CHAPTER EIGHT

Red Tides

About, about, in reel and rout
The death fires danced at night
The water, like a witch's oils,
Burnt green and blue and white.

Samuel Taylor Coleridge, *The Rime of the Ancient Mariner*

Perhaps the manifestations of plankton best known to Puget Sound residents are phenomena called "colored water"—red, brown, and luminescent—collectively known as "red tide." Red tides occur anytime from spring through fall, though they are most common during late summer. They form impressive displays in bays, along shorelines, and in boat wakes. Most red tides are caused by one of several genera of pigmented dinoflagellates, and most are nontoxic. *Gonyaulax, Gymnodinium, Ceratium,* and *Prorocentrum* appear to be toxic; but *Peridinium,* the animal *Noctiluca,* and the unique symbiotic protozoan *Mesodinium* are nontoxic. Many of these organisms are also bioluminescent, as are some crustaceans, ctenophores, medusae, larvaceans, annelid worms, and fishes.

Any of these organisms can form a "bloom" dense enough to discolor water at the surface, particularly when acted on by physical concentrating forces. They are often seen in windrows or discrete patches, where they accumulate like flotsam. *Gymnodimium* colors the water a deep pink or chocolate brown, *Noctiluca* a tomato-soup red, and *Mesodinium* brick red to purple. The colors come from accessory pigments to the ever present chlorophyll, which are related to the pigments we see unmasked in autumn leaves.

However pleasing to the eye, these incidences can sometimes have sinister effects, resulting in morbidity and mortality of both marine animals and humans. The two most prominent effects are paralytic shellfish poisoning and oyster larvae mortality.

Paralytic Shellfish Poisoning (PSP)

In June 1793, Captain George Vancouver and his crew were reconnoitering the area around the central coast of British Columbia when one party of four men pried some mussels from the rocks of a small cove for their breakfast, as they had done on many previous mornings. On this unfortunate day, however, all four of the men, within a few minutes after breakfasting, were beset by a numbness of the lips and fingertips. This was followed by paralysis of the arms and legs, a feeling of dizziness, and nausea. For one man, John Carter, it meant death. The

Figure 8.1 *Gonyaulax* (*Protogonyaulax*) *catenella* (above left), the chain-forming dinoflagellate responsible for paralytic shellfish poisoning in Puget Sound. The enlarged cell (center) has been infected by the parasitic dinoflagellate *Amoebophyra ceratii*, and will soon burst and die. Actual size approximately 30 micrometers per cell. (Photo courtesy Louisa Nishitani). *Ceratium fusus*(above right), a spiny dinoflagellate linked to oyster larvae mortality in the southern Sound. Actual length approximately 100 micrometers. (After Cardwell et al., 1977)

other three men, acting on the advice of a fellow crewman who had experienced a similar malady in England, exercised vigorously and, coincidentally, survived. They named the location Poison Cove. This was the first recorded incidence of paralytic shellfish poisoning (PSP) on the Pacific coast of North America.

Paralytic shellfish poisoning is found on coasts throughout the world, including Northern Europe, Southern Africa, Japan, and both coasts of North America. God is alleged to have slain Egyptians by this means on Moses' behalf: "All the water changed into blood. The fish died and the river stank" (Exodus 7:20-21). It was not until an outbreak of shellfish poisoning in California in 1927 killed several persons and sickened over one hundred more that the poison was connected to red tides. One scientist, thinking that it might have come from the food of the offending mussels, managed to isolate a species of phytoplankton that produced a toxin matching that in the shellfish. This was the first instance in which plankton was found to be an enemy, albeit an unwitting one, of humans.

Although there have been repeated outbreaks in the Puget Sound area, notably with several deaths in 1942 and 1957 in Canada and Washington, it was not until an outbreak in the northern Strait of Georgia in 1965 that the local planktonic culprit was first identified. It is now thought to be *Gonyaulax* (or *Protogonyaulax*) *catenella*, an armored dinoflagellate that ranges from 15 to 55 microns in diameter, and which unlike most dinoflagellates occurs in chains of from two to eight cells (Figure 8.1). It has been grown in culture and its life habits studied. *G. catanella* is ten times more toxic in Washington than in Califor-

nia, but only a tenth as toxic as a sibling species (variously called *G. tamarensis* or *G. excavata*) that has been responsible for poisoning and death from Long Island Sound to Nova Scotia.

Although sparse *G. catenella* populations had been detected before, the first PSP related health problems in the inner waters of Puget Sound appeared in September of 1978, during warm "Indian Summer" weather following heavy rains in August and September. They occurred on Saratoga Passage along the eastern shore of Whidbey Island, and gained public notice when nine people became sick, four of them seriously enough to be hospitalized. PSP spread southward as far as Vashon Island over the course of three weeks, necessitating closure of beaches to shellfish gathering. Toxin levels of 30,000 micrograms per 100 grams of tissue (80 is sufficient to close a beach) were found in shellfish meat. The PSP did not reach south of The Narrows, nor into Hood Canal, and by the end of the month some beaches were reopened in Puget Sound. Beaches on Whidbey Island and the San Juans never reopened, however, and additional closures began again the following April. By July 1979, all beaches north of Tacoma were again closed. (A fatality occurred in the northern Strait of Georgia in May 1980.) It is still a mystery why PSP-related illnesses were never reported from within Puget Sound proper until 1978.

Of all the animals in Puget Sound that feed on phytoplankton, primarily only bivalves acquire PSP and are eaten by humans: the mussels *Mytilus edulis* and *M. californianus*, the oysters *Crassostrea* and *Ostrea*; the butter clam *Saxidomus*, the soft-shell clam *Mya*, the Manila clam *Venerupis*, the littleneck clam *Protothaca*, the cockle *Clinocardium*, and some others. All of these bivalves obtain their food by pumping water into their shells and over their gills, where plant cells are trapped and directed toward the mouth. The mussels and oysters, which live on rocks and atop the sediment, simply open their shells to obtain water. The clams, living below the sediment, have siphons that extend into the overlying water. All of these bivalves live in the intertidal zone near the water's surface, where phytoplankton is most abundant. Mussels can become poisonous within a few days of an outbreak of *Gonyaulax*, making them an excellent organism for monitoring the onset of toxicity. Mussels also rid themselves of toxin soon after a bloom. In contrast, the butter clam, which concentrates the toxin in its siphon, can retain it there for as long as two years after the initial outbreak.

The effects of PSP are of course worst when eaten on an empty stomach. There is no antidote; treatment is to induce vomiting as soon as possible, and to administer a fast-acting laxative to minimize the absorption of the toxins. In the most serious cases, death occurs by respiratory paralysis within 2 to 12 hours. The principal (but not only) toxin

Table 8.1 Minimum lethal dose to humans (micrograms of toxin per kilogram of body weight) for selected natural poisons. The 600-microgram dose of saxitoxin needed to kill a 68-kilogram (150-pound) person can be obtained from a single clam.

Toxin	Dose
Botulinus	0.00003
Tetanus	0.001
Diptheria	0.3
Cobra Venom	0.3
*Saxitoxin	9.0
Curare	500
Strychnine	500
Muscarin, from *Amanita* mushroom	1100
Sodium Cyanide	10,000

produced by *Gonyaulax*, saxitoxin, has been isolated and synthesized artificially. Saxitoxin is an alkaloid nerve poison (neurotoxin) that acts by blocking transmission of impulses from nerve to muscle, and is one of the more potent natural poisons (Table 8.1). Pure samples of it are kept on hand by the Army at Fort Dietrich, Maryland, in case the Russians land looking for clams.

There is no truth to beliefs that garlic will neutralize PSP toxins, or that they can be detected by the discoloration of silver in cooking water. High-temperature frying can reduce the toxicity slightly, and a portion of it can also be discarded with steaming liquor. Nevertheless, enough toxicity can remain to sicken or kill humans. A dangerous old-wive's tale claimed that shellfish were safe to eat in the months of the year which contained the letter "R"—that is, that they were unsafe from May through August. Blooms of *Gonyaulax* can occur from April to November, however, and shellfish can be toxic all year. The only assurance of safety is the method used by the Health Department for assaying the toxins in shellfish tissues. A standardized amount of meat is ground up and injected into a white mouse. If nothing happens, the stuff is safe to eat. If the mouse suddenly stiffens, begins wildly leaping about its quarters, gasps for breath and dies, so might you. The length of time it takes for the mouse to die is a measure of the strength of the toxins.

PSP toxins do not seem to harm most shellfish in which they are concentrated, despite their toxicity to humans and other, mostly warm-blooded animals. Cats in particular are extremely vulnerable. The reasons for these sensitivity differences are still not well understood, but the toxins are apparently harmless unless acted upon by acid, as occurs during digestion by humans but seemingly not by shellfish. When acid-hydrolyzed saxitoxin is injected into many fish and shellfish, they show clear signs of poisoning; but conversely, some shellfish have an apparent ability to break down the toxin. On the Atlantic Coast, large kills of herring have been blamed on their ingestion of zooplankton which had eaten *Gonyaulax*, and further kills have been traced to other red tide organisms. PSP toxins are found in some other animals, but the place of *Gonyaulax* in the food web has not yet been determined.

Several competing theories still have not fully explained the appearances of PSP. *Gonyaulax* seems to like quite warm water, around 14°C (a typical surface temperature in the main basin in summer), and

can grow well at any salinity encountered in Puget Sound. *Gonyaulax* seems to appear most frequently in protected inlets during later summer spells of prolonged warm clear weather, when nutrients are depleted from a stratified surface. Its summer abundance is inverse to that of diatoms. Before invading Puget Sound, it was historically most common in Sequim Bay (on the southern shore of the Strait of Juan de Fuca), which is almost completely isolated from the Strait by a narrow mouth and a sandspit, and receives little freshwater runoff. Its abundance there has been correlated with both the intensity of sunshine and the duration of spells of clear weather. Mixing is quite slow here during the summer, and experiments in New England demonstrated that just stirring a flask of different species of *Gonyaulax* (*G. excavata*) stopped its growth.

Gonyaulax also appears during periods in which rainfall (particularly a large amount of rainfall without heavy winds to cause mixing) is followed by prolonged clear weather. This may produce necessary stratification. Laboratory cultures of *Gonyaulax* can be stimulated by extracts of terrestrial soil, however; an essential nutrient may thus be provided by the runoff from rainfall, or the organic chemicals in soil may chelate toxic trace metals. More speculative yet is the hypothesis that in some parts of the world PSP may be getting worse due to the chelating effect of sewage dumped into the sea.

The appearances of PSP, like those of phytoplankton in general, are determined in part by localized circulation patterns in coastal and estuarine areas. Although the results have not yet been applied to Puget Sound, examples from England, Florida, and Maine show that dinoflagellates (including *Gonyaulax*) accumulate where highly stratified waters meet mixed waters. Invisible blooms can occur below the surface in stratified, nutrient depleted areas, and blooms also can be highly patchy. This historically has been a problem in observing shellfish toxicity on the long, sparsely populated shoreline of British Columbia where a toxic bloom could appear, last a few days, and depart before scientists could even know it existed—much less study it—and where shellfish taken only a mile apart could vary twentyfold in toxicity.

Finding PSP outbreaks in time to warn the public is complicated by two more problems. Shellfish can acquire toxicity even when *Gonyaulax* is too dilute to color the water. Furthermore, *Gonyaulax*, like other neritic phytoplankters, forms resting cysts under certain conditions, which are yet to be determined. These cysts can be more toxic than the swimming cells, and can contaminate shellfish throughout the year. Once cysts are dropped to the bottom of a body of water, there apparently is no way to eliminate them, although they eventually will die if they do not germinate. The cysts may be spread to uncontaminated areas by dredging and by transportation of shellfish that contain

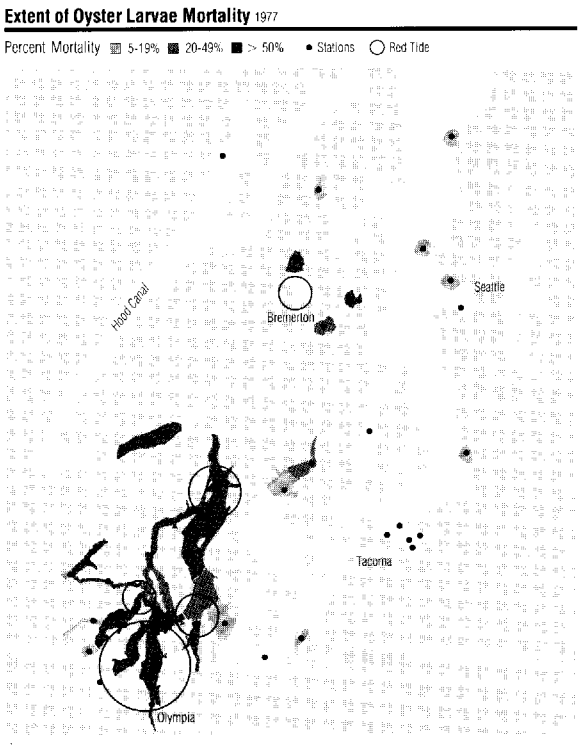

Figure 8.2 Oyster larvae mortalities in the central and southern Sound, as determined by surface water bioassays during 1977. Visible red tides are noted. (After Cardwell et al., 1979)

them. Low levels of PSP that appeared in the southern Sound in 1981 may have originated in this manner.

A couple of promising developments make the story of *Gonyaulax* not an entirely negative one, however. Saxitoxin shows some promise as an insecticide. Research at the University of Washington has also uncovered a dinoflagellate, *Amoebophyra ceratii*, that can parasitize several other dinoflagellates—including *Gonyaulax*—in the wild, and may in fact exert some control on outbreaks of PSP. This discovery suggests the possibility that *Gonyaulax catenella* might be controlled in confined bays by growing *Amoebophyra* on a nontoxic host such as *Peridinium* in the laboratory, and releasing it in those bays.

Other Toxic Red Tides

Although southern Puget Sound may (so far) have fewer problems with paralytic shellfish poisoning than the northern Sound, recent research has disclosed a red tide-related problem of a different sort. Very high levels of oyster larvae mortality—over 50 percent of the larvae tested in bioassays—have frequently been observed in shallow inlets of the southern, central, and northern Sound, and Hood Canal (Figure 8.2). In some cases these have been correlated with pulp mill effluent (e.g., Port Gardner, Bellingham Bay), but in the southern Sound some peculiar traits emerge. Well-mixed areas, even those very close to areas

of high mortality, are free of the problem. The toxicity is often most severe at a depth of roughly three meters. Larvae are not sickened by small amounts of the harmful water (as they might be if a chemical pollutant were responsible), but rather are either totally unaffected or are killed.

Oyster larvae mortality correlates best, it turns out, with abundances of the dinoflagellates *Ceratium fusus* (Figure 8.1) and *Gymnodinium splendens*, and sometimes *Prorocentrum gracile*. They seem not to be poisonous, as *Gonyaulax* is; the water by itself is nontoxic, either without cells or with ground-up cells. Instead, *Ceratium* at least may impale the larvae on its long spines.

Similar effects are observed when larvae are exposed to sharp-edged particles from dredge spoils. A kill at a commercial oyster hatchery on Liberty Bay in 1975, first thought to have been caused by mercury from a nearby Navy installation, was later attributed to a red tide. Larval bioassay results also correspond closely with observed mortality of adult oysters in the southern Sound. *Ceratium* blooms were observed years ago in such places as Hood Canal and San Juan channel, before they were linked to mortalities.

Toxins have recently been isolated from related phytoplankton species, including *Gymnodium breve*, which causes fish kills in Florida, and *Prorocentrum minimum* from the Strait of Georgia. There also appears to be a link between the phytoflagellate *Olisthodiscus luteus* and fish mortality in northern Puget Sound and elsewhere, seemingly due to bacterial stimulation by carbon excreted from the alga. The dinoflagellate *Gyrodinium* has been linked to kills of shoreline fish, snails, and limpets in Ireland, and large kills of shellfish have been caused off New York City by oxygen depletion from decay of red tide blooms of another species of *Ceratium* (*C. tripos*).

Are all these harmful red tides really increasing in frequency and severity, as seems to be the case, and if so, why? That question cannot yet be positively answered. The increases in red tides recorded within the last few decades do appear to be real, but they may stem from increased surveillance and reporting, due to higher population density and better scientific knowledge. There may be long-term fluctuations in red tide incidence related to natural causes such as climatic cycles, of which we are seeing only a small segment. The possible link between human activities and red tides is still a speculative one. Every theory of the effect of pollution on red tides has its counter-theory, and as yet none has been reliably confirmed. Certainly toxic red tides have occurred and still cause problems where they could not have been aggravated by civilization nor scrutinized by science. At worst, humans have perhaps only exacerbated an entirely normal process of nature.

CHAPTER NINE

Marine Pastures

> There, said he, pointing to the sea, is a green pasture where our children's grandchildren will go for bread.
>
> Obed Macy, *A History of Nantucket*

Perhaps the most persistent belief about life in the sea is that one day food from the sea will eliminate world hunger. This myth has been perpetuated by people with more idealism than knowledge, for the realization of this worthy and far-sighted goal is at best years or decades away. There are substantial obstacles to developing the ocean's food supply—obstacles for which there would seem to be no easy solutions.

The first problem is in finding any more food to harvest. Certain of the world's fish stocks appear already to be badly overfished, and the area within which to pursue new fisheries is limited to the more productive coastal and polar regions. Although global phytoplankton production exceeds the global harvest of cultivated crops by a factor of five, most of the world's plankton production takes place in the open seas, where it is so widely dispersed that it is impractical either to harvest it directly, or even to harvest the fishes it supports. The higher rates of plankton and fish productivity, the technology of harvesting, and even issues of international law all favor a concentration of effort in the areas already exploited.

The strong stratification responsible for this low productivity in mid-ocean also restricts the potential for artificially enhancing the productivity of the sea at large. Some means would be needed to stir the ocean to depths of as much as 100 meters over a wide area, in order to bring up enough nutrients to start the food chain going, and even then it is not clear what sorts of organisms would grow. Perhaps the energy for this pumping can someday be derived from projects on the drawing boards today, such as Ocean Thermal Energy Conversion (a sort of floating reverse heat pump, which would generate electricity by pumping deep water to the surface), or from wave or tide power. Clearly, global cultivation of the ocean would require forces not yet even imagined.

The barren condition of the open ocean makes coastal areas such as Puget Sound very important to the future harvest of the sea. Here, many technical difficulties are reduced—the area is easily accessible, well-mixed, and already quite productive. Schemes for extracting more seafood from coastal areas fall into the same categories as food-providing schemes on land: hunting, ranching, and farming. All have applications to the role of plankton in the harvest of food from Puget Sound.

Hunting

Marine hunters, the commercial and sport fishermen, harvest seafood without participating in its rearing. At the present time, increasing the hunting effort is the quickest and cheapest method of increasing the yield from the sea. New fishing equipment is more efficient at catching those fishes and shellfish that are already being harvested, and with the advent of the 200-mile offshore fishing limit there are new possibilities for exploiting previously underutilized species.

The ceiling on natural fish catch is imposed ultimately by the production of plankton. The types of plankton that grow also determine (and are determined by) the species of fish, shellfish, and other animals that grow. Coastal waters are believed to be most productive because they are well-mixed and because they have large plankters and short food chains with a minimum of tropic inefficiency. When harvesting fish populations, both the natural limits on production and the complex interactions that account for production must be considered.

Peru is a classic example of how attempts to hunt more food from the sea can go awry. Coastal upwelling enriches the coast of Peru and supports a vigorous growth of large diatoms, fed upon by anchovies—a highly-efficient, two-link food chain. At one time, one in every five pounds of fish caught in the world was caught off Peru. But in the waters off South America, as in Puget Sound, biological productivity is intimately tied to the physics of the ocean, and to the weather. Periodically, upwelling ceases, nutrients become scarce, and the planktonic food supply for the anchovies is cut drastically, apparently because of large-scale weather patterns over the South Pacific. The large diatoms are frequently replaced by flagellates, or even by red tides.

Such an event is called an *El Niño* (Spanish for "The Christ Child," since it appears most frequently around Christmas), and has apparently always been a normal feature of the region's oceanography. The anchovies dependent on the diatom production simply die back during an *El Niño*, then rebuild themselves when favorable conditions return. In the early 1970s, however, unregulated numbers of fishermen were already taking almost as much fish tonnage as the system would sustain (or perhaps more), when a sequence of *El Niños* decimated the stock. Desperate fishermen worked all the harder to catch what they could. The unfortunate result was that the anchovy population dropped to a level from which it may never recover.

A similar fate may also be overtaking North Pacific and Puget Sound fisheries. The potential harvest of the sea is limited both by the area of the sea from which we can expect to harvest fish, and by a ceiling on the harvestable fish within that area. Both of these limits are set by the plankton and by the meteorological and physical processes that govern plankton production.

One proposed escape from catch limitations is to harvest organisms lower on the food chain; that is, to harvest plankton directly. Although the idea is not totally new—jellyfishes are a traditional food in Asia—its magnitude is new. Already, the richest crop of plankton in the world, the large herbivorous antarctic krill, *Euphausia superba*, is the subject of trial harvests by the Russians and Japanese, and many more countries are contemplating joining them. Antarctic krill grows rapidly and has a standing crop of 40 to 1,000 million metric tons (44 to 1,100 million long tons), compared to the annual world fish harvest of about 60 metric million tons (66 million long tons). Krill has the flavor and nutritional value of its larger cousin, the shrimp, although it is said to resemble cooked maggots in appearance. Antarctic waters are currently unregulated and are open to international exploitation. Additionally, because of the overharvesting of one of the krill's principal predators, the blue whale, there may be an uneaten "surplus" of many millions of tons of krill.

There has been speculation about harvesting copepods, although these smaller crustaceans are more difficult to collect and contain a higher proportion of indigestible chitin exoskeleton. Zooplankton could be used both for animal and human food, as either a dish unto itself or ground into meal as a protein supplement.

There are problems with this potential harvest, however. It is not clear, first of all, that a surplus of antarctic krill really exists, and it is difficult to determine what effect removal of large quantities of krill could have on the remaining whale populations, or on seals and birds. Some preliminary euphausiid harvests have been conducted in the Strait of Georgia for a number of years, but an extensive zooplankton fishery in Puget Sound and the North Pacific would almost certainly conflict with the fishery supported by a major zooplankton predator—the popular, tasty, high-priced Pacific salmon.

The main obstacles to the exploitation of plankton as a food source are technical and economical. Put simply, the question is whether enough plankton can be caught, using state-of-the-art plankton nets, to pay for the effort of pursuing it. Although seafoods in general require less energy than terrestrial foods to bring to market, the plankton resource is so dilute, and the organisms so tiny, that it seems more economical in most cases to allow specialized animals to harvest for us and to accept the loss of efficiency in the food chain than to try to beat nekton at its own game. Imagine, for comparison, humans gathering nectar to make honey, instead of allowing bees to do it for them. The prospects for harvesting zooplankton are supported only because it is found in dense swarms—patches—detectable with echo sounders. Ultimately, the feasibility of zooplankton fisheries will depend on the price it will bring at the grocery store.

One of the most successful and biologically efficient methods of obtaining a harvest from the plankton has been to gather naturally occurring planktivorous shellfish, such as clams, oysters, and mussels. These animals are efficient and powerful at extracting plankton and suspended matter from moving water, and have few predators that compete with humans. Potential shellfish harvest in the wild is even more limited than that of finfishes, however, since the area of suitably productive shallow water habitat is less than the area of open coastal waters. Furthermore, natural growth of some shellfish species is hampered by sporadic failures in larval production and high mortality due to cold water, predators, and pollution. New mechanical shellfish harvesting technologies, such as water jets, conveyor belts, and suction dredges, promise increased supplies and reduced costs for this mode of marine hunting, but are running afoul of political and environmental complications. To increase the harvest of seafood, therefore, scientists and growers are turning to ranching and farming techniques.

Ranching

Marine ranchers, like their terrestrial counterparts, breed their stock, rear them as young, then turn them loose to feed and mature on open rangeland before finally rounding them up for sale or slaughter. Puget Sound ranchers raise fish and shellfish in hatcheries, which reduce reproductive mortality by providing suitable spawning and rearing habitat. It is a form of ranching because the animals are released from human control and allowed to graze freely in their marine pastures, then are harvested upon their return, and because there is a degree of selective breeding.

Ranching techniques have achieved their greatest successes with bivalve molluscs. For years clam and oyster larvae have been reared under controlled laboratory conditions, using a phytoplankton diet, until they could be transplanted to a beach as spat. The rancher may thus breed the shellfish stocks selectively, feed the larvae an optimal food at an optimal temperature and salinity, add antibiotics and vitamins, and control the time and place at which the spat are introduced into the wild, selecting favorable environmental conditions and reducing competition for food and space. Washington growers once imported most of their spat for the Pacific oyster from Japan, since natural sets in Puget Sound are not sufficiently reliable or predictable for commercial operations. Local hatcheries now produce most of the spat planted in Puget Sound oyster beds, however. In addition, the Washington Department of Fisheries has recently begun raising razor clams (*Siliqua patula*) for planting on outer coast beaches, and experiments are underway elsewhere for the raising of Dungeness crab (*Cancer magister*), geoducks (*Panope generosa*), and abalone (*Haliotis* sp.).

Hatcheries have also been successful in maintaining the salmon harvest. In terms of yield per unit of area required and feed consumed, and therefore per dollar spent, such hatcheries are the best investment available for increasing the current yield of the sea. This method cannot increase the capacity of marine ecosystems for producing animals, but in places like the Pacific Northwest, where unexploited plankton food may be available because of declining of salmon stocks, and where many natural spawning grounds have been destroyed, hatcheries can help maintain viable fish populations. Still, the potential benefits of hatcheries are constrained by other limits on salmon populations, including overharvest and loss of genetic diversity. Hatchery rearing of salmon has been carried out in the Puget Sound area for decades, and expansion of salmon-rearing efforts remains one of the best hopes for maintaining the yield of protein from Northwest inland waters.

Farming

Marine farming, more popularly known as aquaculture or mariculture, entails the husbandry of marine animals (and some plants) from birth to death. Aquaculture is amazingly undeveloped in the United States considering (or perhaps because of) our technological advancement. Americans obtain less than 10 percent of their protein from aquatic animals, eating only 5.5 kilograms (12 pounds) of fish per capita per year, compared to 32 kilograms (70 pounds) in Japan. American aquaculture production is minimal compared to that of the Orient and satisfies but a small portion of our seafood appetite. Research on marine farming falls into two categories: raising planktivorous animals on or in a confined structure within a natural body of water, and growing plankton and planktivores artificially in completely enclosed systems.

One form of mariculture emerging on Puget Sound is net-pen rearing of salmon and cutthroat trout. The fish are kept in large pens immersed in Puget Sound from the time they leave the hatchery as juveniles until they reach a marketable weight of about one pound, called "pan-size." The advantages of this approach are that animals are not lost to either migration or predation, and that they live in very nearly their natural environment, saving growers the trouble and expense of duplicating those conditions artificially. Similar experiments aimed at raising prawns have met with more difficulty, owing to a more complex life cycle.

The disadvantage of net-pen farming is that although natural zooplankton is available, fish populations are so dense that their diet must be augmented with costly feed. Fish cultivation in general is ecologically more efficient than red meat production, but supplementing salmon diets amounts simply to converting one expensive food into another, with a net loss of energy. Also, as in hatcheries, crowding and

genetic uniformity resulting from controlled breeding make fish more susceptible to oxygen depletion and disease. Finally, some forms of plankton can even be hazardous to the penned fish; dense phytoplankton blooms of spiny *Chaetoceros* and *Ceratium* have been known to puncture the sensitive gills of young fish and cause heavy mortality because the animals are not free to swim away from the algal masses as they would in the wild. Nevertheless, because of the attractive prices and demand for salmon, net-pen farming is achieving commercial success on Puget Sound.

Currently the most successful form of marine farming worldwide—second only to hatcheries in efficient use of energy and space, and second only to seaweeds in global tonnage of cultivated harvest—is the raising of bivalves using suspension culture. Oysters and mussels, in particular, are allowed to attach to ropes or are placed in cages as spat, then hung from posts, buoys, or rafts in waters that offer both suitable protection from storms and healthy flushing by currents, tides, and winds. Suspending bivalves off the bottom tremendously increases the volume of water from which these animals can filter their phytoplankton food by extending their habitat both vertically and offshore. Suspension culture maintains more animals in the productive surface layer and eliminates exposure during low tides. Shellfish in suspension culture reach market size twice as fast as those in bottom culture and produce a higher quality of meat since less bottom sediment is ingested.

One advantage of using shellfish as a means of extracting more plankton protein from the sea is that the shellfish are extremely efficient filterers and are able to capture very small plant prey such as flagellates. This is a simple, two-link food chain, with a minimum of the trophic inefficiency that accompanies longer food chains, and the crop is sessile and relatively easy to harvest. The yield of raft cultures of mussels approaches the phenomenal figure of 30,000 metric tons (33,000 long tons, fresh weight) of meat per square kilometer of raft area per year. That compares to yields of a few hundred to a few thousand metric tons for bottom culture of oysters; less than a hundred metric tons for coastal finfisheries such as those of Puget Sound, Georges Bank, and the North Sea; and at most 50 metric tons of beef or pork on a feedlot. These figures further demonstrate that the potential productivity of water is much higher than that of land—if the limitations of fluidity can be overcome—because marine bivalves do not have to expend as much energy as terrestrial animals in supporting themselves, moving about, or maintaining their body temperatures, and so can devote proportionally more energy to protein production.

Suspension culture of oysters is beginning in Washington State, and there is potential for mussel culture as well. Some problems still must be dealt with in raft culture: red tides, bacteria, viruses, and pollu-

tants can contaminate entire crops. Labor is expensive, and on Puget Sound there is an aesthetic consideration as well: it can be difficult to convince citizens to accept rafts, buoys, and posts along their expensive waterfronts and in their favorite boating spots.

The ultimate marine farm would not depend on natural plankton production. Artificial stimulation of phytoplankton production in a natural setting to enhance the yield of shellfish farming has been successful in ponds in Alaska and in the Virgin Islands. These experiments involved pumping deep, nutrient-rich water to the surface, in an enclosed area where enrichment effects would not be dissipated, and where raft or net-pen cultures could be maintained. Such a project might be useful in those Puget Sound embayments where surface stratification limits primary production, such as in Dabob Bay. First, however, the problems of conflicting shoreline uses, impact on the indigenous food chain, and pumping technology and costs would have to be solved.

The economic prospects of smaller scale, completely enclosed marine farms may be bright, especially when used to treat sewage and pulp effluent before it is discharged to the environment. Considerable research, in fact, has gone into the possibility of turning sewage into food via phytoplankton and shellfish in artificial ponds. There are problems with ingestion of sewage pollutants, bacteria, and viruses by the shellfish, and it remains to be demonstrated whether the products—clean water and food—will repay the cost of pumps, land, labor, and fuel, particularly in well-watered and productive regions like Puget Sound. Nevertheless, such self-contained ecosystems are ranked among the brightest of aquaculture prospects nationwide.

There may also be prospects for farming phytoplankton for direct human consumption. Natives in Africa have for hundreds of years eaten filamentous microalgae from Lake Chad. Formal research on cultivation of plankton as human food began in the 1950s, and at one point algal cultures were proposed as a food and oxygen source for space travelers. Research efforts today are leading to enclosed farming of such freshwater organisms as the cyanobacterium *Spirulina* and the green algae *Chlorella* and *Scenedesmus*, which are filtered, dried, and eaten as a food supplement in powdered form. These genera grow rapidly under harsh conditions, and can have a higher protein content and a higher per acre yield than such terrestrial crops as soybeans, but require bright sunlight and must also repay the additional costs of containers, pumps, and processing.

Algal cultures appear to be economical in arid climates where water itself is precious. They may be useful for sewage treatment in Israel, and for supplementing protein intake of both people and animals in underdeveloped countries, such as Peru, Thailand, and India. There

seems little prospect for their application to the Puget Sound region. Perhaps their presence here will remain limited to the newly-developing market for *Spirulina* as a health-food supplement. Popular in Japan, the alga is cultured in Mexico, and in 1981 sold in Seattle for $30 per pound.

From all of this mixture of encouraging and discouraging news, what then is the consensus about the potential for plankton in increasing the harvest from Puget Sound and the rest of the world's oceans? The greatest potential for enhancing the harvest of food from Puget Sound seems to be in controlling the high reproductive mortality of already popular species of planktivorous animals, particularly salmon and shellfish. In addition, for the sedentary and highly efficient shellfish, there seems to be bright prospect in the creation of additional habitat for adult growth if political problems can be overcome. But these resources, even if developed to the fullest extent, will likely boost only slightly the supply of what will always be luxury foods. The great popular hope for feeding the world's starving masses remains, if not totally spurious, at least far beyond our present technological, economic, or political capabilities.

Civilization is altering its relationship with the sea and its organisms in the same way that it has changed the face of the land. We have domesticated wild animals from the dog to the chicken, and plants from the geranium to the Douglas fir. In so doing we have transformed the landscape from a wilderness into a patchwork of farms. Even more drastically, we have altered the course of evolution for entire species, intervening to perpetuate those breeds which were of value to us and neglecting or even exterminating others.

We stand today, perhaps, at the threshold of doing the same in the sea, this time with more scientific maturity and awareness of the possible consequences. Although it may seem impossible to ever change the face of the open ocean, human activities are already having an impact on coastal areas such as Puget Sound, and many difficult choices are ahead. Coastal areas can be maintained in their natural states, or developed for industry or food. Wild marine creatures can be allowed to exist in their natural habitats, or domesticated and made forever dependent on people. We may be trading in the ethic of the hunter for that of the farmer, and turning the marine wilderness into marine pastures.

Glossary

alga (plural **algae**) Plant having simple internal organization without fluid-transporting structures; unicellular or multicellular
anoxic Containing little or no oxygen
aphotic The deeper pelagic zone where sunlight is insufficient for plant growth
autotroph Organism (usually a plant) that manufactures its own food from raw materials and energy (usually sunlight)
bacterioplankton Bacteria suspended in the sea, or attached to other suspended matter
benthic Associated with the sea bottom
benthos Benthic plants and animals
binary fission Reproduction of a cell by duplication of its parts and separation into identical daughter cells
bioaccumulation Retention of pollutants in organisms at concentrations higher than in ambient water
bioassay Estimation of pollutant concentration by toxic effects on a standard test organism
biomagnification Higher body content of pollutants in animals at higher trophic levels
biomass Standing stock of organisms as measured by their collective weight
bloom Rapid, enormous increase in phytoplankton standing stock during favorable environmental conditions
B.O.D. (biological oxygen demand) Consumption of dissolved oxygen in water after addition of chemicals or organic matter
calorie Amount of energy required to heat one gram of pure water one degree Celsius
carnivore Animal that eats only other animals
Celsius (or **Centigrade**) Temperature scale having 0° at freezing point and 100° at boiling point of pure water
centimeter One-hundredth of a meter; 0.4 inches (**square centimeter** equals 0.16 square inch, **cubic centimeter** equals 0.06 cubic inch)
CEPEX (Controlled Ecosystem Pollution Experiment) Plankton growth experiment series performed in large cylindrical plastic bags deployed in Saanich Inlet, Vancouver Island, during the mid-1970s
chelation Binding of metallic ions to a complex organic molecule, affecting their solubility and activity in seawater
chelator Organic molecule causing chelation
chlorophyll *a* Principal green plant pigment, used as a measure of phytoplankton biomass
cilia Short bristly hairs that move in unison in cellular feeding or propulsion
ciliate Protozoan having distinct ciliary structure
Coelenterate Phylum of animals with stinging cells and an ancestral two-stage sedentary (hydroid) and mobile (medusoid) life cycle
colony Aggregation of organisms that could survive individually
Competitive Exclusion Principle Theory that in a constant homogenous environment, a single superior species should drive all competitors to extinction
continental shelf Shallow sea bottom fringing the continents to a depth of roughly 200 meters

copepod Small torpedo-shaped crustacean with antennae, probably the dominant metazoan in the sea
copepodite Later juvenile stage of a copepod
cyst Hard pellet formed by many neritic plants and some animals for overwintering or other long-term refuge
cytoplasm Mixture of fluid and structures in the interior of a cell exclusive of the nucleus
detritus Nonliving particles, suspended or on the bottom
diapause Period of inactivity in winter among crustaceans, analogous to hibernation in vertebrates
dinoflagellates Unicellular plants and animals possessing two characteristic flagella, and frequently outer cellulose plates
direct uptake Uptake of pollutants from water directly into organisms
El Niño Short for *El Niño de Navidad* (Child of Christmas), Peruvian term for occasional catastrophic mortalities of fish and birds, usually during December, caused by decreased upwelling
embryology Study of development of the egg from conception to mature organism
estuary Area in which fresh water meets salt water, usually in an inlet
euphotic Upper hundred meters or less of the pelagic zone, where sunlight is sufficient for plant growth
eutrophication Overenrichment of a water body by nutrients, causing nuisance phytoplankton overgrowth
fjord A long, narrow, steep-sided marine inlet, carved by a glacier, usually with a sill at its mouth
flagellum (plural **flagella**) Long whiplike cellular hair used for propulsion
fluorometer Instrument that measures chemical concentrations from how they re-emit incident fluorescent light
flushing Turnover of water in a basin by the outflow and inflow of runoff and tides
flushing time Same as **residence time**
food chain Simple model of a community having organisms assigned in a linear sequence of numbered trophic levels
food web Complex community model in which interlocking feeding patterns create a multidimensional trophic mesh without discrete levels
Foraminifera (forams) Class of protozoa having a spiral outer shell of calcium carbonate
frustule The two halves of the silica outer shell of diatoms
gram 0.035 ounce
herbivore Animal that eats only plants
hermaphrodite Animal with both sets of sexual organs
heterotroph Organism dependent for food on other organisms or their organic products
holoplankton Organisms that spend their entire lives as plankton
holotrich Group of ciliate protozoa
hydra (hydroid) The sedentary phase of the coelenterate life cycle
ichthyoplankton Planktonic fish larvae
intertidal Benthic zone between the highest and lowest tide levels
ion Chemically reactive atom or molecule having an electrical charge
kilocalorie Amount of energy required to heat one kilogram of pure water one degree Celsius; one thousand calories
kilogram One thousand grams; 2.2 pounds

kilometer One thousand meters; 0.62 miles. (**square kilometer** equals 0.4 square miles or 247 acres)
K-selected Evolved to maintain a constant population despite environmental fluctuations
Langley Radiation delivering an energy flux of one calorie per square centimeter
Langmuir cells Small-scale current spirals visible as slicks and bands paralleling the wind
larva (plural **larvae**) Earliest stage of maturity, after hatching from the egg
Limiting Nutrient Concept Theory derived from agriculture that a single nutrient, in scarcest supply relative to requirements, limits yield of a plant crop
lipid Fat or oil molecule
liter One thousand cubic centimeters; 1.06 quarts
littoral Shallowest benthic zone, often used synonymously with "intertidal"
lorica Outer sheath of a tintinnid ciliate, frequently adorned with cemented sediment
medusa (plural **medusae**) Free-floating jellyfish stage of the coelenterate life cycle, named for the resemblance of its tentacles to the snake-haired woman of mythology
meroplankton Planktonic (usually larval) stages of animals that are nekton or benthos the rest of their life cycle
meso-zooplankton Intermediate-sized zooplankton (about 0.25 to 10 millimeters) reliably sampled with a net
metazoa multicellular animals
meter 3.28 feet; 1.09 yards (**square meter** equals 10.7 square feet; **cubic meter** equals 35.3 cubic feet, 1.3 cubic yards)
metric ton One thousand kilograms: 2,200 pounds; 1.1 English tons
microalga Alga having only one or a few cells per organism
microgram One millionth of a gram
micrometer (micron) One millionth of a meter, one thousandth of a millimeter
micronekton Larger zooplankton (more than about one centimeter) with significant net-avoiding swimming ability
micro-zooplankton Smaller zooplankton (less than about 250 micrometers) poorly sampled by nets
milligram One-thousandth of a gram
millimeter One-thousandth of a meter, one-tenth of a centimeter
mitosis Duplication of a cell's genetic material prior to binary fission
morphology Internal and external structures of organisms, and their functions
nanoplankton Organisms too small (less than 20 micrometers) to be sampled even by a fine-meshed phytoplankton net
nauplius (plural **nauplii**) Earliest larval stages of copepods and many other crustaceans
neap tides Biweekly periods of weaker tidal currents and narrower tidal ranges associated with the quarter moons
nekton Pelagic animals swimming strongly enough to oppose ocean currents
neritic Shallow pelagic waters overlying the continental shelf
net plankton All plankton large enough to be caught with a fine-meshed phytoplankton net (above about 20 micrometers)
neuston Organisms associated with the very thin water-air interface
nutrient Dissolved chemical essential for plant growth
oceanic Deep pelagic waters beyond the edge of the continental shelf
oligotrich Ciliate protozoan with weak or absent sheath

omnivore Animal that eats both plants and animals
organic Pertaining to or derived from organisms; a chemical containing a carbon-hydrogen complex
organism A living entity: plant, animal, or otherwise
Paradox of the Plankton Apparent violation of the Competitive Exclusion Principle by the observed diversity of coexisting plankton species
pelagic Contained within a body of water, off the bottom
periphyton Organisms living on rooted aquatic plants
phylum (plural **phyla**) The coarsest division (after kingdom) into which organisms are categorized by their morphological and evolutionary similarities
physiology Study of metabolic systems and processes in organisms
phytoflagellates Small flagellate microalgae from several phyla, including chlorophytes, chrysophytes, and cryptophytes
phytoplankton Planktonic microalgae
plankton Aquatic organisms living unattached to the bottom and having swimming powers insufficient to resist water currents
population Standing stock of organisms as measured by their collective numbers
ppb (parts per billion) One part in 10^9 by weight, or one milligram per metric ton
ppm (parts per million) One part in 10^6 by weight, or one gram per metric ton, one milligram per kilogram
ppt (parts per trillion) One part in 10^{12}, or one microgram per metric ton
predator A carnivore, especially a mobile one
prey An animal eaten by a carnivore
primary productivity Productivity by autotrophs that supports the remainder of the community
productivity Rate of generation of new living matter by organisms
protozoa Unicellular animals
PSP (paralytic shellfish poisoning) Nerve poisoning due to eating shellfish containing toxin ingested from the dinoflagellate *Gonyaulax*
radiolarians Class of protozoa with a star-shaped silica outer skeleton
red tide Discoloration of surface water by a dense plankton bloom, including but not limited to those associated with toxicity and luminescence
residence time Average time spent by a water molecule in a basin before being flushed to sea; estimated as ratio of basin volume to inflow or outflow
r-selected Evolved for rapid population changes in response to environmental fluctuations
saxitoxin The principal neurotoxin generated by *Gonyaulax catenella* that causes paralytic shellfish poisoning
seta (plural **setae**) Small immobile bristle; its branches are "setules"
sill Shallow submerged pile of debris left across a basin by a retreating glacier; called a moraine on land
spectrophotometer Instrument that measures chemical concentrations from their absorption of known colors of light
spores Small, thinly covered bodies shed by plants for vegetative asexual reproduction or short-term refuge
spring tides Biweekly periods of stronger tidal currents and wider tidal ranges associated with the full and new moons
standing stock Quantity of organisms at a given time and place, expressed per unit area or volume

synergism Interaction of controlling factors (e.g., pollutant concentrations) in which the effect of one is enhanced by the presence of the other
taxonomy Categorizing organisms by their structural and evolutionary similarities
tintinnid Ciliate protozoan with a sturdy vase-shaped outer sheath (lorica) with cemented sediment grains
ton see **metric ton**
trophic Pertaining to the feeding relationships among organisms
trophic energy Energy fixed during primary production and available to animals as organic matter
trophic level Theoretical numerical ranking that expresses how many organisms trophic energy must pass through from its source to reach a given organism
trophic uptake Uptake of a pollutant via food
unicellular Having only one cell per organism
upwelling Upward water motion that stimulates phytoplankton growth by nutrient supply, caused by winds and currents
vacuole Hollow space in a cell for storage or buoyancy
vortex (plural **vortices**) Spiral motion
zooplankton Planktonic animals, including meroplankton
zygote Original cell of any organism, a fertilized egg

Guide to Pronunciation

Acartia uh-CAR-sha
Aequorea eye-QUOR-ee-uh
Amoebophyra ceratii uh-mee-boy-FY-ruh sir-AY-she-eye
aphotic ay-FO-tick
Brachionus brack-ee-OH-nuss
Burien BYOO-ree-un
Calanus KAL-un-us
CEPEX SEE-pecks
Ceratium sir-AY-shum
Chaetoceros kee-TAH-sir-us
Chaetognath KEE-tog-nath
chelation kee-LAY-shun
Chlorella klor-ELL-uh
chordates KORE-dates
cilia SILL-ee-uh
Clione kly-OH-nee
Coelenterates suh-LEN-ter-ates
copepod KOH-puh-pods
Corycaeus koh-RIH-see-us
Coscinodiscus kah-sin-oh-DISS-kuss
Ctenophore TEEN-oh-for
detritus dee-TRITE-us
diatoms DYE-uh-toms
dinoflagellates dye-noh-FLAJ-uh-lates
El Niño El-NEEN-yoh
Euchaeta you-KEET-uh
Euphausiid you-FOW-zid
euphotic you-FOH-tick
fjord fyord
geoduck GOO-ee-duck
Gonyaulax gonn-ee-AWL-ax
halocline HAY-loh-kline
ichthyoplankton ICK-thee-oh-plank-tunn
larvaceans lar-VAY-shuns
medusae muh-DOO-see
Mytilus MIH-tih-luss
Navicula nuh-VICK-you-luh
Neocalanus nee-oh-KAL-uh-nuss
Nereis NEAR-ee-us
neritic nuh-RIT-ick
neuston NEW-stun
Nitzschia NITCH-ee-uh
Noctiluca nock-tih-LOO-kuh
Oikopleura oy-koh-PLOO-ruh
Olisthodiscus oh-liss-thoh-DISS-kuss
Pasiphaea pass-ih-FEE-uh
phytoflagellates fy-toh-FLAJ-uh-lates
Pleurobrachia ploo-roh-BREAK-ee-uh

polychaetes PAHL-ee-keets
Polyorchis pahl-ee-OAR-kiss
Pseudocalanus soo-doh-KAL-uh-nuss
pycnocline PICK-noh-kline
Puyallup pyoo-AL-up
Pyramimonas puh-ram-ih-MOAN-us
Saanich SAN-itch
Sequim skwim
Skeletonema skeleton-EE-muh
Spirulina spy-roo-LEAN-uh
Synchaeta sin-KEET-uh
Thalassiosira thuh-lass-ee-oh-SIGH-ruh
Tintinnids tin-TIN-idz
trophic TROH-fick

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The extensive collection of references consulted in preparing this book has been compiled and will be available as a Washington Sea Grant Technical Report (The Fertile Fjord: Annotated Bibliography) in late 1983. Much of the same literature has also been reviewed and discussed in Dexter et al., 1981 (see Chapter 6). Below are the sources of quotes and illustrations, along with selected references to further interesting reading.

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