish sticks, and as fish meal. Fishing operations have been known to diversify into businesses that develop new products such as boats and fishing gear. Some even get involved in the management of fishing resources to prevent them from disappearing. Modern fishing ventures thus provide jobs not only to fishers but also to technicians, marine biologists, marketing specialists, economists, and other experts. Women and the elderly often undertake processing and marketing in developing countries, which contributes to social equity. Commercial fisheries provide a considerable portion of the export earnings of countries like Canada and Iceland and help sustain these nations' economies.

The amount of seafood consumed in various cultures varies widely because of consumer tastes, price, and availability. The average Japanese eats 17.1 kg (37.7 lb) of fish a year, while Americans consume an average of 7.5 kg (16.6 lb) per person a year. Seafood consumption has been steadily increasing in the United States, Canada, and other developed countries as consumers broaden their tastes and look for healthy, low-fat sources of protein.

Major Fishing Areas Most of the world's major fisheries are located near the coast (Fig. 17.4). These coastal fisheries exploit the rich waters of the **continental shelf.** Because shelf waters are shallow compared with the open ocean, it is relatively easy to harvest bottom-dwelling, or **demersal,** species. Coastal fisheries also include **pelagic** catches: fishes, squids, and other animals that live in the water column. **Primary production** is higher over the shelf than farther offshore, supporting much more abundant life (see Table 10.1, p. 225, and Fig. 15.26). Significant coastal fisheries are found where the continental shelf is very wide, such as the Grand Banks of Newfoundland, the North Sea, and the Bering Sea.

Most of the world's fisheries are coastal. Coastal fisheries take both bottom, or demersal, and open-water, or pelagic, catches. Other valuable fisheries are found in the open ocean far from the coast.

Continental Shelf The shallow, gently sloping edge of the continents, extending from the shore to the *shelf break,* the point where the slope gets steeper.

• Chapter 2, p. 33; Figure 2.19

Primary Production The conversion by autotrophs of carbon dioxide into organic carbon, that is, the production of food.

• Chapter 4, p. 68

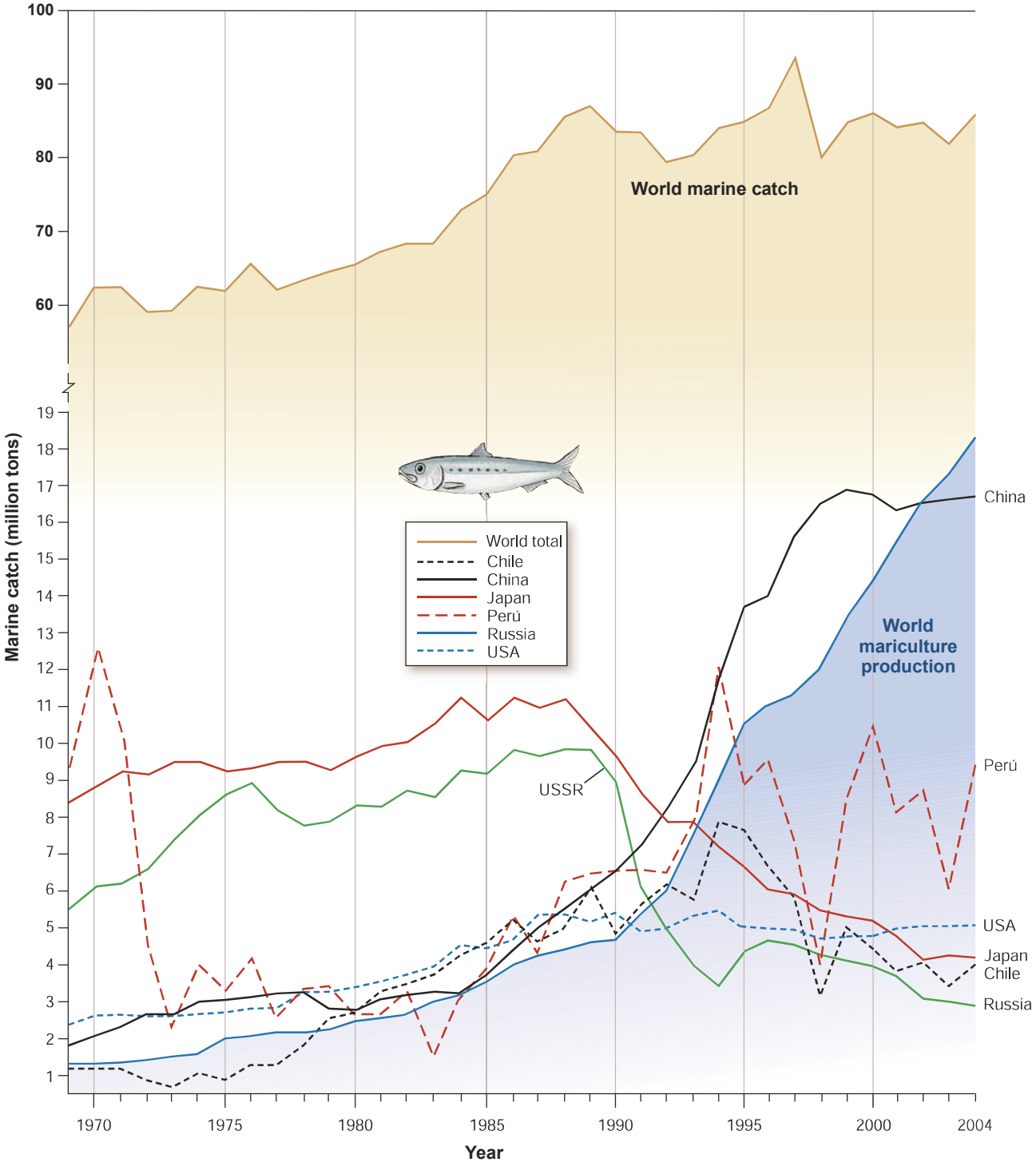


FIGURE 17.3 World marine catch, world mariculture production, and catches by the world's six major fishing nations. Marine fishes constitute the bulk of the catches, but shellfish are also included. Notice that annual catches by two of the leading nations, Japan and Russia, have decreased since the late 1980s. Economic and political instability have affected Russian catches, which until 1990 included those from the former Soviet Union. The figures for Perú (and Chile to some extent) show the dramatic ups and downs of its huge anchovy fishery (see "Of Fish and Seabirds, Fishers and Chickens," p. 389). Chinese catch statistics may be inflated by a tendency of local managers to overstate catches to enhance their promotion prospects. Thus, global catches may have actually declined instead of remaining more or less stable as shown here.

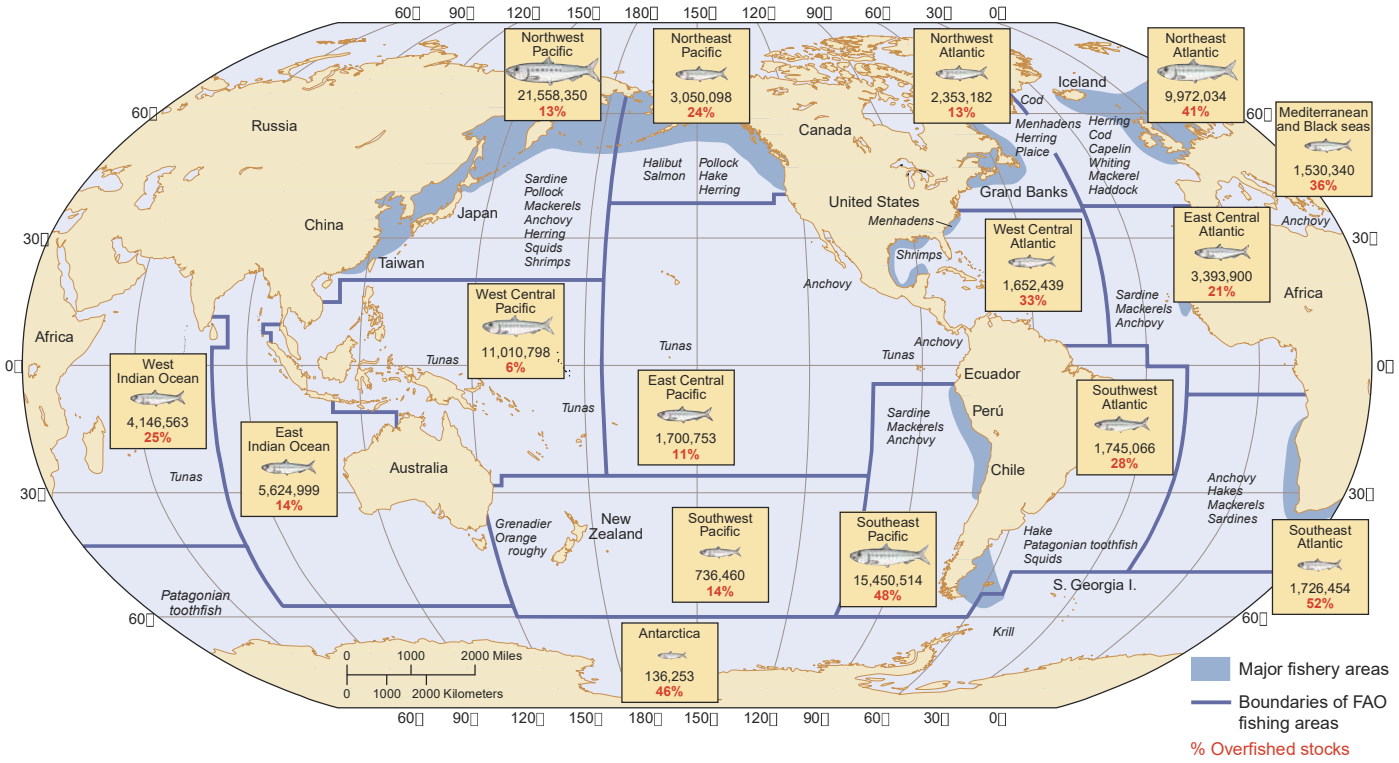


FIGURE 17.4 The major marine fishing areas of the world, based on boundaries established by the Food and Agriculture Organization of the United Nations (FAO). Figures refer to the 2004 marine fish and shellfish catches (in millions of tons) of each region. Figures in red refer to the percent (%) overfished stocks. The figure for Antarctica incorporates catches for three separate FAO regions. Half of the 18 FAO regions showed higher catches in 2004 than in 2003. These figures do not include illegal fishing, particularly for Patagonian toothfish in Antarctic and subantarctic waters.

Notice from the map in Figure 17.4 that some of the largest catches are taken from the northwest Pacific and the northeast Atlantic. Being close to the major industrial nations, these areas have been intensively exploited for the longest time. Most fishing grounds in the Atlantic, Pacific, and Mediterranean are in decline or exhausted. A few other areas are less heavily exploited and still have some underexploited resources. This is the case in the Indian Ocean and around Antarctica. These areas are more remote and therefore more expensive to exploit. Fisheries in such remote areas, however, are rapidly increasing.

The open ocean, 92% of the total area of the ocean, supports fewer fisheries than the continental shelf but they are nevertheless very valuable. Some of the richest fishing areas of the world are located in **upwelling** areas just beyond the continental shelf, including those of Perú and northwest Africa (Fig. 17.4). Other fisheries, like those for migratory species like tunas, extend far into the open ocean.

Major Food Species There are thousands of species of fishes, crustaceans, and molluscs, but relatively few support major fisheries. A summary of the major commercial catches for the world is given in Table 17.1.

The largest catches in the world are those for **clupeoid fishes,** small, **plankton-feeding** fishes that form huge schools. They include herrings (often sold as "sardines"), anchovies, sardines (sometimes called pilchards), menhadens, and shads (Table 17.2). Clupeoid fishes are usually concentrated over the continental shelf, but some species can also be found offshore in upwelling areas. They are caught with large **purse seines** that surround and trap the schools (Figs. 17.5*b* and 17.6*b*).

Herrings, anchovies, and sardines are eaten fresh, canned, or pickled. **Fish protein concentrate (FPC),** or **fish flour,** an odorless powder used as a protein supplement for human consumption, is also made from these and other fishes. Most of the clupeoid catch, however—particularly that of menhadens and herrings—is ground into **fish meal,** an inexpensive protein supplement used in feed for poultry, livestock, and even other species of fish that are farmed. The fish are also pressed to obtain **fish oil,** used in the manufacture of products like margarine, cosmetics, and paints. Some of the catch finds its way into fertilizers and pet food. Fisheries such as these, where the catch is used for purposes other than direct human consumption, are now estimated to account for over a third of the world's total.

Clupeoid fishes, herrings and their kin, provide the largest catches of fish. Most are used not directly as food but in fish meal and other products.

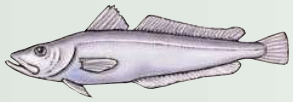
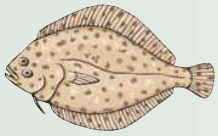
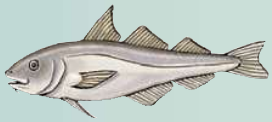
Upwelling The upward flow of nutrient-rich deep water to the surface, resulting in greatly increased primary production.

• Chapter 15, p. 351

Plankton-feeding fishes use gill rakers, slender projections of the gills, to strain plankton from the water.

• Chapter 8, p. 161

Table 17.2 Examples of Commercially Important Fishes around the World

Species	Distribution and Habits	Species	Distribution and Habits
Herrings (*Clupea*)	North Atlantic and Pacific; schooling, plankton feeders; 38 cm (15 in)	 Hakes and whiting (*Merluccius*)	Temperate worldwide; demersal, feed on bottom invertebrates and fishes; 1 m (3 ft)
Sardines, or pilchards (*Sardinops, Sardinella, Sardina*)	Mostly temperate worldwide; schooling, plankton feeders; 30 cm (12 in)	 Flatfishes: flounders, halibuts, soles, and others (*Platichthys, Hippoglossus*, etc.)	Mostly temperate worldwide; demersal, feed on bottom invertebrates and fishes; 2 m (6.5 ft) in some halibuts
Anchovies (*Engraulis*)	Worldwide; schooling, plankton feeders; 20 cm (8 in)		
Menhadens (*Brevoortia*)	Temperate and subtropical Atlantic; schooling, plankton feeders; 38 cm (15 in)	Tunas (*Thunnus, Katsuwonus*, etc.)	Tropical and temperate; schooling, carnivores; 4.3 m (14 ft) in the bluefin tuna
Cods (*Gadus*)	North Atlantic and Pacific; demersal, feed on bottom invertebrates and fishes; 1.5 m (5 ft) in the Atlantic cod (no longer this large)	Mackerels (*Scomber, Scomberomorus*)	Tropical and temperate worldwide; schooling, carnivores; 2.4 m (8 ft)
Alaska, or walleye, pollock (*Theragra chalcogramma*)	Temperate North and Central Pacific; demersal, feeds mostly on bottom invertebrates and fishes; 90 cm (35 in)	Salmon (*Oncorhynchus, Salmo*)	North Pacific and Atlantic; open ocean and rivers, carnivores; 1 m (3 ft)
 Haddock (*Melanogrammus aeglefinus*)	North Atlantic; demersal, feeds mostly on bottom invertebrates; 90 cm (35 in)		

Note: Fishes are not drawn to scale. The measurements given are the approximate maximum length.

Cods and related fishes—the pollock, haddock, hakes, and whiting (Table 17.2)—make up another important component of the worldwide catch. These fishes are all demersal, cold-water species. They are mostly caught with **trawls** that are dragged along the bottom (Fig. 17.6*d*). The Alaska, or walleye, pollock (*Theragra chalcogramma*) is the largest fishery in U.S. waters.

The Atlantic cod (*Gadus morhua*) supported a very important fishery for centuries. European fishers were already fishing for it on the Grand Banks of Newfoundland a century before the arrival of the first colonists (and probably before Columbus). It was a vital source of inexpensive protein in many parts of the world. In an age before refrigeration, cod was salted and dried for preservation before being sent to Europe and the Caribbean. The dried fish was soaked in water before cooking, just as it is done today in the Mediterranean and Caribbean. Now, however, most cods and related fishes are sold fresh or frozen.

The cod fishery on the Grand Banks lasted until 1992 when a moratorium was declared in an attempt to save the fishery from extinction. The fishery had peaked in the late 1960s, almost 25 years before the moratorium. The Georges Bank fishery off New England was similarly closed in 1994, that off Newfoundland and Labrador in 2003. The closures caused high unemployment among Canadian and American fishers and related workers, as well as higher prices for consumers. The closures also threaten to destroy traditional fishing cultures. But even worse, some

(a)

(b)

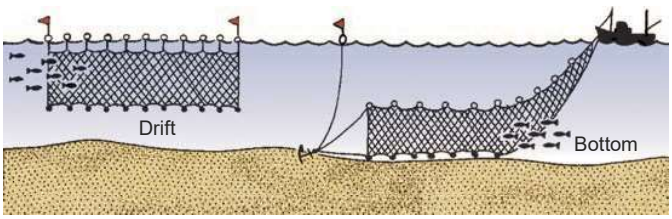
(c)

(d)

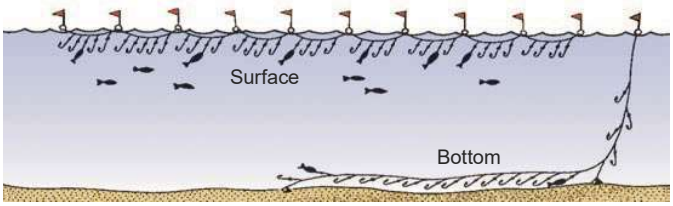
FIGURE 17.5 The European anchovy (*Engraulis encrasicholus*) is an important food fish. It is canned, salted, or cooked fresh. Basque fishers from the port of Bermeo (*a*) in the Bay of Biscay, northern Spain, make bountiful catches using purse seines (*b*). Fish is unloaded (*c*) and sold in the fish market (*d*). Women workers, or *neskatillas,* play an important role in the fishing routine. They are in charge of carrying and selling the fish.

experts predict that the cod populations will never recover. It appears that juvenile cod have little chance of surviving because fishes such as herring and mackerel, which are normally eaten by adult cod, are now feeding on the juveniles. Cod is now listed as an endangered species in Newfoundland, unthinkable a few decades ago. Cod fisheries are also exhausted elsewhere in the North Atlantic. North Sea catches dropped from 277,000 metric tons in 1971 to 59,000 metric tons in 2000. As a result, vast areas were closed to cod fishing in 2001. Cod, however, is now commercially farmed in Norway (see Table 17.3).

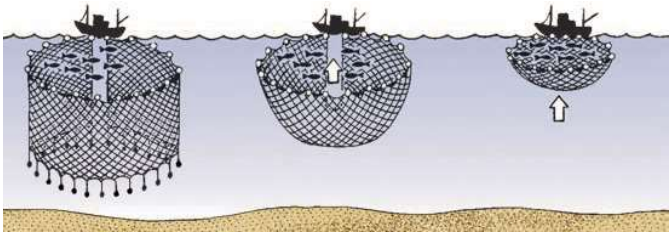
Jacks, mullets, rockfishes (including the ocean perches, also known as redfishes), and mackerels (Table 17.2) are also important in terms of worldwide tonnage. Canned mackerel from Japan, South America, and elsewhere has become an important source of cheap protein in some parts of the world. Flounders, halibuts, and other flatfishes are important catches in the United States, Canada, and other countries. Salmon, though now caught in much smaller numbers than formerly, are a very valuable catch. The salmon fishery is still important in the North Pacific in terms of the



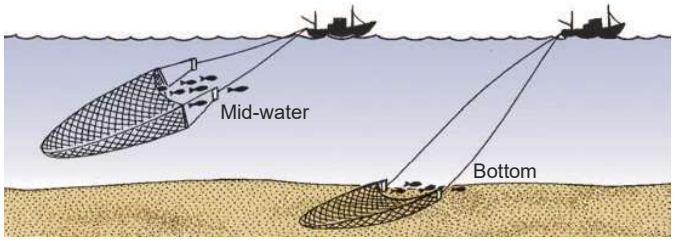
(a) Gill nets



(c) Longline



(b) Purse seine



(d) Trawls

FIGURE 17.6 Examples of fishing methods.

FIGURE 17.7 Octopuses have long been valued as a culinary delicacy. These freshly caught individuals were cleaned and left to dry on the Greek island of Paros in the Aegean Sea.

FIGURE 17.8 Raw fish, shrimp, seaweed, scallops, and sea urchin roe are used in *sushi* and *sashimi,* Japanese delicacies that have become popular around the world.

dollar value of the catch. Salmon are caught both along the coast and in the open ocean. The fishery is threatened, however, by overfishing and environmental degradation, especially the destruction of salmon breeding sites (see "Migrations," p. 168). Most of the salmon consumed now is farmed.

The most important open-ocean fisheries are those for several species of tunas (Table 17.2). The migration routes of tunas criss-cross the oceans, mostly in tropical waters (see Fig. 8.22). Skipjack, yellowfin, albacore, bigeye, and bluefin tunas command high prices in world markets. Most are eaten in affluent countries, either canned or raw as *sashimi.* They are caught by modern fleets that use sophisticated techniques to spot the schools in mid-ocean. The fishes are caught with large seines, surface **longlines,** or **gill nets** (Fig. 17.6). The fishing boats are equipped with freezers so that the fishes can be brought to port long after they are caught. Besides these high-tech fleets, some local, small-scale fisheries continue to exploit bonito, skipjack, and other tunas.

Molluscs are the second most valuable group of marine food species after fishes. Several types of **cephalopods** provide the largest catches of molluscs (Table 17.1). Squids, cuttlefishes, and octopuses are especially popular in Far Eastern and Mediterranean countries (Fig. 17.7). Fishers use lighted boats to catch squid at night. Other important food molluscs are clams (*Macoma* and many others), oysters (*Ostrea*), mussels (*Mytilus*), scallops (*Pecten*), and abalones (*Haliotis*).

Crustaceans are prized as food the world over. Major fisheries exploit many species of shrimps and lobsters, all of which bring a high price. Crabs such as the blue (*Callinectes sapidus*), king (*Paralithodes camtschaticus*), and Dungeness (*Cancer magister*) are also harvested. *Langostino* (some species of *Cervimunida* and *Pleuroncodes*), sometimes called "langostino lobster" or "squat lobster," has become an important food item. It is neither a true lobster nor a shrimp but a galatheid crab more related to hermit crabs (see Fig. 17.13 for a similar species of *Pleuroncodes*).

Other groups of marine organisms are also eaten (Fig. 17.8), though they do not contribute much to global fisheries production. Seaweeds, for instance, are eaten in many cultures, especially in the Far East (see "Seaweeds for Gourmets," p. 111). Sea urchins are esteemed for their gonads, or roe, which command an astronomical price, particularly in Japan. In California there is a fishery for the red sea urchin (*Strongylocentrotus franciscanus*). Most of the roe is exported to Japan or sold to Japanese restaurants where, known as *uni,* it is eaten raw. Some species of sea cucumber are another common seafood. Called *trepang* or *bêche-de-mer,* they are dried, boiled, smoked, or eaten raw in the Orient. Examples of other invertebrates used as food are jellyfishes in the Orient, gooseneck barnacles in Spain, and polychaete worms in the South Pacific.

Sea turtles are still hunted and their eggs still gathered, even where they are officially protected. Seals and whales are also eaten in some places, and there are traditional fisheries for marine mammals in the Arctic (see Fig. 4.2), North Atlantic, West Indies, and South Pacific. These traditional fisheries are a source of considerable controversy because most of the species involved are endangered and modern technologies like powerboats are used. Should traditional fisheries be banned or left entirely unregulated? A compromise between these two extremes involves questions of the rights of indigenous cultures, the ethics of conservation, and international politics.

Optimal Yields and Overfishing Like all living things, species we harvest for food can reproduce to replace the individuals that are lost to disease and predators, including humans. Because these living resources can replace themselves, they are known as **renewable resources.** Resources that are not naturally replaced, like oil and minerals, are called **non-renewable resources** (see "Non-Living Resources from the Sea Floor," p. 396). Experience has shown, however, that, though the food resources of the ocean are renewable, they are not inexhaustible.

Imagine that fishers discover a new, untapped population of sardines. The new fishery is very successful, and the fishers make

handsome profits. The news spreads, and soon other fishers join in. After several years, **overfishing** results: Catches dwindle, and the fish caught are smaller. The fishery becomes unprofitable, and many, if not most, of the fishers go out of business.

What happened? The reproductive rate of sardines—or salmon, scallops, or sharpnose surfperches—depends, at least in part, on the size of the population, or **stock,** as it is known to fisheries biologists. Like dinoflagellates growing in a jar (see Fig. 10.2), fish stocks grow fastest when there are neither too few nor too many individuals in the population. If the population size is very small, the number of young being born is also small because there are not many potential parents. If the population is too large, competition, overcrowding, and diseases slow down the growth rate. The number of new young, that is, the population growth rate, is highest at some intermediate population density (Fig. 17.9).

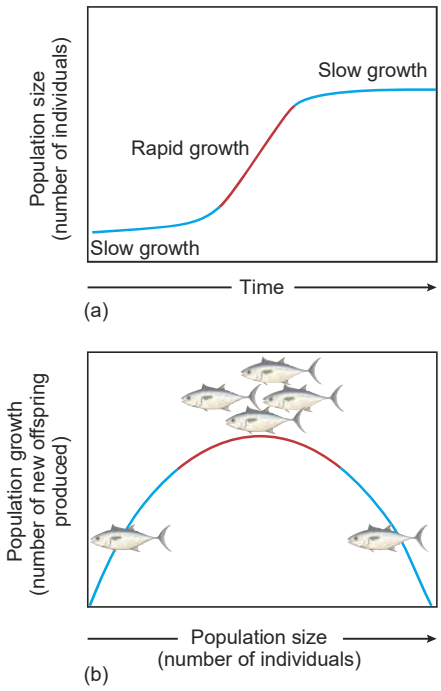


FIGURE 17.9 (*a*) The theoretical growth of a population that begins with just a few individuals. At first, with only a few adults to produce offspring, the population increases very slowly (blue line). As the population size gradually increases, so does the number of offspring, and the rate of growth begins to increase (red line). Eventually, the population reaches the point where limiting factors such as food shortage and crowding prevent further growth (blue line). (*b*) Thus, the rate of growth is directly related to population size and is maximal at intermediate abundances. Also see Figure 10.4.

To harvest the stock in the optimal way, one must consider this feature of population growth. Obviously, it would be foolish to harvest the entire stock at once, because no individuals would be left to reproduce, and the fishery would be destroyed forever. If the fishery is to last indefinitely, or to be **sustainable,** the number of fish caught can be no more than the number of new fish added through reproduction; if more are caught, the population will decline. The **sustainable yield** of a population is the amount that can be caught and just maintain a constant population size. In other words, the catch is just large enough to prevent the population from growing but not so large as to reduce it.

Because the growth rate depends on the population size, so does the sustainable yield. When the stock is large, it is held in check by natural mortality; even a small harvest causes a reduction in the population. Very small populations also have a low growth rate. In this case, fishing is more dangerous because it can threaten the seed stock and drive the species to the brink of extinction.

The highest catch that can be continued year after year without threatening the stock is called the **maximum sustainable yield.** It occurs at medium population size, when the natural growth rate is highest. From the point of view of profit and food production, this can be thought of as the optimal catch.

The size of the catch, and therefore of the stock, is directly related to **fishing effort:** how many boats and fishers there are, how long they stay at sea, and so forth. When little effort is put into the fishery, of course, the catch is small. Only a small fraction of the stock is removed by fishing, and the population grows until limited by natural factors. The population remains secure, but the fishery yields less food and less profit than it could safely sustain.

With intense effort the catch exceeds the maximum sustainable yield. Before long the stock declines and catches fall no matter how much fishing effort is expended: Overfishing has occurred.

A plot of the sustainable yield versus fishing effort gives us a **catch-effort curve,** which is very similar to a plot of the population growth rate versus the size of the stock (Fig. 17.10). The maximum sustainable yield occurs at moderate levels of effort, which result in intermediate stock sizes.

Unfortunately, the biological properties of most fisheries stocks do not mix well with the principles of economics. Most fisheries are profitable when harvested at the level of the optimum catch. As long as there is money to be made, more fishers and more boats will be attracted to the fishery, and the catch will exceed the optimal level. In an open fishery, one that

Cephalopods Squids, octopuses, and related molluscs that use sucker-bearing arms to capture prey and, with a few exceptions, lack a shell.
• Chapter 7, p. 130

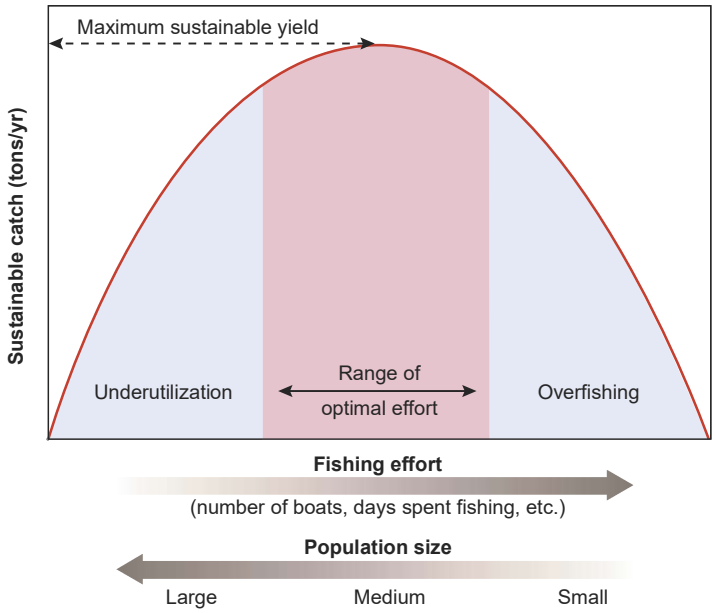


FIGURE 17.10 A generalized, theoretical curve showing that, as fishing effort increases, so does the catch, but only up to a point, which is the biologically optimal catch. After this point the overexploited fishery will yield smaller and smaller catches as the effort increases. The curve is called a catch-effort curve.

is completely unregulated, market forces inevitably lead to overfishing. A fishery may still be profitable to some fishers, even if below the maximum sustainable yield. The total profit from the fishery, however, decreases.

Overfishing results when catches are higher than the maximum sustainable yield, or optimal catch, of a fishery. Free-market forces almost always result in overfishing if a profitable fishery is left unregulated.

Overfishing is not just a theoretical problem. FAO has estimated that over 70% of all marine commercial fisheries are fully exploited or depleted. Good examples are the stocks of cod, herring, halibut, salmon, Alaskan king crab, and other species in the North Sea and the North Atlantic and North Pacific oceans. As with the great whales (see "Whaling," p. 194), fishing effort in these fisheries has long surpassed the optimal catch. Overfishing is by far the biggest threat for fish species listed as endangered or vulnerable to extinction. The traditional major fishing areas of the world are not the only ones becoming exhausted. Small-scale local fisheries in the tropics, where most people live and where food is needed the most, are being rapidly decimated.

Most of the world's fisheries are already fully exploited, and at least a quarter or more are overexploited or even exhausted.

The danger of overfishing can be particularly serious in herrings, anchovies, and other clupeoid fishes. These species often undergo dramatic population cycles and may therefore be especially vulnerable to fishing pressure. This is the situation in the Peruvian anchovy, or *anchoveta* (*Engraulis ringens;* see "Of Fish and Seabirds, Fishers and Chickens," p. 389).

Overfishing is threatening many other species, particularly large fishes such as tunas, swordfish, and sharks. Recent studies have shown that around 90% of the biggest fishes in the world oceans are already gone, taken by big commercial fishing fleets. Only around 10% of the original stocks remain. The fish that now remain are also smaller than before the intensive fishing started, an average of half the size 20 years ago in the case of tunas. Small females produce less eggs than large females, and, at least in some species, larvae from small females are smaller and grow slower than larvae from larger females.

The disappearance of the most valuable fishes, which happen to be higher in the trophic pyramid, has forced fishing lower on the pyramid. Such a shift may cause unknown changes in the whole ecosystem, such as an increase in the number of non-utilized plankton or in undesirable predators like jellyfishes and comb jellies.

Bigeye tuna (*Thunnus obesus*) were about two times as heavy and eight times more abundant in the 1950s than at present. The northern bluefin tuna (*Thunnus thynnus;* see Fig. 1.18), among the largest of bony fishes and the most valuable (*sashimi* and *sushi* lovers have been known to pay as much as $770 per kilogram, $350 per pound, in Tokyo) has fallen by 90% since 1970 in the western Atlantic. It was not until 1995 that nations agreed to cut their catches in half, which many fisheries scientists regard as too little, too late.

Sharks, slow to grow and reproduce, have critically declined in many parts of the world. A 2002 study showed that populations of most species of sharks along the eastern coast of the United States had declined by at least 50% from the previous 15 years.

Another prized food fish, the swordfish (*Xiphias*), has also been victim of overfishing. North Pacific populations fell approximately 70% between 1960 and the late 1990s, and most of the fish caught by U.S. fishing boats were caught before they were old enough to reproduce. Fisheries that targeted swordfish closed in large areas of U.S. waters in the Atlantic and Gulf of Mexico. Longline fishing for tuna was closed in some areas because many swordfish are caught and killed on longlines. There is evidence that these measures have worked, and the number of swordfish in the North Atlantic is on the increase and perhaps on a road to recovery.

Damage to habitats is another threat to fishery resources. Estuaries, mangrove forests, seagrass beds, and other threatened environments are critical breeding grounds and nurseries for fishes, lobsters, shrimps, scallops, and other valuable species. Three-quarters of the commercial catch of the United States consists of species that inhabit estuaries during part of their life. Bottom trawls disrupt the sea floor, another form of habitat damage. Seamounts, inhabited by many unique species, are particularly vulnerable (see "Biodiversity in the Deep Sea," p. 375).

By-catch, organisms that are caught unintentionally while fishing for other species, is another problem. It is estimated that around 25% of the worldwide catch, roughly 25 million tons, is by-catch. A good portion of the by-catch, however, goes unreported. The swordfish caught and killed on longlines set for tuna are one example of by-catch; longlines also catch turtles, seabirds, dolphins, and other marine life. Trawling also produces a lot of by-catch. This is particularly true of shrimp fisheries, where as much as 95% of the total catch is by-catch because of the small size of the net's mesh. Some of the by-catch is kept but much of it is discarded. Even if it is released alive, most of the discarded by-catch dies. A large part of the by-catch in trawl fisheries is juveniles of valuable species sought in other fisheries, or worse, of protected species like cod in the Grand Banks. Yet another threat to fisheries is pollution from oil spills, sewage, and toxic chemicals. The effects of habitat destruction and pollution are examined further in Chapter 18.

The potential effects of overfishing on whales, seals, and other marine mammals that feed on fish are the subject of much debate and controversy. Conservationists see overfishing as a threat to the already endangered marine mammals, while fishers see protected marine mammals as a threat to their diminishing stocks. A 2004 study suggested that on a global scale marine mammals and fishers rarely prey on the same stocks. Significant overlaps between feeding by marine mammals and fishing, however, do exist in some regions.

Overfishing may be responsible for the destruction of kelp forests by sea urchins in the Aleutian Islands in Alaska. Because fish-eating seals and sea lions have become less common, killer whales that normally hunt them have turned instead to sea otters, which keep sea urchins under control (see "Kelp Communities," p. 296).

Of Fish and Seabirds, Fishers and Chickens

The ocean has been good to Perú. As the cold Perú Current flows northward, coastal upwelling (see Fig. 15.30) pumps nutrients from the depths in huge amounts. The resulting increase in primary production supports a rich harvest of plankton that in turn feeds immense schools of the Peruvian anchovy, or *anchoveta* (*Engraulis ringens*). This high productivity is a critical part of a complex cycle that has had tremendous consequences for the economy of Perú.

From time immemorial, clouds of cormorants, boobies, and other seabirds have gorged themselves on the anchovy schools. The birds roost and nest on small islands along the coast. With hardly any rain to wash them away, the birds' droppings slowly build up in the dry climate. Over thousands of years the droppings have accumulated into layers as thick as 45 m (150 ft). This thick crust, called **guano,** is rich in nitrogen and phosphorus and is an excellent fertilizer.

The fertilizer starts out thousands of miles away, when organic matter sinks from the surface to the depths of the Pacific. When the organic material decomposes, nitrate and phosphate, the main nutrients for phytoplankton, are released into the water. The nutrients remain in the dark depths, unavailable to phytoplankton, until upwelling eventually brings them into shallow water along Perú's coast. Here they are taken up by diatoms and other phytoplankton, which form the base of the food web. The plankton are eaten by the anchovies that feed the guano birds. Nutrients thus travel from the depths of the Pacific to the coastal islands of Perú with the help of upwelling, plankton, anchovies, and seabird droppings!

And then people came along. Guano, a valuable agricultural fertilizer, was mined and exported. The guano industry brought considerable wealth to Perú, and by the end of the nineteenth century millions of tons had been mined. What took thousands of years to deposit was used up in a matter of decades.

The anchovies were next. A commercial anchovy fishery was established in the early 1950s and grew to unprecedented dimensions. It became the world's largest single fishery and

Immature boobies (*Sula*) on a Peruvian guano island.

Islas Ballestas, guano islands off Pisco, Perú.

made Perú the largest fishing nation (Fig. 17.3). Catches continued to increase, except in years when El Niño, the warm currents that occasionally arrive at Christmastime, interfered with upwelling (see "The El Niño–Southern Oscillation Phenomenon," p. 353).

Ironically, anchovies are so small that they are not often used for human consumption. Most of the catch was exported as fish meal for chicken feed. Fish meal from Perú became the world's single largest source of protein meal. Most of this protein was consumed by farm animals in other parts of the world, while many Peruvians continued to have protein-deficient diets.

By the late 1960s, the annual catch surpassed the estimated optimal, or maximum sustainable, yield of around 10 million tons a year. After the 12.3-million-ton catch of 1970, the fishery collapsed. The guano birds also suffered a dramatic decline. The El Niño of 1972 added to these woes.

The collapse had widespread effects. The price of other protein meals, particularly soybean meal, increased. In Brazil alone, several million acres of tropical rain forest were cleared to grow soybeans.

Another dramatic collapse of a fishery is that of the Pacific sardine (*Sardinops caerulea*), which supported a booming fishery in California until it crashed in the 1940s. The reasons for its collapse and that of the Peruvian anchovy are not entirely clear. Overfishing was not the only cause. Clupeoid fishes like anchovies and sardines naturally undergo population cycles. It may well have been that the combination of heavy fishing pressure and a dip in the natural cycle pushed these fishes over the brink. El Niño also enters into the picture. Harvest records since the beginning of the twentieth century show that, when the Peruvian anchovy was thriving, the Pacific sardine occurred in low numbers, and vice versa. Populations of these two Eastern Pacific species thus appear to have cycles that are opposite to each other for reasons that are not very clear. It has been speculated that warm water in the Pacific due to a strong El Niño translates into high sardine and poor anchovy harvests; cool water and a weak or absent El Niño bring high anchovy, poor sardine harvests. It is obvious that management of fisheries for species like the Peruvian anchovy needs to be tuned to the fishes' biology, with heavy fishing in some years and sharply curtailed harvests in others.

Since its collapse, annual catches of the Peruvian anchovy have varied from a low of 93,654 tons in 1983 to 9.8 million tons in 1994 (Fig. 17.3), becoming again the world's largest marine fish catch and making Perú the second-largest fishing nation. The 1997–1998 El Niño caused a 78% drop in the catch, to 1.7 million tons in 1998. It soon recovered, however, and by 2000 the catch was 11.3 million tons. It decreased to 6.2 million tons in 2003 but nearly doubled to 10.7 in 2004, the largest fishery in the world. Will the number of anchovy, and guano birds, eventually return to their former levels? Perhaps more important is whether any lessons have been learned. Will the same mistakes be repeated elsewhere?

A fishery is regarded as collapsed if catches fall below 10% of historic highs. Nearly one-third of all the species that are fished have already collapsed, and around 60% are predicted to collapse by 2025. A 2006 worldwide study by 14 marine scientists concluded that *all* of the world's fishing stocks will collapse by mid-century if no drastic measures are taken to curb overfishing, by-catch, destruction of habitats, and pollution.

Managing the Resources Given the danger of overfishing, most people agree that fisheries resources should be harvested in a way that does not deplete them beyond recovery. In other words, fisheries must be managed to ensure their long-term value. The wise management of fisheries stocks is much harder than it sounds. For one thing, the maximum sustainable yield can be very difficult to estimate. To do so, fisheries biologists need

detailed information about the size of fisheries stocks, how fast the organisms grow and reproduce, how long they live, and what they eat (which often changes at different stages of the life cycle; see Fig. 15.24). Such information is rarely easy to obtain and often unavailable. Biologists may have to rely on rough "guesstimates" or questionable assumptions, making their estimates of the optimal catch less reliable.

Furthermore, real fisheries are much more complex than we have indicated. The smooth catch-effort curve shown in Figure 17.10 represents a greatly simplified model and does not take many natural features into account. For example, the harvested species may be **competing** with other species, and fishing pressure might alter the competitive balance. Schools may get smaller as a result of fishing. This might not only make the fish harder to catch but also adversely affect their behavior and reproduction. Simple models do not consider the size of the fish caught, but it makes a difference whether large, older individuals or small, younger ones are caught, for example, because large individuals typically produce many more eggs than small ones. Similarly, the time of year when fishing is done may be important, such as whether the catch is taken before or after the breeding season. These natural complexities can have dramatic consequences and could cause a fishery to fail unexpectedly if not taken into account.

Given the uncertainties of determining optimal catches and the disastrous effects of overfishing, it can be argued that the catch should be set somewhat lower than the estimated optimum just to be on the safe side. A fisher, however, with a family to feed and boat payments to make, might have different ideas. The same can be said of cannery and dockyard workers, gear merchants, bankers, and all the other people who depend directly or indirectly on the fishery. Thus, fisheries management is a complex, often controversial, matter that is affected by economic and political factors as well as biological ones. If the catch is harvested by more than one nation, international relations also come into play.

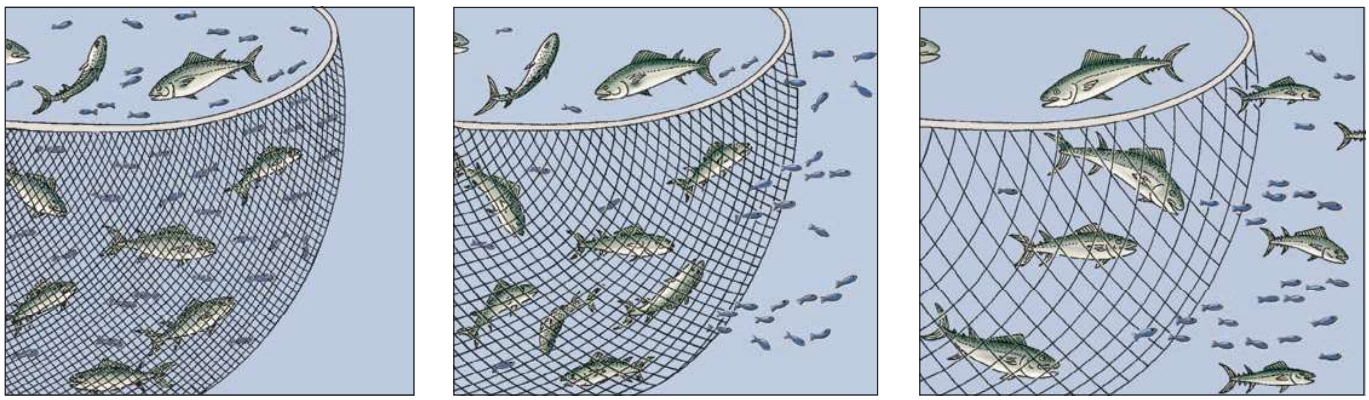
Once a desired catch level is agreed on, there are a number of ways to manage the fishery. The total catch may be limited by closing the season as soon as the target catch is reached or by restricting the length of the season, the number of boats or fishers, or the areas open to fishing. The size and power of boats can be limited or certain methods of fishing can be banned altogether. Limits can be placed on the catch of each boat or, if an international fishery, each nation. By regulating the mesh size of nets, fishers may be prohibited from taking individuals of certain sizes (Fig. 17.11). Leaving the largest individuals to reproduce can help in the recovery of overfished stocks. If sexes can be told apart, fishers may be prohibited from taking females.

The total collapse of once thriving fisheries has sometimes forced the use of drastic measures. Governments may reduce their fishing subsidies, they may pay fishers to give up fishing, or a fishery may be closed altogether. Complete closures, however, are in effect in less than 1% of the world's fishing grounds. The establishment of reserves or sanctuaries to preserve important habitats is another possible way to safeguard the survival of important species, perhaps allowing the species to repopulate outside areas that are open to fishing.

Besides preventing overfishing, management measures may be undertaken to help restore stocks that have become depleted. These measures may involve the improvement and protection of essential habitats or the transplantation of artificially raised young.

The management of fisheries to prevent overfishing includes the establishment of quotas, restrictions on the type of fishing gear, and other measures.

Fishing rights over a nation's territorial waters are a complicating factor in the management of resources. Traditionally, a country's territorial waters extended 3 nautical miles (5.5 km) offshore. Some nations, however, began to exclude fishing fleets from other nations by extending their territorial waters. Fishing disputes even led to wars. A general compromise was finally reached in 1982 with the **United Nations Convention on the Law of the Sea (UNCLOS;** see "Prospects for the Future," p. 427), which so far has been ratified by 149 nations. It allows nations to establish an **exclusive economic zone (EEZ)** 200 nautical miles (370 km) offshore. Within this zone, nations can completely control their fisheries, oil, and mineral resources. Nations are required to use their resources in a sustainable way. They can keep foreign



(a) (b) (c)

FIGURE 17.11 Both the size and species of fishes caught by nets can be controlled by the net's mesh size. (*a*) A fine net might catch both sardines and tuna. (*b*) With a larger mesh size the sardines escape and only tuna are caught. (*c*) With an even larger mesh size only large tuna are taken.

fishers out if they wish or sell fishing licenses to foreign fleets. EEZs cannot always be policed, of course, and foreign fishers may sneak in and fish without permission or with illegal gear. When caught, these pirate vessels are usually impounded.

The establishment of an exclusive economic zone (EEZ) allows nations to protect fishing and other resources 200 nautical miles around their shores.

In the United States, which has not yet signed UNCLOS, the Magnuson-Stevens **Sustainable Fisheries Act** of 1996 required federal fisheries managers to develop management plans to prevent overfishing, restore depleted stocks, and reduce by-catch, the first time protection has been extended to non-commercial species. Vessels of foreign nations that have signed fishing agreements with the United States are allowed to fish in U.S. waters only after receiving a fishing permit. The 2003 **Pew Oceans Commission** went further than the Sustainable Fisheries Act by calling for a reform of the nation's ocean laws and policies to protect marine ecosystems. This independent commission recommended a unified policy to restructure fishery management to ensure not only sustainable exploitation but also the protection of whole ecosystems. It stressed the need to regulate fishing gear that harms the marine environment, the monitoring of by-catch, and the control of pollution caused by mariculture.

More than 90% of the ocean's present fisheries, however, lie within the EEZ of one nation or another, but the high seas are still considered common property. A number of potential new fisheries lie outside territorial boundaries and thus are open to all nations.

Efforts toward the better management of resources have already brought about some positive results. A limited number of fisheries in a few countries are now being successfully managed. Fish from these sustainable fisheries are "eco-labeled," so that consumers can select it over fish from overexploited catches. It is hoped that this marketing strategy will also encourage calls for better fisheries management of overfished stocks.

New Fisheries Fisheries scientists have for decades been absorbed with the possibility of tapping new or underexploited fisheries. One possibility is to increase the use of by-catch. The main problem with much of the by-catch is not so much that there is anything wrong with it but that people simply will not buy it. Consumer tastes are fickle and vary from place to place. What is considered a delicacy in one place is junk in another. Hake (Table 17.2), for instance, is prized in Europe but not in the United States. Croakers and sea robins are common throwaway fishes in the United States that are eaten elsewhere. Squids are caught in large numbers in California, but most of the catch is exported, primarily to Japan. Squids are a delicious source of lean protein, but American consumers were suspicious of the sucker-armed molluscs, though marketing squid by its Italian name of *calamari* has increased its appeal. A name change also helped overcome consumer resistance to eating dolphinfish (*Coryphaena hippurus*), certainly a fish and not a dolphin. The more seductive Hawaiian name of *mahimahi* helped enhance its marketability.

A potential use of the by-catch is to process it into products that have more market appeal. In the *surimi* process, for example, low-value fish is washed to remove fat, minced, and mixed with flavorings and preservatives. Appropriately shaped, it is sold as imitation crab, lobster, shrimp, or scallop. Alaskan pollock is now the main component, but less desirable fish species could also be used. Processed fish products such as fish sticks could also open the market to less popular catches. Unwanted catches could also be converted into fish flour and used to protein-enrich all sorts of processed foods.

The highly productive waters around Antarctica are often mentioned as potential sources of increased commercial catches. Antarctic catches include various fishes, squids, the southern king crab, and krill (Fig. 17.12). Even in the harsh conditions of Antarctic waters, however, overfishing is taking its toll. The waters around South Georgia Island, for instance, are already overfished. The Patagonian toothfish (*Dissostichus eleginoides*), marketed as "Chilean sea bass" in the United States, has been seriously depleted,

Competition When one organism uses a scarce resource at the expense of another.

• Chapter 10, p. 213

FIGURE 17.12 Krill (*Euphausia superba*) form dense schools in Antarctic waters and were thought to be potential human food. Predictions of annual catches in the millions of tons, however, have not yet materialized.

FIGURE 17.13 *Pleuroncodes planipes,* also called the lobster krill or tuna crab, is a pelagic crab that has been suggested as a potential source of human food. Large swarms of the crab, each having a maximum length of 13 cm (5 in), are often washed ashore on the Pacific coast of California and Mexico, turning beaches bright red. A possible problem with this plan is that *Pleuroncodes* is an important food for tunas.

mostly by illegal fishing. Many illegal fishing vessels operate under flag-of-convenience countries that may not enforce international maritime law. Illegal longline fishing has also affected populations of seabirds, especially albatrosses (see "Threatened and Endangered Species," p. 413).

There are other potential sources of food from the sea. Some of these are underutilized. Others are unconventional species like squid and other cephalopods, flying fishes, and pelagic crabs (*Pleuroncodes;* Fig. 17.13). Lanternfishes (*Myctophum;* see Fig. 16.6) represent another potential fishery. They are found in deep water but migrate to the surface at night in the **deep scattering layer.** They form dense schools in most oceans. These and other species remain underexploited or completely unexploited mainly because of lack of consumer acceptance or the absence of efficient fishing methods. Some may eventually support successful fisheries, though probably for fish meal rather than for human consumption.

Measures to increase the supply of food from the sea include an increase in the exploitation of underutilized species and the development of new fisheries.

Mariculture Instead of overfishing the dwindling natural food resources of the oceans, why not raise marine organisms as we do farm animals? This is not a new idea. The Chinese have been doing it with freshwater fishes for thousands of years, the Romans farmed oysters, and the early Hawaiians built walled fish ponds along the coast to raise mullet (*Mugil*) and milkfish (*Chanos chanos*). The application of farming techniques to the growth and harvesting of marine organisms is known as **mariculture,** the agriculture of the sea. A more general term is **aquaculture,** which is applied to the farming of both freshwater and marine organisms. The worldwide culture of marine fish and shellfish alone reached 18.3 million metric tons in 2004, with an estimated value of $28.9 million. These figures, more than three times the volume and more than twice the value of those in 1990, show the rapid growth of mariculture (see Fig. 17.3). The 2004 figures are higher if the culture of seaweeds (13.9 million metric tons with a value of $6.8 million) are included. The culture of freshwater animals in 2004 was 27.2 million tons, with a value of $34.5 million. Aquaculture has also grown more than three times faster than livestock production on land, and according to FAO aquaculture is the world's fastest-growing food-production sector. Approximately 34% of all the fish consumed around the world is farmed, although this is mostly freshwater fish. The growth of fish farming averaged 11% a year during the 1990s, and the output for 2010 is predicted to be higher than cattle ranching around the world. Shrimp mariculture showed tremendous growth, with an increase in volume of more than 300% from the mid–1980s to the early 2000s. Farmed shrimp now account for around 25% of the estimated 3 million tons of shrimp consumed every year around the world. Though mariculture is used primarily to grow food species, it is also used to grow commodities such as cultured pearls (see "Bivalves," p. 130) and fishes for the aquarium trade.

Mariculture is the farming of the sea for food and other resources. The term "aquaculture" includes the culture of freshwater species as well.

Traditional mariculture is still practiced in several parts of the world, particularly in Asia. Milkfish is farmed in ponds filled with brackish water, that is, partially diluted seawater (Fig. 17.14). The immature fish, or fry, are captured from the wild, transferred to the ponds, and fed with agricultural by-products. In this way, wastes are converted to fish flesh that is cheaper to produce than pork or beef. These fish farms provide not only high-protein food but jobs as well.

With various modifications, similar operations are used to farm other fishes, molluscs, shrimps, and seaweeds in many parts of the world. The fry or spat (immature bivalve molluscs) are transplanted to favorable sites in coves (Fig. 17.15), natural ponds, estuaries (including fjords), and mangrove forests. Already, shrimp mariculture is a significant source of foreign exchange earnings for several developing countries. Salmon and other fishes are raised in large floating pens or cages. Pacific threadfin, or *moi* (*Polydactylus sexfilis*), and others are raised in giant cages submerged off Hawai'i. Oysters, mussels, and other

FIGURE 17.14 Milkfish (*Chanos chanos*) is harvested from floating cages and brackish-water ponds in the Philippines. Some will be eaten, others allowed to mature and spawn to replenish the cages and ponds.

molluscs are grown on racks, in baskets, hanging from rafts, and in other ingenious ways. This type of mariculture, in which farming takes place under more or less natural conditions with relatively little manipulation by humans, is known as **open mariculture,** or **semi-culture.**

Sometimes, however, the farming of high-value food species is a different story. In what can best be described as the domestication of marine organisms, growth is maximized by almost totally controlling the organisms and their environment. This type of mariculture is called **closed,** or **intensive, mariculture.**

FIGURE 17.15 The farming of oysters (*Crassostrea glomerata*) in Whangaroa, New Zealand.

Intensive mariculture poses many problems, and only a small percentage of marine food species can be farmed (Table 17.3). Species like clupeoid fishes and tunas that require large, open spaces are not good candidates for intensive mariculture. To be farmed successfully, most species need specialized sites and equipment. Water pumped into tanks, pools, or other holding facilities must be free of pollutants and carefully checked for temperature, salinity, and other chemical factors. Toxic wastes from the organisms themselves must also be removed. Food can be a problem because the various stages of a species usually have different food requirements. This is a particular problem when trying to culture planktonic larval stages because they require specially cultured food. Predators and disease-causing organisms must be periodically removed or killed. Parasites and disease can be devastating under the crowded conditions typical of culture operations (see "Effects of Farmed Salmon on Wild Salmon Populations," p. 396). Viral infections are a serious problem in shrimp farming. Even sneaky seabirds and sea lions have learned to help themselves to the precious fish that are raised so painstakingly. Crowded conditions tend to cause cannibalism among fishes and crustaceans. Juvenile American lobsters, for instance, must be kept apart or they eat each other. Commercial mariculture, however, is a challenge that many enterprising, business-oriented fisheries scientists are willing to accept. It is now possible, for example, to freeze shrimp sperm, ensuring year-round reproduction. We have learned to induce the settlement of the planktonic larvae of abalone, a valuable mollusc. Scientists can even create oysters with three sets of chromosomes, instead of the normal two. This makes them sterile. Normal oysters develop a strong taste when their eggs mature, but sterile ones, which do not produce eggs, are always tasty.

Rather than raising them all the way to harvest, some species are grown for only a short time, then released as fry or juveniles to enrich natural populations in a process known as **seeding.** Salmon are an interesting example of seeding. In some places, especially Europe, salmon are held in captivity their entire lives, from hatching to harvest. In other places the salmon are released as juveniles to feed and grow at sea. Several years later they return as full-grown adults to the stream where they were released. Not only can they be caught by commercial and sport fishers in the usual way, but they swim right back to the hatchery,

Deep Scattering Layer Animals, mostly fishes and shrimps, that migrate vertically between the mesopelagic and epipelagic zones.

• Chapter 16, p. 364

Table 17.3 Examples of Marine and Brackish-Water Species Used in Commercial Mariculture

Species Cultured	Major Areas Where Cultured
FISHES	
Atlantic salmon (*Salmo salar*)	U.S., Canada, Chile, Europe
Bluefin tuna (*Thunnus thynnus*)	Japan
Cod (*Gadus*)	Europe
Flatfishes (*Solea* and others)	U.S., Europe
Horse mackerel (*Trachurus*)	Japan
Milkfish (*Chanos chanos*)	Southeast Asia
Mullets (*Mugil*)	Southeast Asia, Mediterranean
Pacific salmon (*Oncorhynchus*)	U.S., Canada, Chile, Japan
Puffer (*Fugu*)	Japan
Red seabream (*Pagrus major*)	Japan
Yellowtail (*Seriola*)	Japan
MOLLUSCS	
Abalone (*Haliotis*)	U.S., Japan
Clams, cockles (*Anadara* and others)	Southeast Asia
Mussels (*Mytilus, Perna*)	U.S., Europe, New Zealand
Oysters (*Crassostrea, Ostrea*)	U.S., Europe, Japan, Taiwan, Australia, New Zealand
Scallops (*Pecten, Patinopecten*)	Europe, Japan
CRUSTACEANS	
Shrimps (*Penaeus* and others)	U.S., Ecuador, Mexico, Japan, China, Southeast Asia, India, Bangladesh
SEAWEEDS	
Red (*Porphyra, Eucheuma*) and brown (*Laminaria*) algae	Japan, China, Southeast Asia, South Pacific

where the ones not used for breeding can be caught and harvested. This practice, known as **salmon ranching,** originated in the Pacific Northwest of North America but has been transplanted to locations as far away as Chile and New Zealand.

Most mariculture operations require expensive equipment and specialized personnel. These demands further restrict the number of species that are cultured: Some species that could be farmed are not because it is not profitable. Species that are cultured are usually those that command high prices. Thus, instead of mass-producing cheap protein for a hungry world, mariculture tends to provide variety in the diet of the affluent.

Another drawback of mariculture is pollution. Fish farming in which thousands of fish are concentrated in ponds along the coast or in extensive floating pens releases huge amounts of feces, urine, and uneaten food that ultimately degrade water quality. The decomposition of these wastes depletes oxygen in the water and releases nutrients that can trigger harmful algal blooms. Farmed fishes also concentrate toxic chemicals.

Some fish farms also use chemicals like antibiotics, pesticides, and synthetic pigments, which may be harmful to surrounding marine life. Another risk is the introduction of parasites and diseases to local marine species in the wild. Even more devastating can be the destruction of the natural environment. Clearing for shrimp farms, for example, has caused the destruction of mangrove forests, salt marshes, and other coastal communities in the tropics and subtropics (see "Human Impact on Estuarine Communities," p. 281). This destruction has reduced the stocks of local species that use mangrove forests and salt marshes as nurseries. Though shrimp is a more profitable product, less food is actually produced than in the destroyed environments. Introduced farmed species that escape are potentially harmful to native species and the communities they live in, and catching fish from the wild to feed farmed fish, a common practice, may also deplete wild fisheries. Escaped Atlantic salmon breed with wild populations and dilute the **genome** of the wild populations, perhaps making the offspring more vulnerable to diseases and other natural stresses.

Still, some fisheries scientists and economists are optimistic. They predict that someday intensive mariculture will provide a significant amount of relatively cheap food. They pin these hopes on the development of technological improvements and fast-growing varieties of food species, and even turning carnivorous fishes into vegetarians that are much cheaper to raise. Other options are pumping nutrient-rich water from the deep sea to provide better culture conditions (Fig. 17.16), or from sewage discharges and use it to grow the planktonic algae that are fed to the larvae of fish and other species. The application of **genetic engineering** and other forms of **biotechnology** to mariculture is another possibility. Genetic engineering may soon allow scientists to alter the genetic information contained in a species' **DNA** to produce faster-growing, more disease-resistant, or better-tasting strains. There is great concern, however, about the effects of escaped organisms that breed with wild populations.

Marine Life as Items of Commerce and Recreation

The living resources of the sea are used in many ways other than food. Timber and charcoal are obtained from mangroves. Jewelry is made from pearls, shells, and black and precious corals and leather from the saltwater crocodile (Fig. 17.17), sea snakes, sharks, and other fishes. Many of these resources, however, are being overexploited. Rich mangrove forests are being rapidly cleared, and black and precious coral have disappeared in many areas. Many endangered species are taken. Fur seals, for example, are killed for their pelts, and hawksbill turtles are taken for tortoiseshell.

FIGURE 17.16 A Japanese flounder, or bastard halibut (*Paralichthys olivaceus*), grown at a mariculture facility in Hawai'i. This operation uses cold, nutrient-rich water that is pumped from a depth of 600 m (2,000 ft) not just to raise fish but mainly to generate power. The flounder, or *hirame,* commands high prices because it is highly sought for raw fish dishes such as *sashimi.*

Chemical compounds that are obtained from marine organisms, or **marine natural products,** have potential for use in medicine. The medicinal use of marine natural products by the Chinese probably goes back a few thousand years, but such use in the West has been limited. Recent years, however, have seen an upsurge in the collection, analysis, and testing of new material. Seaweeds provide chemicals that are widely used in food processing, cosmetics, plastics, and other products (see "Economic Importance," p. 109). The search for drugs from the sea has become one of the most interesting branches of marine science, combining the fields of biology, chemistry, and pharmacology (see "Take Two Sponges and Call Me in the Morning," p. 397).

For millions, the living resources of the sea provide not a livelihood but relaxation, an ideal way to spend leisure time (see "Oceans and Recreation," p. 426). Recreational anglers catch everything from lobsters to big-game fishes. In the United States the marine recreational catch is estimated to be around 30% of the commercial catch of food fishes. Marine recreational fisheries are the basis of a multibillion-dollar business worldwide. Recreational fishers buy boating and fishing equipment and travel long distances to pursue their hobby, supporting the tourist trade. There is a growing conservation ethic among the recreational fishing community, which in many places is a powerful political voice for conservation. Still, recreational fisheries can exert tremendous pressure on fish stocks and therefore need to be carefully managed. They account for 23% of the catch of overexploited marine fish species in the United States, and for some species the recreational catch is larger than the commercial catch. Large predators, stocks of which are mostly depleted, are prime targets.

Business and fun are also combined in the thriving **aquarium trade.** Though the aquarium hobby is dominated by freshwater fishes, marine aquaria enjoy much popularity. The export of colorful marine tropical fishes such as lionfishes, butterflyfishes, and damselfishes is a significant component of trade in countries like the Philippines and Fiji. The aquarium trade has now extended to other tropical marine organisms: sea anemones, corals, sea urchins, and just about anything else that is colorful and might carry a price tag. Even "live rocks," rocks with their associated marine life, are sold.

The unrestricted and indiscriminate collection of marine life for the aquarium trade can be very destructive to the natural environment (see "Modification and Destruction of Habitats," p. 402). In the Philippines and other places aquarium fish are often collected by using poisons or explosives that kill hundreds or thousands

FIGURE 17.17 Saltwater crocodiles (*Crocodylus porosus*), here grown together with freshwater crocodiles (*C. novaeguineae*), are farmed in Papua New Guinea for their valuable skin. This farm was set up as a way to dispose of chicken offal from a chicken farm and earn some money in the process. Saltwater crocodiles are worth more than their freshwater cousins because they have smaller scales and therefore more of the skin can be used. They are harvested when they reach approximately 1 m (3 ft) in length.

Genome The complete genetic information of an organism.
DNA Nucleic acid that contains the cell's genetic information.
• Chapter 4, p. 65

EYE ON SCIENCE

Effects of Farmed Salmon on Wild Salmon Populations

Farmed salmon has become an important food item in developed countries, where it meets increased consumer demand for fish rich in protein and omega-3 fatty acids. Farmed salmon is cheaper than wild salmon and by now most salmon consumed, especially Atlantic salmon (*Salmo salar*), is farmed. The impact of salmon farming on the natural environment, however, has been the subject of much debate. Salmon farming releases pollutants and potentially harmful chemicals, farmed salmon has generally been found to contain higher amounts of PCBs and similar toxic chemicals than wild salmon, and the breeding of escaped salmon with wild populations may have risky long-term effects (see "Mariculture," p. 392).

Research undertaken in Europe and North America has revealed another type of potentially harmful effect. Results strongly suggest that populations of wild salmon and other fishes could be seriously affected by parasites that are common in farmed salmon. One particular culprit is sea lice (*Callous, Lepeophtheirus*), small copepods that as adults live on salmon and other fishes, where they feed on skin, mucus, and blood. Free-living larvae hatch from eggs that are carried by the parasitic females in two ribbon-shaped sacs. The larvae develop in the plankton and eventually molt into copepodite larvae (see Fig. 7.39) that are adapted to infest fishes. These small, immature stages feed on skin cells and may cause considerable damage to their fish hosts.

Sea lice are normally found on adult wild salmon, which lives at sea. When the fish returns to fresh water to spawn, however, the parasites drop off the fish because sea lice cannot tolerate fresh water. The small, immature salmon, which are born in rivers and migrate to sea (see "Migrations," p. 168), normally have relatively few lice, if any, since they rarely encounter adult salmon, which live far out at sea, during their migration. In contrast, sea lice have become a major pest of farmed salmon, which is raised through its complete life cycle in crowded floating pens along the coast. The parasite is responsible for millions of dollars a year in losses to fish farmers.

Research on the North Sea off Norway has shown that, in two fishes related to salmon, the sea trout (*Salmo trutta trutta*) and the Arctic char (*Salvelinus alpinus*), high lice infestation (over 100–200 lice larvae per fish) was present in populations close to coastal areas where there is extensive salmon farming, while populations in a region with little farming showed significantly lower infestation (few fish with more than 10 lice larvae), which appeared to be the normal infestation rate. Mortality was high in heavily infested fish.

More recent work in British Columbia on the Pacific coast of Canada by a team of scientists, including specialists in mathematical biology, showed similar results. The scientists tracked the migration of juvenile salmon past salmon farms to see where infections began and how they progressed. They then used mathematical models of parasite dispersal and fish migration to analyze the data and estimate the transmission of sea lice from farm to wild salmon and the subsequent decline in salmon survival.

Immature pink, or humpback, salmon (*Onchorynchus gorbuscha*) and chum, or dog, salmon (*O. keta*) were found to be rarely infected with sea lice before they passed a salmon ranch down two narrow corridors on their way to the open sea. Infestation was much higher in immature fish that had migrated past fish farms. Mortality was high, estimated high as 95% of the migrating fish, due to the fact that the small and fragile immature fish are easily harmed by a high load of lice.

The initial research raised many additional questions that lead to research in progress. Do other species of farmed fish have the same effect on wild populations, particularly those that migrate like salmon? Is the incidence of parasites other than sea lice also being increased by the effect of fish farming? Can a vaccine against sea lice infestation be developed and used to control the parasite among farmed fish? The wild stocks of other species of salmon and related fishes have shown alarming declines in recent years. How important is the effect of increased parasite infestation due to fish farming in relation to other potential factors unrelated to fish farming? What factors may be involved?

For more information, explore the links provided on the Marine Biology *Online Learning Center:*

of fish for every one that makes it to the neighborhood pet shop. The management of aquarium-species harvests, however, has helped reduce the impact of collecting in Australia and a few other places by harvesting reef fishes in a sustainable way.

The fisheries resources of the ocean are used for recreation by millions around the world.

NON-LIVING RESOURCES FROM THE SEA FLOOR

In addition to its living resources, the sea contains many non-renewable resources, resources that are not naturally replaced, such as oil, natural gas, and minerals. These resources are much harder and more expensive to locate and exploit under the sea than they are on land. Not surprisingly, the sea's non-renewable resources went largely unused while supplies on land were plentiful. More and more, however, land reserves are running out, and we are turning to the sea floor for new sources.

Oil and Gas

Oil and natural gas were among the first of the sea's non-renewable resources to be used commercially. In the late 1800s it was discovered that some California oil fields extended well offshore beneath the seabed. The oil was extracted using oil rigs mounted on wooden piers that extended out from shore.

The offshore oil industry underwent tremendous expansion during the 1970s, when the high price of oil and gas made offshore drilling immensely profitable. Oil and gas production on the continental shelf now occurs in the Persian Gulf, the Gulf of Mexico, the North Sea, and in other areas on all continents

Take Two Sponges and Call Me in the Morning

Obtaining drugs from the sea is not an easy task. It involves a sharp eye, intuition, good luck, and lots of frustration. It means diving in awesome coral reefs as well as working countless hours in the chemistry lab.

Colorful attached invertebrates that live in coral reefs—sponges, soft corals, sea squirts—are good candidates for biomedical research. Though seemingly defenseless, these very visible, soft, attached animals are rarely eaten by hungry fishes or crabs. This fact suggests that they have some type of defensive mechanism. Many of these colorful invertebrates are known to produce unique chemical substances that make them taste bad or allow them to get rid of hostile neighbors, and these chemical substances may have properties that can be beneficial to humans as well.

Marine organisms of potential value as drugs are collected, frozen, and sent to the lab for analysis. Crude extracts using alcohol and other solvents undergo trials to test their ability to kill or inhibit the growth of bacteria (that is, to act as antibiotics), fungi, and viruses. Extracts are also tested for their effect on cancer cells and for their potential use as anti-inflammatory agents. Laboratory animals and cultures of cells or tissues are used in these trials. Any promising extracts are further separated and chemically identified. Chemicals with particularly promising properties are then used by pharmaceutical companies to develop new drugs. This process entails another long series of tests that ultimately includes rigorous clinical testing on humans.

Many biomedical products have already been obtained from marine organisms. Some

This sponge from coral reefs in Fiji (*Acanthella cavernosa*) contains a potent chemical that kills worms, including some human parasites. The chemical is being tested for its potential use as a drug. The sponges are cultured on ceramic plates tied to plastic netting.

red seaweeds provide laxatives or chemicals that kill viruses. Sponges and gorgonians are a rich source of natural products; some act as antibiotics, whereas others have anti-inflammatory or painkilling properties. A bryozoan (*Bugula neritina*) is the source of bryostatin, a promising drug in the fight against cancer. So is didemnin B from a Caribbean sea squirt (*Tridemnum*). Squalamine, which circulates in the blood of sharks, has antibiotic and antifungal properties. It is being tested for its ability to starve tumors by cutting off blood supply. Shark cartilage, however, has shown not to be effective against cancer, as some had claimed. A glue that is naturally produced by bacteria that live on rocks may be used in the future to seal wounds in the skin and delicate tissues of humans. Horseshoe crab blood is used to test for contaminant bacteria in vaccines, injections, and space probes. Sunscreens have been obtained from corals and an alga. The toxins, or poisonous substances, found in many marine organisms are also of potential value in medicine. Tetrodotoxin, the powerful toxin from certain pufferfishes and porcupine fishes (see "Symbiotic Bacteria—the Essential Guests," p. 90), for example, is used in Japan as a local anesthetic and as a painkiller in terminal cancer patients.

Marine organisms are also used as remedies in Eastern medicine. Chinese traditional medicine, for instance, recommends red seaweeds for weight loss and for lowering cholesterol. Seahorse extracts are believed to strengthen the kidneys and the circulatory system, but as a result seahorses are rapidly becoming rare worldwide.

Many other marine organisms are being investigated as potential sources of drugs. Deep-sea bacteria and archaea, dinoflagellates, and seaweeds are cultured to study their antitumor capabilities. Compounds from sediment bacteria might be used to combat antibiotic resistance in bacteria that cause infections. Even bacteria that are normally found on the eggs of shrimps and other crustaceans are being targeted as sources of antibiotics and antifungal drugs. A gel from seaweeds is being investigated to prevent HIV infection. A toxin from cone shells, one of several known conotoxins, was recently approved in the United States for the treatment of chronic pain. Other conotoxins are undergoing clinical tests as painkillers and in the treatment of epilepsy and depression.

Marine natural products may eventually provide us with the long-awaited miracle drugs that will conquer cancer or AIDS. They are probably waiting to be discovered in the tissues of a sponge, sea cucumber, or sea anemone on a distant coral reef.

except Antarctica. A large percentage of the continental shelves around the world is considered a potential source of oil and gas. Drilling is now extending into deeper water beyond the shelf. The enormous economic potential of these reserves was one of the factors that prompted the establishment of EEZs to protect national interests.

The continental shelves are a major source of oil and natural gas.

Exploiting offshore oil and gas can be a difficult and costly operation, especially when the deposits lie many miles offshore as they do in the North Sea. Powerful currents, huge waves, and miserable weather compound the problems.

Overcoming these difficulties has been a major accomplishment of ocean engineering. Exploratory drilling is done from drill ships or partly submerged or elevated platforms that can be towed from place to place and anchored in position on the sea floor. Once oil or gas is found, huge steel or concrete platforms are erected and secured to the bottom to extract it (Fig. 17.18). Remotely controlled submarines are being used to build facilities on the bottom, which include pipelines to transport the oil or gas to terminals on land. Floating platforms now allow oil and natural gas to be extracted as deep as 3,000 m (10,000 ft).

Another potential source of energy from the sea floor is **methane.** Vast stores of methane, both as bubbles and in the form of frozen compounds, **methane hydrate** (or **clathrates**), have been found in deep water worldwide. It will be some time,

FIGURE 17.18
Oil-drilling rigs, like this one in the Gulf of Mexico off the Louisiana coast, are artificial islands built to cope with inhospitable conditions. They are serviced from land and incorporate the latest developments in undersea technology.

however, before the technology needed to exploit this resource is developed.

The potential threat of oil pollution, however, is a factor of great concern (see "Effects of Oil on Marine Life," p. 408). Pollution from drilling operations can affect coastal fisheries, tourism, and recreation. As a consequence, oil and gas drilling have been banned or strictly regulated in some coastal regions such as California.

Ocean Mining

The seabed is a potential source of many types of minerals; in fact, some people believe the bottom of the sea to be the planet's richest source. Though most marine deposits are not presently exploited, ocean mining will become more viable as we develop new technologies and as high-grade ores on land become exhausted.

Sand and gravel for the construction industry are mined along beaches and offshore in many parts of the world, exceeding quantities extracted on land. Sand is also extracted for its use in the glass industry. The galleries of some coal mines on land extend offshore underground. Some tin and even diamonds and gold are mined from offshore deposits brought to the seabed by rivers.

Among the most promising sources of minerals from the sea are offshore deposits of phosphates, which are widely used as fertilizers. Another potential source of minerals are **polymetallic nodules,** lumps of minerals that are scattered on the deep-ocean basins beyond the shelf. Polymetallic nodules contain manganese, nickel, copper, and cobalt, all of which are important to industry. Only a few areas have nodules with a mineral content high enough to make deep-sea mining economically feasible. Some of the richest deposits are found about 5,000 m (16,000 ft) deep in the equatorial Pacific south of the Hawaiian Islands.

Other mineral-rich sediments are found along the mid-ocean ridges and **hydrothermal vents.** The minerals are extracted from deep in the earth's crust as hot water percolates through volcanic fissures and vents. They are deposited when the hot water emerges and hits the cold ocean water. These deposits are rich in iron, copper, and zinc.

Polymetallic nodules and other mineral-rich deep-sea deposits are potential sources of valuable minerals.

There are many technical problems associated with mining the deep-sea floor. It is expensive, mainly because of the tremendous depths. The possible detrimental effects of mining on the surrounding marine environment have also been raised. The ownership of mineral resources that lie outside the EEZ is another unresolved issue. As metal prices rise, however, deep-sea mining may become more attractive. Several agencies and private companies continue to investigate the prospects of deep-water mining (Fig. 17.19). Future prospects include the use of specially designed dredges or suction pipes suspended from ships.

NON-LIVING RESOURCES FROM SEAWATER

Ordinary seawater, which contains a combination of many different **ions,** is a potential source of resources. It is certainly plentiful and easily accessible to coastal nations.

Fresh Water

Desalination plants that convert seawater into fresh water have been built in coastal regions that lack a sufficient supply of fresh water, mainly in desert and semidesert regions such as the Arabian Peninsula, Israel, and North Africa. Desalination is also used to supplement the water supply in densely populated areas like Hong Kong and Singapore, but it is extending around the world.

A few desalination systems are currently employed. The process of reverse osmosis, for example, uses a membrane that allows water to pass through but blocks the passage of ions, thus desalinating the water. Reverse osmosis plants are becoming very common in small-scale projects like resorts as well as in large desalination plants. Desalination, however, requires a great deal of energy and is therefore expensive. It also produces a highly saline residue that can cause environmental problems (see "Thermal Pollution," p. 413). New methods, perhaps using a renewable energy source like wind or wave power, may one day make desalination more practical and economical.

Minerals

Every element on earth is present in seawater, but mostly in extremely small quantities. The chief product presently obtained from seawater is **table salt,** or sodium chloride (NaCl), which is composed of the two most abundant ions in seawater, sodium and chloride. Salt, a precious commodity to ancient civilizations,

FIGURE 17.19 ROVs (remotely operated vehicles) are being used to commercially explore and sample the ocean floor off Papua New Guinea for minerals containing gold, silver, zinc, and, shown below in an underwater view, copper.

has been produced for centuries by evaporating seawater (Fig. 17.20). Most of the other constituents of seawater are difficult to extract because they are present in such small amounts (see Table 3.1, p. 44). Magnesium and bromine are also obtained from seawater in significant amounts, but valuable trace metals like uranium may one day be commercially extracted.

Seawater is a potentially rich but currently limited source of fresh water and minerals.

Energy

Most people don't realize that the ocean is a vast reservoir of energy that might be put to human use. Harnessing the sea's energy is the objective of several concepts that may help ease our dependency on fossil fuels and reduce CO_2 emissions.

Mill wheels have been used since ancient times to harness **tidal energy,** the tremendous energy contained in the normal ebb and flow of the tides. Modern schemes call for the construction of large barriers across narrow bays and river estuaries in areas where the **tidal range** is high, at least 3 m (10 ft). Water moving in with the high tide is caught behind the barrier, and locks are opened to release the water at low tide. The flowing water drives turbines that generate electricity from mechanical energy, just as in the hydroelectric plants in river dams. One such electrical generation plant has been operational

Hydrothermal Vents Undersea hot springs associated with the mid-ocean ridges encircling the earth, where new material is added to the earth's crust.

• Chapter 2, p. 37

Ions Charged atoms or groups of atoms that are formed when salts are dissolved in water.

• Chapter 3, p. 43

Tidal Range The difference in height between successive high and low tides.

• Chapter 3, p. 60

FIGURE 17.20 Aerial view of salt-evaporating ponds on the southwestern tip of Puerto Rico. The shallow ponds are flooded with seawater, and the sun and wind evaporate the water. Ponds like these have also become an important habitat for seabirds.

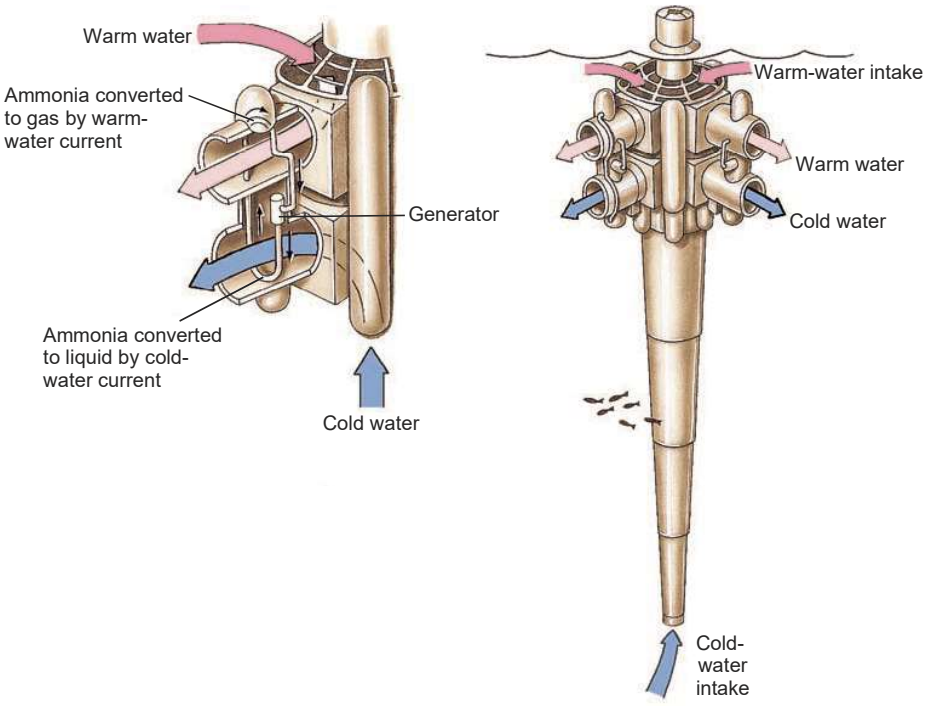


FIGURE 17.21 This ocean thermal energy conversion (OTEC) plant is an experimental model consisting of a platform containing a control room, living quarters, and generators, plus a tube several hundred meters long for collecting cold water.

in northwestern France, since 1966. A few other facilities have been built on an experimental basis in western Europe, Canada, and other countries. One became operational in New York's East River in 2006.

The use of tidal energy is pollution-free and relatively efficient, but the resulting changes in the tidal patterns can be highly destructive to the nearby environment. The rich marshes in estuaries may be damaged or destroyed. Pollutants from other sources tend to accumulate upstream because normal tidal flushing is restricted. River flows can also be altered, increasing the risk of floods inland. On the other hand, the artificial lagoon created upstream can be used in recreation, as in the case of the French plant.

Wind-generated waves and strong ocean currents are other potential sources of energy, particularly in areas subject to powerful, regular waves. As with tidal energy, water flow can be converted into electricity by turbine generators. Wave energy is also used to power navigation buoys. Several projects, mostly in western Europe, plan to use waves to produce energy for seawater desalination or to pump nutrient-rich deep water to the surface for use in mariculture.

Another way to harvest energy from the ocean is to take advantage of the temperature difference between surface and deep water, a process called **ocean thermal energy conversion (OTEC).** Pilot OTEC plants (Fig. 17.21) circulate ammonia, propane, or another liquid that boils at low temperature through pipes bathed in warm surface water. The liquid evaporates and the gas is forced through turbine generators to produce electricity. The pipes then flow through cold water pumped up from the deep, condensing the gas back into a liquid, and the cycle repeats. This process, in which a difference in temperature is used to produce electricity, is like the reverse of a refrigerator, which uses electricity to produce a difference in temperature between the inside and outside. Temperature differences of at least 20°C (36°F) between the surface and below are needed, a condition met in the tropics. Electricity generated by OTEC could be sent ashore by power lines, or used at sea for various industrial operations. The cold, nutrient-rich water pumped from the deep can also be used in mariculture for human food (see Fig. 17.16) and to grow algae for animal feed and plant fertilizers.

Potential sources of electricity from the sea include tides, waves, currents, and the temperature difference between surface and deep water.