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Biology of the Red Sea Urchin, *Strongylocentrotus franciscanus*, and Its Fishery in California

SUSUMU KATO and STEPHEN C. SCHROETER

Introduction

Since Kato (1972) reported on the beginning of the sea urchin fishery in California, it has grown dramatically. The catch has exceeded 11,000 metric tons (t) in 1981 in California, and up to 500 t have been harvested in 1 year in Washington. Most of the product of the fishery, the roe (both male and female gonads), is marketed in Japan, where the sea urchins as well as the roe are called "uni."

Inevitably, development of the fishery has raised questions about the status of populations, and effects of the fishery on the urchins and environment. Because fishermen, processors, potential investors, and management officials all require information, several scientific studies were initiated by researchers in Canada and the United States to answer some of these needs. This report presents relevant information from the literature, much of which is not readily accessible to persons in the industry, as well as from our own investigations. A review of red sea urchin, *Strongylocentrotus franciscanus* (Fig. 1), biology is given to promote understanding of natural processes which can have a bearing on the commercial use of sea urchins. Descriptions of the harvesting, processing, and marketing sectors of the industry are also presented. We hope that this information will aid in maintaining a commercially viable and environmentally sound fishery for many years. We hope that this report will fill the needs of the hundreds of persons from throughout the United States as well as other countries who have requested information to help them develop fisheries for their species of sea urchins.

Description of Sea Urchins

Sea urchins belong to the phylum Echinodermata, which also includes starfish, sea cucumbers, sea lilies, and brittle stars. All sea urchins have a hard calcareous shell called a test, which is covered with a thin epithelium and is usually armed with spines. The mouth, located on the underside, consists of five calcareous plates called "Aristotle's lantern" in honor of the Greek naturalist and philosopher. The mouth leads to the digestive tract which empties through the anus located on the top of the test.

Five skeins of roe comprise the most prominent structures in the internal cavity of sea urchins. Sea urchins are

Susumu Kato is with the Tiburon Laboratory, Southwest Fisheries Center, National Marine Fisheries Service, NOAA, Tiburon, CA 94920, and Stephen C. Schroeter is with the Department of Biological Sciences, University of Southern California, University Park, CA 90089.

ABSTRACT—The California fishery for the red sea urchin, Strongylocentrotus franciscanus, *has grown steadily since its inception in 1972, and the maximum annual catch has exceeded 11,000 metric tons. Most of the product of the fishery, the roe, is exported to Japan, though a significant amount is also consumed in the United States. This paper describes aspects of red sea urchin life history, distribution, abundance, ecology, and management. A detailed description of the fishery, including harvesting, processing, shipping, and marketing methods, is also given.*

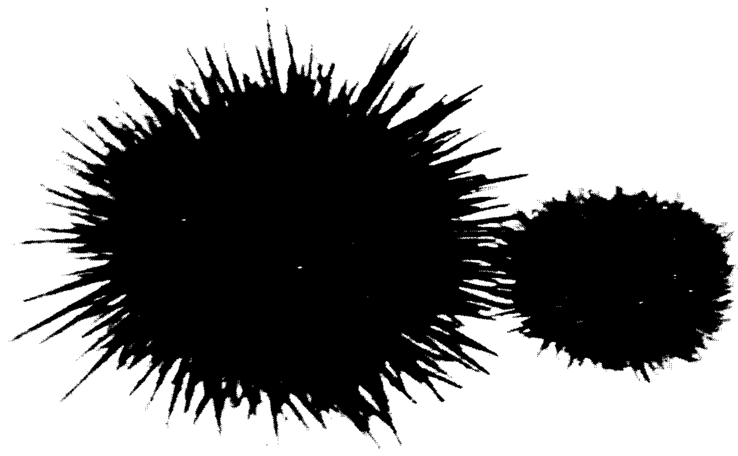

Figure 1.—The red sea urchin, *Strongylocentrotus franciscanus* (left), and the smaller purple sea urchin, *S. purpuratus*.

unisexual, being either male or female, but cases of hermaphroditism (i.e., with both male and female gonads) have been recorded in several species (Boolootian and Moore, 1956). Between the skeins of roe are gill-like structures which are part of the water vascular system, important in movement, respiration, and food gathering. The gut is dark and often filled with partially digested plant material.

Two species of sea urchins are common in shallow coastal waters off California: The red, *S. franciscanus*, and purple, *S. purpuratus*, sea urchins (Fig. 1). Several other species also occur in California, but they are either too small or too rare to be of economic significance. In fact, only the red sea urchin is presently harvested, although the purple sea urchin offers potential because of its abundance. The red sea urchin is one of the largest species of sea urchins in the world, growing to a test diameter of about 18 cm. Its test and spine color is usually dark purple. Not infrequently, however, either the test or spines—or both—are reddish or light purple. The length of the spines may be correlated with the habitat; sea urchins in deeper, calmer waters tend to have longer spines than those in shallower waters where greater abrasion of spines occurs (Silver and Brierton, 1974). The purple sea urchin, which has relatively short spines, is usually light purple or lavender.

Sea urchin roe contains an assortment of nutrients. Major components of the roe of red and purple urchins are given in Table 1. The percentages of various constituents are likely to change, depending on the nutritional and reproductive states of the urchins. Sea urchin roe also contains calcium, phosphorus, iron, Vitamins A, B_1, B_2, B_{12}, nicotinic acid, pantothenic acid, folic acid, and carotenes (Higashi et al. 1959, 1965).

Since polychlorinated biphenols (PCB) and other potentially toxic hydrocarbons are of major concern to the Japanese, an analysis was undertaken to learn the extent of pollution from these noxious compounds. Red sea urchins collected at Fort Bragg, Calif., in 1973 were found to have no detectable amounts of DDT, but contained an average of 0.026 ppm (parts per million of wet weight) of DDE (range 0.006-0.050 ppm). Amounts of PCB averaged 0.04 ppm and ranged from 0.01 to 0.09 ppm[1]. Tolerance levels for PCB set by the Japanese government vary depending on the foodstuff. In flesh of coastal fishes a level of 3.0 ppm is allowed[2]. In the United States, the maximum allowable in "shellfish" is 2 ppm. Thus the California sample fell well within acceptable levels.

Table 1.—Proximate analyses of red and purple sea urchin roe (percent of total roe weight)[1].

Item	Red sea urchin 1	Red sea urchin 2	Purple sea urchin 3	Purple sea urchin 2
Moisture	70.0	70.8	68.6	71.8
Protein	7.7	9.6	9.5	12.3
Lipid	7.6	8.3	5.4	5.2
Ash	1.6	1.5	1.3	1.7
Glycogen	1.3		1.7	
Nonprotein nitrogen	0.1	0.5	0.1	0.5

[1]Sources: 1. Modified after Greenfield et al., 1958; 2. from Kramer and Nordin, 1979; 3. Modified after Giese et al., 1958.

Distribution and Abundance

Red sea urchins are found on the west coast of North America as far south as the tip of Baja California, although their abundance declines south of lat. 27°N (Malagrino Lumare, 1972). They range northward to Sitka and Kodiak, Alaska, and along the Asiatic coast as far south as the southern tip of Hokkaido Island, Japan (McCauley and Carey, 1967). Off the California coast, dense concentrations occur patchily throughout the state. Notable exceptions are those areas off central California where sea otters, *Enhydra lutris*, a major predator of sea urchins, are abundant (McLean, 1962; E. E. Ebert, 1968; Lowry and Pearse, 1973).

Both the red sea urchin and its close relative, the purple sea urchin, usually occupy shallow waters, from the mid to low intertidal zones to depths in excess of 50 m, but red sea urchins have been found as deep as 125 m (McCauley and Carey, 1967). Individuals of both species prefer rocky substrates, particularly ledges and crevices (Schroeter, 1978), and avoid sand and mud.

Both species are often found in and around stands of the giant kelp, *Macrocystis* spp., and other brown algae. Typically, sea urchins are most abundant near the outer edges of kelp beds and less numerous inside (Pearse et al., 1970; Low, 1975; Pace, 1975; Mattison et al., 1977; Tegner and Dayton, 1981). Adult sea urchins that live within kelp beds are larger than those outside, and recent recruits (<10-20 mm) are much more abundant outside than inside the beds (Pearse et al., 1970; Bernard and Miller, 1973; Tegner and Dayton, 1981). Similar patterns have been documented for green sea urchins, *S. drobachiensis*) on the coast of Nova Scotia, Canada (Bernstein et al., 1981). Several hypotheses have been advanced to account for these patterns. Individuals within kelp beds may be larger either because they grow faster, survive longer, or both (Pearse et al., 1970). T. A. Ebert's work (1968) supports the conjecture that individuals inside are larger because they have more food. He studied intertidal populations of purple sea urchins and found that the maximum size attained by individuals in a population is influenced directly by food supply. Additional studies on red sea urchins in southern California (Pearse et al., 1970; Baker, 1973) also support this hypothesis.

The much greater abundance of very small individuals outside of kelp beds may be due to higher rates of settlement, higher survival after settlement, or both (Pearse et al., 1970; Ebert, 1983). Higher rates of settlement could result from active selection by larvae or from the passive concentration of larvae. Alternatively, larvae may be equally abundant inside and outside of beds, but may suffer higher mortality in the former habitat (Pearse et al., 1970).

Juvenile red sea urchins are frequently found under the spines of larger red urchins, and are scarce elsewhere in the same habitat (Low, 1975; Breen et al., 1976; Tegner and Dayton, 1977; Schroeter, 1978). One possible explanation for

[1]Reuben Lasker, National Marine Fisheries Service, NOAA, La Jolla, Calif. Personal commun.
[2]Katsutoshi Miwa, Tokai Regional Fisheries Research Laboratory, Tokyo, Japan. Personal commun.

this distributional pattern is that larvae selectively settle in areas where adults are abundant, and soon find shelter under the larger sea urchins. This hypothesis was tested and rejected by Cameron and Schroeter (1980), who conducted laboratory and field larval selectivity experiments with red and purple sea urchins. They concluded that the pattern of juvenile distribution was due either to increased survival rates under adults, or to migration of young sea urchins under adults following settlement. Hinegardner (1969, 1975) and Cameron and Hinegardner (1974) found that the larvae of white sea urchins, *Lytechinus anamesus*, selectively settle and metamorphose on bacterial films. These films are ubiquitous (Sheer, 1945) and are probably abundant inside as well as outside kelp beds.

An hypothesis that higher mortality of larvae or juveniles inside versus outside kelp beds accounts for patterns of juvenile abundance remains untested; however, the higher abundance of filter-feeding organisms, known to eat sea urchin larvae, inside kelp beds suggests that predation of larvae may be significant (Pearse et al., 1970).

The importance of predation after settlement is suggested by a number of studies which have identified sea urchin predators that are abundant inside or near the edges of kelp beds. These predators include rock crabs, *Cancer* spp. (MacGinitie and MacGinitie, 1968); leather starfish, *Dermasterias imbricata* (Rosenthal and Chess, 1972); sun stars, *Pycnopodia helianthoides* (Tegner and Dayton, 1981); agile sea stars, *Astrometis sertulifera* (Leighton, 1966); bat stars, *Patiria miniata* (Schroeter et al., 1983); and spiny lobsters, *Panulirus interruptus* (Tegner and Dayton, 1981; Tegner and Levin, 1983). Among fishes, the horn shark, *Heterodontus francisci* (Limbaugh[3]) and wolf-eels, *Anarrhichthys ocellatus* (Bernstein et al., 1981), have been observed to feed on sea urchins. In southern California, however, the most significant fish predator is the California sheephead, *Semicossyphus pulcher* (Quast, 1968; Feder et al., 1974; Tegner and Dayton, 1981; Cowen, 1983).

In and near the boundaries of kelp beds, Tegner and Dayton (1977, 1981) and Tegner and Levin (1983) found bimodal size distributions which they attributed to size-specific predation by spiny lobster and California sheephead. Red sea urchins larger than 80 mm in test diameter are less vulnerable to predators because of their size; those smaller than 50 mm take shelter from predators beneath the spines of adults or in cryptic habitats. Because shelter sites are relatively scarce for urchins between 50 and 80 mm (these animals are too large to hide under larger urchins), they suffer high mortality. The mode of larger sea urchins therefore consists of those survivors which accumulate over time. The other mode is made up primarily of small sea urchins <2 years old.

Although bimodal size distribution (with only very small and large sea urchins being represented) can be explained by size-selective predation in areas where spiny lobsters and sheephead are prevalent, studies over many years by the Kelp Habitat Improvement Project[4] have shown that size distribution can vary markedly in different habitats and over time. Local populations in southern California consisted of all small or all large individuals, and any number of combinations of small, medium, and large individuals (State Water Quality Control Board, 1964; Pearse et al., 1970; Anonymous, 1977). Bernard and Miller (1973) also noted varied size distribution patterns for red sea urchins in British Columbia where major predators of small sea urchins are not so prominent. Progressions in size distribution over time in a particular habitat have been well documented by Pearse et al. (1970) and Ebert (1983) who found that food availability and rates of settlement and survival of juveniles were important in determining distribution patterns.

The rate at which existing populations are replenished and the regularity of this recruitment increase from north to south along the west coast of North America. Annual recruitment rates of red sea urchins were lower and often more variable in British Columbia, Canada (Bernard and Miller, 1973; Breen et al., 1978), than in southern California (Mitchell et al., 1969; Pearse et al., 1970; Tegner and Dayton, 1981; Ebert, 1983). The mechanisms underlying such patterns are poorly understood, but latitudinal gradients in temperature, predation, and disease, or interactions of these factors have been hypothesized (Frank, 1975; Fawcett, 1984).

Two other patterns of distribution and abundance are of interest to those engaged in the red sea urchin fishery. The first is clumping, and the second is possible competitive interactions. We've already noted that red sea urchins are often found in high abundance around the edges of kelp beds (Fig. 2). Rosenthal et al. (1974) found that even within kelp beds where adult sea urchins are comparatively rare, individuals occur in aggregations rather than being randomly or uniformly distributed. Low (1975) noted that red sea urchins in British Columbia often occurred in groups or clumps of 50 or more. Smaller groups, as well as solitary sea urchins, tended to merge with the other groups until this apparently critical number was reached. Low (1975) speculated that clumping may be a mechanism to increase the chances of fertilization, to compete with macroalgae for space, or for protection of adults as well as juveniles from predators.

Interspecific competition between abalones, *Haliotis* spp., and sea urchins is known to affect the distribution and well-being of both groups. Abalones seem to outcompete sea urchins for space (Lowry and Pearse, 1973; Shepherd, 1973), although sea urchins may be more efficient in feeding (Tegner, 1980). In southern California, both groups prefer giant kelp, *Macrocystis pyrifera*, to other seaweeds (Leighton, 1966, 1971), so competition for food is likely to occur. Selective fishing for abalones, both in Australia and, in the past, in California, may have contributed to increases in numbers of urchins (Lowry and Pearse, 1973; Shepherd, 1973). Under present condi-

[3]C. Limbaugh, 1959, personal commun. cited by Leighton (1971).

[4]W. K. Keck Laboratory of Environmental Health Engineering, California Institute of Technology, Los Angeles, Calif.

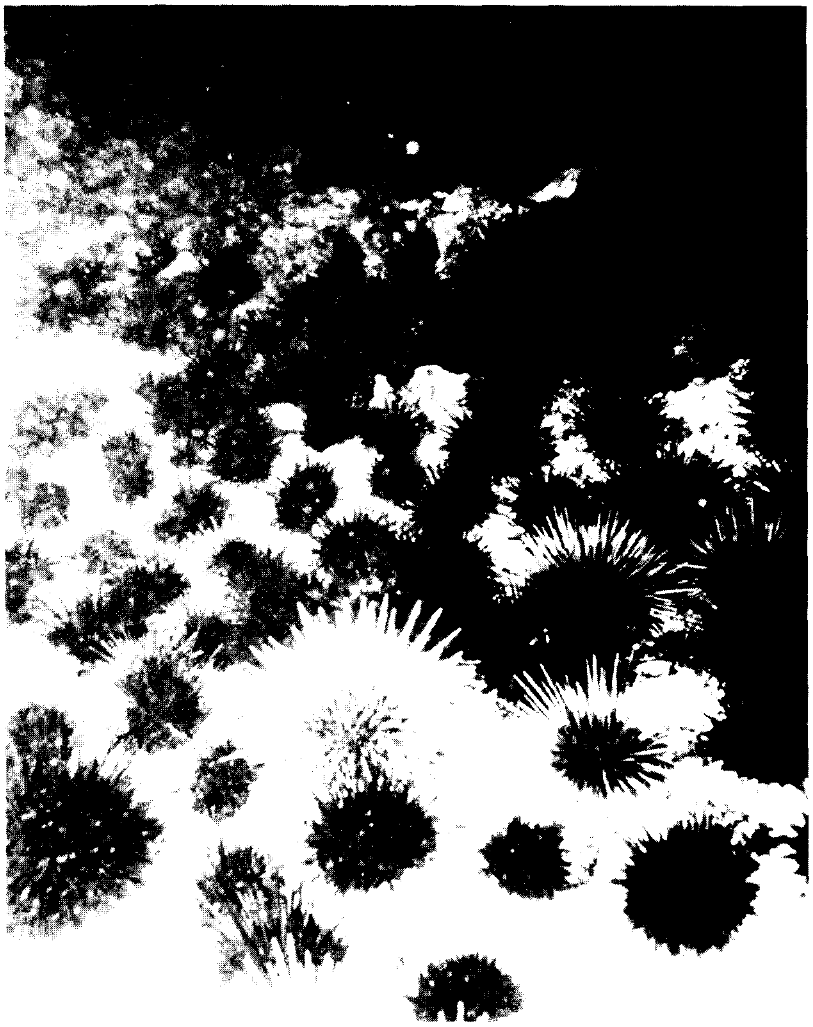

Figure 2.—A group of red sea urchins near kelp beds at Santa Cruz Island, southern California.

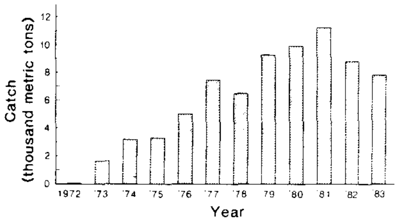

Figure 3.—Annual landings of red sea urchins in California. Source: California Department of Fish and Game.

tions in southern California, however, environmental factors, as well as fishing pressure and predation on sea urchins—rather than on abalones—may be more important than competition in determining distributional patterns and abundance of sea urchins and abalones (Tegner and Levin, 1982).

Schroeter (1978) studied red and purple sea urchins near Santa Barbara, Calif., and at nearby Santa Cruz Island, and concluded that competition for space plays an important role in determining the distribution and abundance of purple sea urchins. The distributions of the two species overlap, but purples dominate in harsh habitats (e.g., mid-intertidal and intertidal, as well as subtidal habitats exposed to waves and surge) while reds dominate in benign habitats (sheltered habitats in the low intertidal and subtidal areas). Purples are more abundant than reds in the harsher habitats because they are more tolerant of physiological stress and wave and surge action. Although purples actually prefer benign to harsh habitats, reds outcompete them there and so reduce their abundance. Because the two species compete, the selective removal of reds by the sea urchin fishery may cause an increase in the abundance of purples in the subtidal habitat. This in fact happened following small-scale experimental removals of reds in the shallow subtidal zone.

Any discussion of sea urchin distribution would be incomplete without inclusion of the effects of predation on sea urchins by sea otters, *Enhydra lutris*. Once almost extinct in California, sea otters now inhabit much of the central California coast, and it is not coincidental that sea urchins are scarce wherever sea otters are present. Sea urchins are among the most common food items of sea otters, and those sea urchins remaining in subtidal waters where otters are present are usually found deep in crevices (McLean, 1962; North, 1965; Leighton, 1966; E. E. Ebert, 1968; Lowry and Pearse, 1973).

No data are available on the abundance of red sea urchins along the California coast, but annual catch totals (Fig. 3) give some measure of harvestable populations. At first glance it would appear that the California fishery reached its harvest potential in 1981, when 11,300 t were landed. The lower catches in 1982 and 1983 may not have been directly related to abundance of sea urchins, however, and the declining catch may not signify that the maximum catch has been attained.

A major climatological event, commonly called "El Niño," occurred in 1982, affecting fisheries throughout the west coast, and indeed the whole Pacific Ocean. Unusually warm water invaded the southern California coast and weakened or killed kelp, the major food of sea urchins. Later in the year, severe storms associated with El Niño finished the job by tearing the weakened kelp from the seafloor[5]. The same storms made it impossible for divers to work in the winter and spring of 1982-83. Too, during much of 1983 the roe yield of red sea urchins was lower than normal, often to the point of making processing uneconomical[6]. The small gonads might also be linked to lower feeding activity. For red sea urchins, feeding rate is greatest at 16°C. The rate declines as the temperature increases (Leighton, 1971). During most of 1982-83 bottom temperatures were significantly above 16°C in red sea urchin habitats (Shelton et al., 1982). Several processors had to close their plants, while others continued operating at lower production levels. Thus, whether or not the southern California populations are presently being fished to their maximum potential is open to question. However, northern California fishing grounds have certainly not been worked to any extent, and expansion of the fishery is likely to occur there when conditions warrant.

Movements and Aggregating Behavior

Patterns of movement and aggregation of red sea urchins are important to fishermen and resource managers, as moving hordes of sea urchins can sometimes decimate large fields of algae (Leighton et al., 1966; Leighton, 1971; Dean et al., 1984). In many cases, however, red sea urchin populations are stationary and highly aggregated where food is abundant; they are less aggregated and move more when food is scarce (Vadas, 1968; Pace, 1975; Russo, 1979; Harrold and Reed, In press). Mattison et al. (1977) found such a pattern and documented differences in rates of movement. Movement of red sea urchins inside a kelp bed where food was abundant averaged about 7.5 cm per day. In comparison, in areas some distance from the kelp bed (15-100 m away) where food was relatively scarce, movement averaged over 50 cm per day. Experimental studies by Lees (1970) in Mission Bay in San Diego, Calif., also showed that food scarcity stimulates the movement of both red and purple sea urchins. On the other hand, Silver and Brierton (1974) found no mixing between two groups of red sea urchins which were located close together in depths of 3 and 11 m, separated by a nearly vertical rock face. The shallow group had an abundant supply of kelp, while the deeper group lived in an area with much less food and devoid of attached kelp.

Reproduction

Knowledge of sea urchin reproductive biology is valuable to those conducting the fishery; the yield of roe is greatest just before spawning when it may reach 20 percent of the total body weight. However, during the peak of reproductive activity, uptake of water by the gonads causes them to exude a great deal of gonadal material (Miller and Mann, 1973), and the roe has low marketability. Thus, the best quality roe is found just before the onset of proliferation of sex cells and before the mature gonads absorb water. After spawning, the gonads are small and the yield is too low for economic use, being 50 percent or less of the peak yield (Kramer and Nordin, 1975).

Increase in gonad size is actually related to feeding, rather than to some intrinsic reproductive cycle, and to storage of glycogen (a carbohydrate) in the gonads (Giese et al., 1958). Bernard (1977) explained the somewhat complicated processes that occur during the development of mature gametes, and concluded that food availability is the key to synchronization of the reproductive cycle in red sea urchins. The reproductive events of sea urchins follow a more or less annual cycle, but there are significant and interesting variations in the pattern.

The spawning season of red sea urchins appears to vary depending on locality and sometimes even from year to year at the same place. In various coastal localities from Papalote Bay, Mexico (near central Baja California), to Whites Point, Calif. (near Los Angeles), Pearse et al. (1970) found indications of spawning between June and November. Most of the populations showed no large increases in gonad size prior to spawning, and the gonad weight was usually less than 10 percent of the body weight. In these populations the gonads underwent a sharp decrease in weight during some time of the year, however, indicating that the populations had spawned. An exception was the population at Point Loma, in San Diego, Calif., which maintained large gonads throughout the year (March 1969-March 1970) and failed to show the marked decrease in gonad size which accompanies spawning. This population was thought to spawn throughout the year. The Point Loma population was the only one of those studied that existed in an area with abundant food.

Baker (1973) also studied red sea urchins at Point Loma in 1972-73 and found a similar lack of a well-defined period in which the decreased gonad weight indicated spawning. On the other hand, he found a lower gonad weight during summer in populations inhabiting nearby Mission Bay. Evidently the populations at the two areas were in different physiological condition; gonads of Point Loma sea urchins averaged 11.58-15.71 percent of the total weight of the sea urchin throughout the year, while those from Mission Bay sea urchins averaged 8.60-10.75 percent. Bennett and Giese (1955) found a late spring-early summer spawning season in central California; workers in Canada detected possible spawning periods from spring to fall (Bernard and Miller, 1973; Kramer and Nordin, 1975, 1979; Bernard, 1977).

A measurement commonly used to estimate a sea urchin's reproductive state on a gross (nonmicroscopic) level is the "gonad index." The index, a relative measure of gonad size, is simply the ratio (expressed as a percentage) of the gonad weight or volume to the total weight or volume of the sea urchin. An abrupt loss of gonadal bulk evidenced by a decline in the gonad index indicates that spawning has taken place.

To determine the reproductive condition of red sea urchins harvested by the

[5]Ron McPeak, Kelco Co., San Diego, Calif. Personal commun.
[6]Neal Matsushita, S/M Uni Co., Los Angeles, Calif. Personal commun.

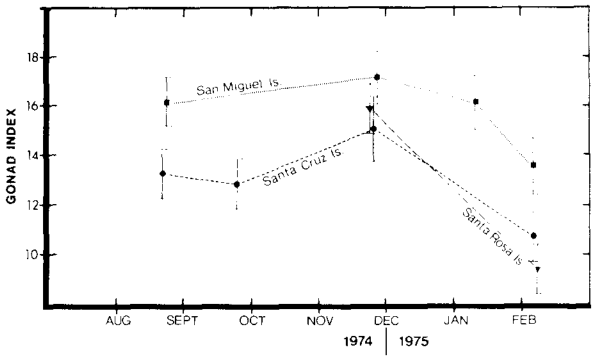

Figure 4.—Means and standard error for gonad indices of commercially caught red sea urchins (percent gonad weight of total weight of drained sea urchins).

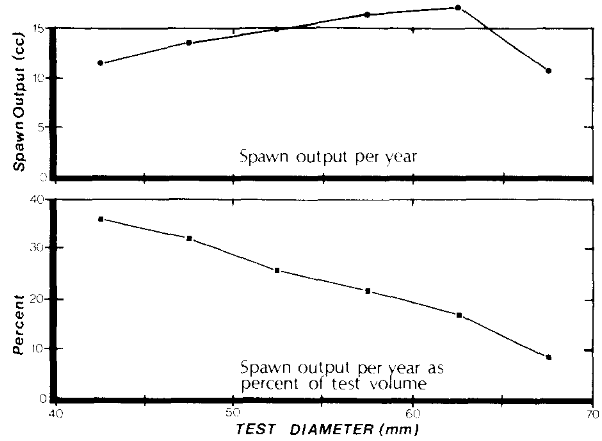

Figure 5.—Spawn output related to test diameter for the white sea urchin, *Lytechinus variegatus* (after Moore et al., 1963).

fishery, we calculated gonad indices (100 × gonad weight ÷ drained body weight) of red sea urchins harvested in 1974-75 by commercial divers from the northern Channel Islands (Santa Cruz, Santa Rosa, and San Miguel Islands). When these samples were taken, spawning was fairly synchronous among the different sites. The gonad indices were high from August to December, but they dropped from December to February (Fig. 4), thus indicating spawning during the latter period.

It should be noted that our samples were not representative of the whole population because spawned-out animals are usually not collected by divers; thus, on the whole, harvested sea urchins are likely to have a higher gonad index than the general population. Even with this bias toward higher indices, the results clearly indicate a discrete spawning period lasting at least from December through January. Red sea urchins that we sampled from commercial landings in 1976 in northern California (Fort Bragg) (unpubl. data) also indicated a winter-to-spring spawning period.

The maximum gonad size attained differs not only from locality to locality (Leighton, 1967; Pearse et al, 1970; present study, Fig. 4), but also from year to year at the same locality (Bennett and Giese, 1955). The causes of this variability have yet to be determined, but according to several sea urchin divers, differences in food supply may be most important. Divers often report that sea urchins near lush algal stands have much larger gonads than individuals located several meters away where algae are scarce or absent. Others have also noted the importance of food to the growth of gonads, which are not only reproductive organs, but also sites for food storage (Giese et al., 1958; Bernard, 1977; Dean et al., 1984).

The amount of gametes produced (usually measured by size of gonads) may not be directly correlated with size or age of the urchins. Bernard and Miller (1973) indicated that red sea urchins in British Columbia probably first spawn at age 2 at around 50 mm test diameter. We were able to induce spawning in red sea urchins as small as 40 mm at Santa Cruz Island. The production of gametes by these tiny individuals is, of course, very low.

Bernard (1977) found that the ratio of gonad weight to shell diameter increases with size, until red sea urchins attain 95 mm; the ratio then decreases slightly. Moore et al. (1963) found similar results in their study of the east coast's white sea urchin, *Lytechinus variegatus*. The total spawn output (Fig. 5, above) was greatest for large sea urchins (but not the largest size class), but smaller sea urchins were relatively more productive when spawn output was expressed as a percentage of test volume (Fig. 5, below). Thus, to assess the spawning potential of a sea urchin population, one must know the relative abundance of different sized sea urchins, as well as the amount of spawn produced by individuals in the size range.

Another reproductive process important to the sea urchin fishery is the length of time it takes for gonads to regain their bulk after spawning. Data we obtained from a commercial sea urchin processing firm in 1975-76 indicate a rather protracted recovery period lasting from spring to early summer, after the sea urchins had spawned from December through February or March. On the other hand, Bernard (1977) found that in British Columbia the gonad index of red sea urchins returned to 80 percent of maximal levels by October, only 1 month after spawning. The gonads attained their greatest size several months later in May. Kramer and Nordin (1975), however, found an intermediate interval of time between spawning and recovery in their study of British Columbia red sea urchins. The differences may be due to the amount of food available in the respective habitats.

Development and Growth

Development of red sea urchins from fertilization through various free-swimming larval stages to settling of the juvenile takes about 6-8 weeks, depending primarily on water temperature (Johnson, 1930). Depending on a host of environmental and genetic factors, young sea urchins can grow to sexual maturity between 1 and 2 years after they settle on the bottom (Bernard and Miller, 1973; Tegner[7]).

Marks on hard parts have commonly been used to study the age of animals. In sea urchins, rings similar to those found in tree trunks can be seen in the spines, and growth lines or zones also occur in the plates that make up the test. Both have been used to ascertain the age of certain species (Jensen, 1969; Pearse and Pearse, 1975). Detailed studies of the formation of growth zones in the tests of purple sea urchins have disclosed, however, that rings or zones do not necessarily correlate with seasonal phenomena, and are thus not useful for indicating age (Pearse and Pearse, 1975). Breen and Adkins (1976) reported similar negative results for red sea urchins, and our attempts using Jensen's (1969) methods failed to find reliable age indicators in the test plates.

Growth of red sea urchins, measured by increases in test diameter, has been studied in the laboratory (Leighton, 1967, 1971), in cages in the field (Swan, 1961; Schroeter, 1978), and with uncaged field populations (Baker, 1973; Bernard and Miller, 1973). The studies indicated an annual growth increment of 13-25 mm, with smaller individuals showing faster gains in test diameter, as expected. Thus, on the average, red sea urchins probably attain harvestable size (90-100 mm) in around 4-5 years.

Many factors affect growth rates of sea urchins and the maximum size attained by individuals in a local population. These include availability and nutritional value of algae, competition, temperature, and the severity of wave and surge action (Bennett and Giese, 1955; Swan, 1961; Ebert, 1967, 1968; Leighton, 1971; Baker, 1973; Schroeter, 1978).

Food and Feeding

Although red sea urchins feed on many species of algae, they clearly prefer the giant kelp, *Macrocystis* spp., when it is available (Leighton, 1966, 1971). Off the coasts of Washington and British Columbia, red sea urchins prefer the bull kelp, *Nereocystis leutkeana* (Vadas, 1968, 1977).

As one might expect, diets consisting of preferred foods result in much higher growth rates (Leighton, 1971; Vadas, 1968, 1977). A striking demonstration of this phenomenon can be found in southern California, where locally dense populations of red sea urchins eliminated all fleshy algae, forcing individuals to feed on less preferred and nutritionally inferior encrusting coralline algae (e.g., *Lithothamnion* spp. and *Bosiella* spp.). Sea urchins in such areas typically have only the rudiments of gonads and appear to be starved (State Water Quality Control Board, 1964).

Plankton, as well as organic suspensions produced by sewage outfalls, are also utilized by sea urchins. In fact, the latter source seems to have relatively high nutritional value, and may be the primary factor responsible for persistence of dense sea urchin populations even after they have overgrazed and eliminated their normal algal food source (Pearse et al., 1970). Finally, when food is scarce or absent, sea urchins can derive energy necessary for maintenance by resorbing their gonadal and gut tissues.

Feeding rates of red sea urchins are influenced by temperature. The optimum feeding temperature is about 16°C, and red sea urchins feed as long as the temperature remains between 6° and 25°C. In southern California, at depths where red sea urchins are most abundant, bottom temperatures are generally higher and nearer the 16°C optimum in winter than in the summer (Leighton, 1971).

Ecology and Management

As noted above, grazing by red sea urchins has a profound influence on the types of algae that ultimately dominate a particular habitat. This is because sea urchins prefer to eat certain species, thereby leading to the dominance of the less preferred species. In some cases, the less preferred species are poor competitors, and owe their persistence in the community to the grazing activity of sea urchins. Experimental removal of sea urchins often results in local competitive elimination of the less preferred species of algae (Vadas, 1968; Paine and Vadas, 1969; Palmisano, 1975; Pearse and Hines, 1979; Duggins, 1980).

The influence of sea urchin grazing on giant kelp in southern California has received a great deal of attention, since sea urchins have been held responsible for the widespread disappearance of this economically and environmentally valuable species (North and Pearse, 1970; Leighton, 1971; North, 1974). Researchers from the California Department of Fish and Game, Scripps Institution of Oceanography, California Institute of Technology, and Kelco[8] (a commercial kelp harvesting firm), and groups of recreational divers have worked on the restoration of kelp beds for over 20 years. Almost without exception, attempts to restore kelp forests have started with the eradication of sea urchins, and successful results of some of these efforts seem to demonstrate that sea urchin grazing is a principal reason for failure of giant kelp to become reestablished in certain habitats (North, 1974). Of course, other factors such as competing vegetation, other grazers, and adverse environmental conditions also act to hold down kelp growth (Wilson et al., 1978).

In areas where the standing crop of algae is well established, sea urchin presence is not necessarily detrimental to the plant community (Rosenthal et al., 1974), and removal of large numbers of sea urchins may not affect the algal abundance or distribution (Breen et al., 1978).

From the point of view of those favoring kelp propagation, it is clear that reduction in numbers of red sea urchins would be beneficial. Indeed it has even been suggested that sea otters be reintroduced into southern California for this purpose. It would seem, however, that the commercial fishery is a more satisfying means of controlling growth

[7]Scripps Institution of Oceanography, La Jolla, Calif. Personal commun.

[8]Mention of trade name or commercial firms does not imply endorsement by the authors or by the National Marine Fisheries Service, NOAA.

in populations of red sea urchins, which are valuable renewable natural resources. The fishery brings income to the industry as well as helping in some measure to lower our deficit in the balance of trade of seafood products. On the other hand, selective removal of red sea urchins may allow growth in the population of purple sea urchins, which can also cause overgrazing when large numbers are present. These two species overlap to a great degree (except at the shallow end of the range), and their food preferences are similar.

To maintain a long-term fishery, some management measures may need to be instituted, for it is clear from studies by Canadian researchers that recovery of exploited red sea urchin populations is a slow process (Breen et al., 1978). In the absence of regulations, divers should take it upon themselves to ensure that enough large sea urchins are left in harvest areas to support recruitment of young urchins, which need the protection afforded by the spines of larger individuals. Perhaps a maximum size limit would help in this regard.

Most persons involved in the California fishery feel that management is called for to prevent damage to sea urchin stocks. One management option favored by many divers, according to two polls, is a limit on the number of persons allowed to fish for sea urchins[9]. Some processors we interviewed also felt that economic returns should be considered in any management scheme. For example, they advocate closure of the fishery during spawning season when the roe is soft and unappealing, and until the gonads recover to near maximum bulk.

Since the precise time of spawning may vary from year to year and at different locations, however, it would be unwise to set prescribed open and closed seasons. Obviously, divers and processors have the best and earliest knowledge of these events when they occur, and it behooves them to work together to stop fishing in areas where gonad quality and quantity are low. Another period of marginal profitability is during spring and early summer when the roe yield is still rather low, as are the prices in Japan. However, market conditions do vary, and in some years it has been profitable to export roe even in summer.

Not all processors and fishermen advocate long seasonal closures of the fishery. They point to the difficulty of keeping key personnel during the off-season, or counting on their return when processing resumes, and also to the fact that some good sea urchins can be found throughout the year. Those firms that supply the domestic market especially need to operate throughout the year or chance the loss of their markets to imports.

The State of Washington has a rather simple management system, whereby the coast is divided into three zones, one of which is closed to sea urchin fishing each year to foster repopulation[10]. In Japan, seasonal, depth, and gear restrictions are all used to help ensure against overfishing, and habitat improvement programs are also employed to encourage settlement and growth of sea urchins (Mottet, 1976).

In the absence of State-mandated fishery regulations, members of the California industry might well impose self-regulatory measures to ensure the future of the fishery. The collapse of the sea urchin fishery in northwest France in the 1960's (Southward and Southward, 1975) should serve as amble reminder to all that sea urchins are susceptible to overfishing, and the authors pointed out that sea urchins are important for maintaining a balance in the ecosystem. They plead: "The lowly sea urchin is strongly in need of friends to come to its rescue."

History of the Fishery

In the 1960's, a few individuals harvested small numbers of sea urchins for home consumption and for the domestic market in California. With increasing numbers of Japanese restaurants opening in the United States to serve the growing Japanese business communities in the financial centers—New York, Chicago, Los Angeles, San Francisco—the demand for exotic (at least to conventional American tastes) fish products increased. Much of the fare served in these restaurants was traditional Japanese, including raw fish and shellfish, fish eggs (including uni, or sea urchin roe), eels, jellyfish, and the like. Since many of these were not readily available in the United States, they were imported from Japan. And, owing to the high cost of air freight, most of these items were transported by ship in the frozen state which, although unacceptable in Japan, was the only form available in the United States.

In 1968, the NMFS Southwest Fisheries Center started looking into the feasibility of developing a sea urchin fishery to supply the growing domestic markets and for export to Japan. The decision to try to initiate a fishery was prompted not only by the demand for the product, but also because sea urchins were considered pests by kelp harvesters, recreational fishermen, and the abalone industry. In fact, groups of sport divers regularly held organized "urchin kills," whereby divers armed with hammers would smash any and all sea urchins found in selected habitats. Quicklime (calcium oxide) was also used to control sea urchins in commercial kelp beds. Now, however, state regulations prohibit the use of quicklime because of strong objections by sea urchin divers and other fishermen.

Since the processing of sea urchins requires a large number of low-skilled workers, a new fishery also offered increased employment opportunities for such workers. Other advantages of a sea urchin fishery included reduction in fishing pressure on abalone, possible improvement in the habitat for abalone and other invertebrates and fishes that depend on seaweed for shelter or food, and lowered deficit in the U.S. international seafood trade.

In the early phases of development in 1972, we sent trial shipments of frozen roe to Japan, the principal market. Because the defrosted roe became soft and unappealing due to cell rupture, no interest was shown by the Japanese market for the frozen product. Since the prevail-

[9]David Parker, California Department of Fish and Game, Long Beach, Calif. Personal commun.

[10]Richard Burge, Washington Department of Fisheries, Shellfish Laboratory, Brinnon, Wash. Personal commun.

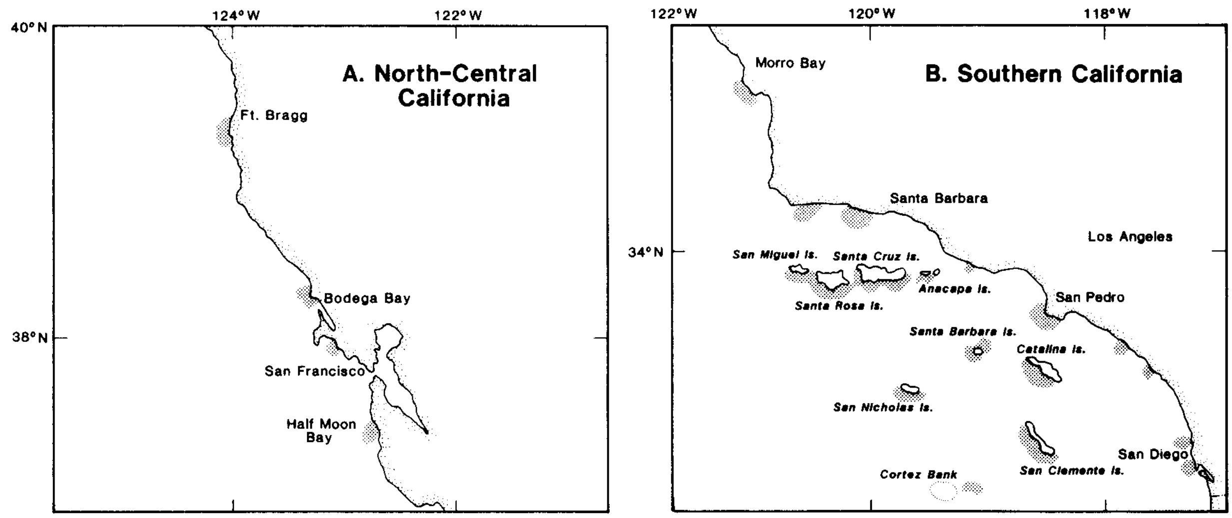

Figure 6.—Major California fishing grounds (shaded) for red sea urchins.

ing monetary climate prohibited air freight of fresh roe to Japan, we decided to concentrate on supplying the domestic market while experimenting with means of preserving the roe in better condition. First, we had to experiment with processing methods since we were unable to find descriptions in the literature. Time and motion studies and cost analyses were carried out in a pilot operation at Avila Beach, Calif., to determine if the business had potential profitability. All studies indicated good potential, especially if initial investment was low (Kato, 1972). In 1972 a trip to Japan by the senior author provided detailed information on the processing and marketing of sea urchin roe and contacts with potential buyers. This new information, and the right monetary conditions (the Japanese yen had just been raised in value relative to the dollar by 25 percent), convinced a Los Angeles processor to open the first major sea urchin processing plant in late 1972. A technician from Japan was hired by the firm to provide processing expertise in handling fresh roe, and the industry was underway.

Since its inception in 1972, the fishery has grown steadily to become one of the leading fisheries in California. Annual landings increased to 11,000 t in 1981, but declined somewhat in the next 2 years. The following sections describe the harvesting, processing, and marketing sectors of the California sea urchin fishery.

Harvesting

The bulk of the California sea urchin catch comes from the northern Channel Islands (Fig. 6) off the southern California coast. Anacapa and Santa Cruz Islands were formerly the areas of highest production, but presently San Miguel, Santa Rosa, San Nicolas, and Santa Barbara Islands produce most of the catch. Divers are forced to seek new localities as sea urchin density becomes too low for economic harvesting, or when the quality and quantity of roe fall below acceptable levels. Santa Catalina and San Clemente Islands, as well as Cortez Bank, have also provided some sea urchins, as have many localities along the mainland coast from San Diego to Fort Bragg. The relative amounts landed in various regions in California are shown in Table 2. The fishery now appears to be harvesting those sea urchins that have reached marketable size in areas previously exploited.

Table 2.—Annual California landing of sea urchin by district (percent of total landings).

Year	Eureka[1]	San Francisco	Monterey	Santa Barbara	San Pedro	San Diego
1973	<1	<1	<1	96	4	<1
1974	<1	<1	<1	97	1	1
1975	<1	<1	<1	95	3	2
1976	<1	<1	<1	94	1.3	4
1977	2	<1	<1	78	10	9
1978	<1	<1	<1	70	19	11
1979	1	<1	<1	76	18	5
1980[2]						
1981	<1	<1	<1	71	16	12
1982	<1	<1	<1	74	15	10
1983	<1	<1	<1	72	18	10

[1]Most of these landings were made at Fort Bragg and Albion.
[2]Statistics for 1980 were not available.

Vessels and diving gear in the sea urchin fishery are similar to those used by the abalone fishery. All harvesting is done by divers using conventional "hookah" gear, i.e., a low-pressure air compressor connected to a reservoir which feeds air through a hose to a faceplate. The compressor is usually rated at 80-125 p.s.i., and most can accomodate up to three divers. Divers wear 6-10 mm thick rubber "wet suits" or thinner "dry suits" to ward off the cold.

The most popular diving boats are

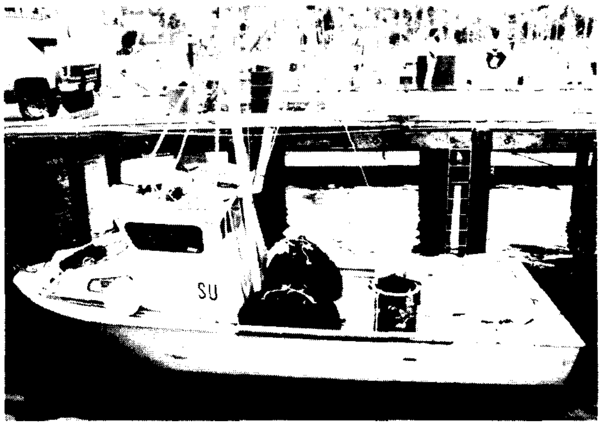

Figure 7.—A 9.1 m (30 foot) Wilson drive boat; note the two large mesh bags full of sea urchins.

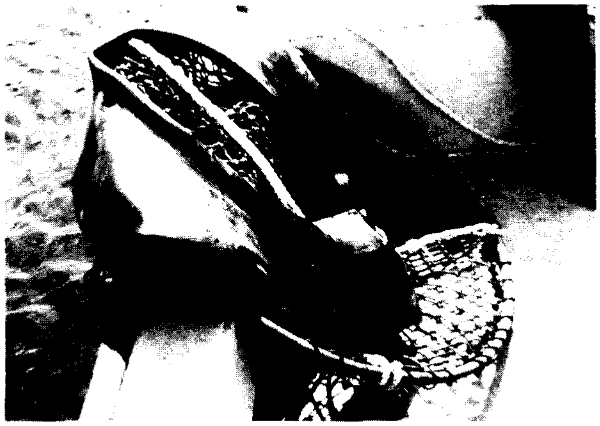

Figure 8.—Sea urchin collecting bag with rubber tube.

made by Radon and Wilson (Fig. 7). The vessels are made of fiberglass, usually around 8-9 m long, and powered with diesel engines. The carrying capacity is 1.5-3 tons. The chief criterion, besides adequate carrying capacity, appears to be speed, which is important because some of the fishing grounds are a considerable distance from port. Most sea urchin boats can cruise at 15-20 knots. In the past, vessels with large capacity, such as albacore trollers, were used as carriers for transporting sea urchins from the fishing grounds to dockside. Some divers operate by themselves, while those in larger vessels usually work in pairs or threes. All the divers on a boat may be in the water at the sime time, or one may act as a tender, loading the catch into the boat. Major home ports of the sea urchin diving boats are Santa Barbara, Oxnard, Port Hueneme, and San Pedro.

Diving operations begin with preliminary searches for concentrations of sea urchins. After finding an area with adequate numbers, the diver cracks open a few sea urchins to check the quality of roe. If satisfactory, harvesting begins. Most divers have their own methods for collecting sea urchins. One effective method is to use a short-handled rake to dislodge sea urchins and scoop them into a small collecting bag or wire cage. As this is filled, the sea urchins are transferred underwater into a larger mesh bag, about 2 m long, with a 1.4 m ring opening (Fig. 8).

After the first batch of sea urchins is transferred, air is pumped from the breathing apparatus into a rubber tube attached to the ring. This causes the ring to rise, and the bag is maintained at a convenient height, anchored by the weight of the sea urchins. As the bag is filled with more sea urchins, additional air is put into the tube to increase the height of the bag. When the collecting bag is completely filled with 50-70 kg of sea urchins, the tube is filled with enough air to float the bag to the surface. A line attached to the boat keeps the bag from drifting away[11]. This method is especially useful for single-diver operations. Boats with tenders (or diver-tenders) often store collected sea urchins in large cargo nets, which facilitates unloading (Fig. 9).

All harvesting is currently done by hand, although an airlift system was tested by one firm, with reported success. In our own experiments, we successfully pumped red sea urchins through a 25 cm hose from depths of 15 m, but we found it difficult to get enough force with an airlift system at shallower depths. Further, we found the hose too cumbersome and impractical to use in areas of dense kelp.

[11]Jerome Betts, commercial sea urchin diver, Lompoc, Calif. Personal commun.

Because of the hard physical labor, cold water, and pressure, divers are forced to surface often to rest, and actual diving time is restricted to a few hours (usually 3-4) per day. Weather conditions and other factors further limit a diver's fishing time to around 80 days per year. Although most divers make daily fishing trips, some with large vessels make 2-day trips. On these occasions, collected sea urchins are kept in mesh bags underwater in sheltered spots until the trip home.

Divers were interviewed periodically between July 1974 and February 1975, and again in January and February 1977 to get catch data. These divers fished at the Channel Islands and at mainland sites just north of Santa Barbara. Data thus obtained revealed that catch rates did not change significantly during the two periods (Table 3). Boats with a single diver averaged around 250 kg/hour during both periods, and diving

Table 3.—Comparison of catch per day by single-diver boats during two periods.

Item	July 1974-Aug. 1975 N = 38	Jan.-Feb. 1977 N =12
Average catch per day (kg)	918	922
Average time spent underwater (hours)	3.4	3.7
Average catch per hour underwater (kg/hour)	269	249

time averaged about 3.5 hours per day. Data from 48 deliveries made by single-diver boats (including the 38 in Table 3) and 16 deliveries by two-diver boats showed that the latter were somewhat more productive. The single-diver boats averaged 986 kg/day while the two-diver boats averaged 2,258 kg/d (or 1,129 kg/diver). In 1983 the average catch for single-diver boats was lower, probably on the order of 780-900 kg/day[11]. In some areas, such as near San Diego, the daily catch is usually even lower.

The average depth fished during 1974-75 was 8.2 m (range 4.0-15.2 m). Most divers interviewed recently reported diving a bit deeper on the average.

The number of boats engaged in the fishery varies considerably by year. During the peak year of 1981, 271 boats reported sea urchin landings. Of these, 42 boats (15 percent) landed 56 percent of the total catch, and 85 boats landed 85 percent[9].

In port the catch is weighed and loaded directly into waiting trucks which haul the sea urchins to processing plants. The unloading booms are usually equipped with scales to weigh the catch. Some divers sell their catch through a "middleman" who handles unloading and transport, as well as market orders and dispatching boats.

The average size of red sea urchins changes with harvesting intensity, becoming progressively smaller with time. At times, however, the size increases (Fig. 10, Santa Rosa and Santa Cruz) rather than declining. This can probably be explained by the movement of divers into deeper waters as the number of large sea urchins decreases in shallower depths. Thus, a longer sampling period would probably have shown a second decrease in the size of the sea urchins harvested from the same area, as indicated by the San Miguel Island sea urchins (Fig. 10).

The mean test diameter of red sea urchins sampled from the commercial landings at Santa Barbara from July 1974 to February 1975 was 108 mm (95 percent measured 102-114 mm and 99 percent measured 100-116 mm). Recently, however, the average size has been considerably lower; the diameter of 27 red sea urchins measured at a processing plant in October 1983 averaged 87 mm. All processors interviewed at that time agree that the size has decreased considerably.

Those wishing to harvest sea urchins in California must obtain a commercial fishing license ($40). A revocable sea urchin fishing permit is also now required under a State law enacted in 1984. All vessels used in commercial fishing operations require a certificate of boat registration ($125). These fees are assessed each license year (1 April-31 March).

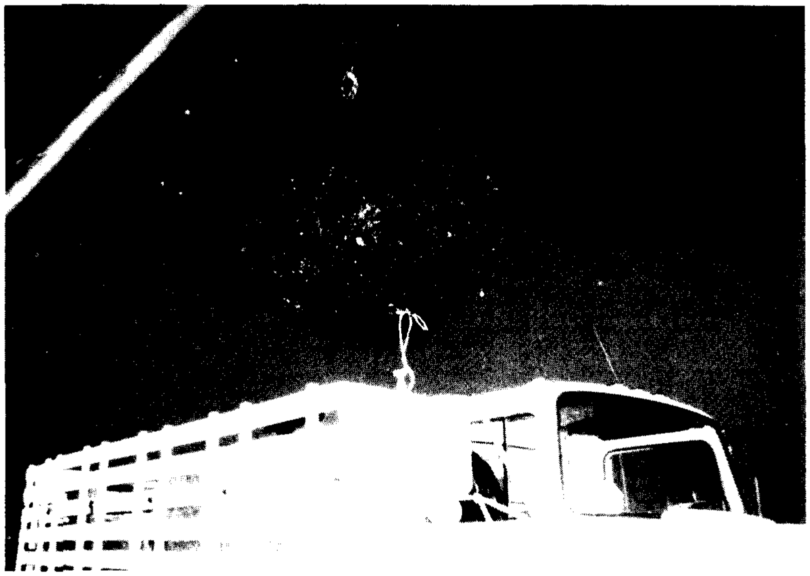

Figure 9.—Sea urchins retained in cargo nets on dive boats are easily and quickly unloaded into trucks.

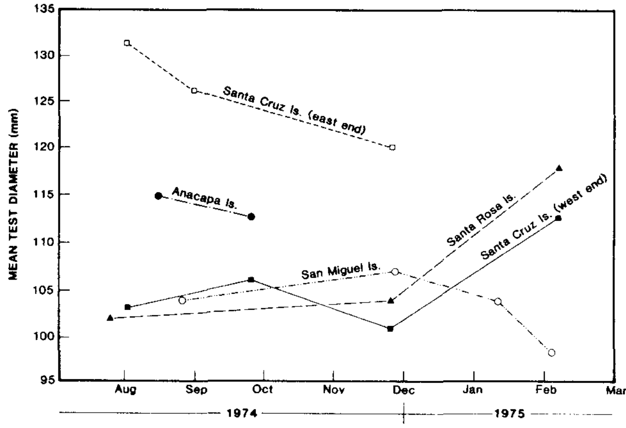

Figure 10.—Mean test diameter of red sea urchins taken by the commercial fishery at the northern Channel Islands in 1974-75.

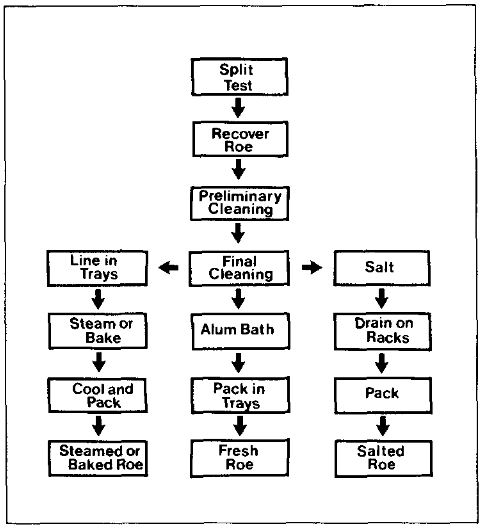

Figure 11.—Flow diagram of sea urchin processing steps. Frozen roe is treated similarly to fresh roe.

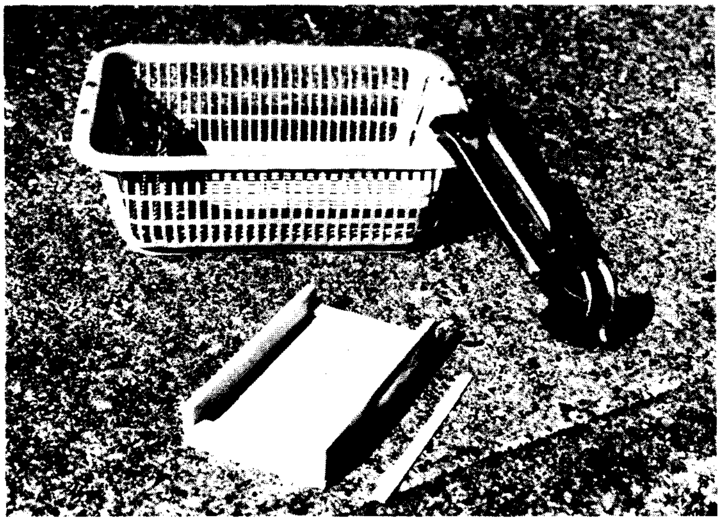

Figure 12.—Some tools of the trade: Stackable plastic strainer for cleaning roe, metal shell-cracking device, wood tray for packing roe.

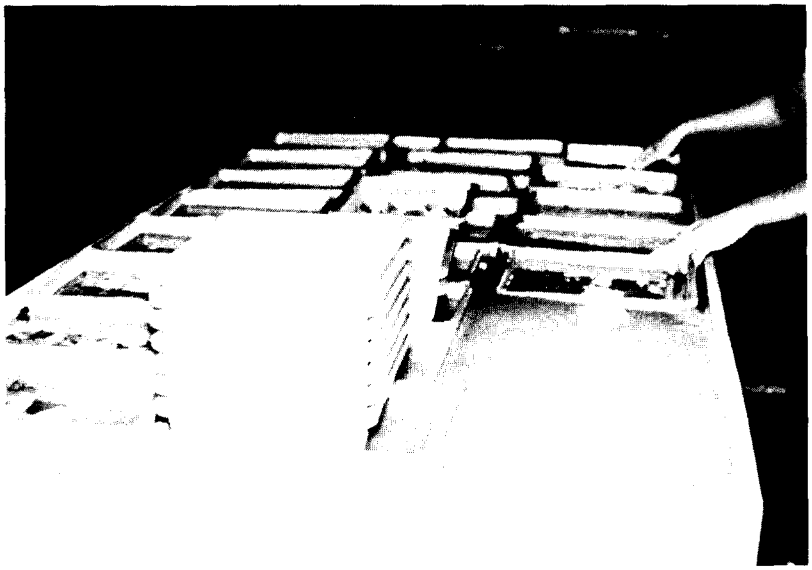

Figure 13.—Sea urchin roe becomes firm when soaked in a saltwater solution containing alum.

Processing

Sea urchin processing has not changed appreciably since the earlier report of Kato (1972). Because the product is now primarily sold fresh rather than frozen, however, packing methods are different, and a chemical treatment is used to improve the appearance of the roe. Only a small amount of roe is salted, steamed, baked, or frozen.

Sea urchins delivered to processing plants in the evening are kept overnight. During warm weather, sea urchins must be stored in refrigerated rooms. Sea urchins kept at 2°C for 1.5 days stay alive, but the roe is noticeably softer and darker (Kramer and Nordin, 1979). Processing consists of several steps which readily lend themselves to an assembly-line operation (Fig. 11). The test is split with a cleaver or a special tool (Fig. 12). The instrument's tip is forcibly inserted into the top of the shell, which is cracked open when the handles are squeezed, forcing the flat blades outward. The roe is removed with a spoon and placed in plastic strainers, then rinsed in cold saltwater to remove viscera and extraneous matter. Final cleaning of attached membranes is done with tweezers or small forks. From this point, processing methods depend on the type of product. The Japanese name is given for each of the products described here.

1) Fresh roe (uni or nama uni):

A) The roe is placed in stackable plastic strainers.

B) The strainers are placed in tanks containing a solution of anhydrous potassium alum, $KAl(SO_4)_2$, in cold

Figure 14.—Roe is drained thoroughly before packing; a layer of cloth helps absorb moisture.

saltwater until the roe becomes firm (Fig. 13). Concentrations used vary from 0.4-0.7 percent, and soak times vary from 15 minutes to 1 hour.

C) The roe is then drained (Fig. 14) and packed in small wood trays. At least 250 g, and up to 280 g, of roe are packed in a standard tray (Fig. 15). A medium-sized tray containing around 170 g is gaining in popularity, however. Occasionally, smaller trays holding 100, 50, or 30 g are also used. The standard trays measure about 9 cm × 16 cm × 1.3 cm deep (inside

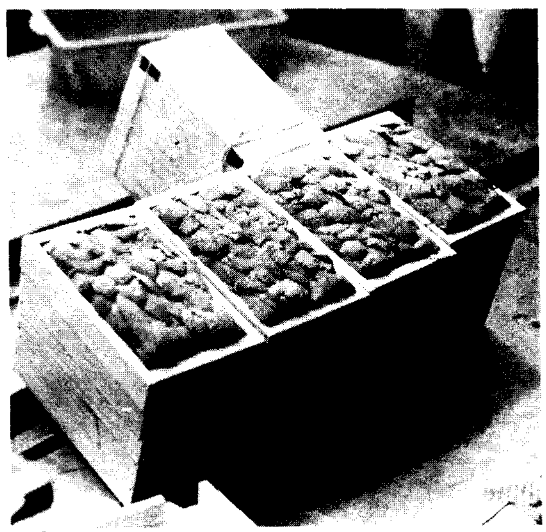

Figure 15.—Wood trays, each packed with around 250 g of red sea urchin roe.

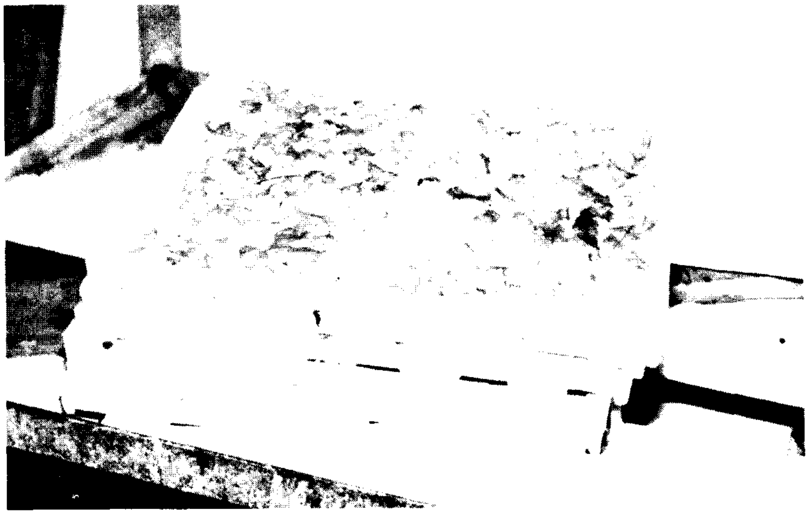

Figure 16.—Roe bulk-packed in foam trays. This roe will probably be used in salted or cooked products.

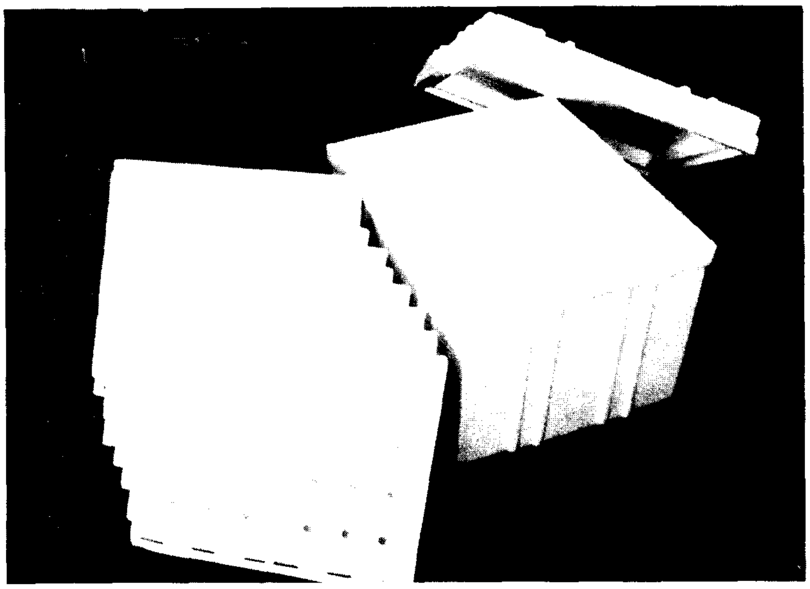

Figure 17.—Insulated master carton used to ship sea urchin roe packed in wood or foam trays. Source of cartons: Plasti Personalities, 1214 W. 252nd St., Harbor City, CA 90710.

dimensions) and cost about $0.30 each.

D) Alternately, the drained roe is bulk-packed in larger perforated foam trays, 32 cm × 40 cm × 2 cm deep (Fig. 16), sometimes lined with absorbent cloth to prevent sliding and damaging of roe in transit. Only one layer of roe is packed in a tray. These trays normally hold about 1 kg of roe.

E) The wood trays are tied in bundles of 8 to 13 trays, with a wooden cover over the top. These are placed in a plastic bag and the roe is allowed to drain further in a refrigerator. It is important that the roe not be exposed to drafts while draining.

F) Just prior to shipment, the trays are placed in insulated master cartons (Fig. 17), each holding 50-54 trays. The bulk-pack foam trays are also stacked and placed in insulated master cartons with about 8-9 trays in each carton. Artificial coolant (commonly called "jelly ice") is added prior to shipment (about 1.4 kg per carton in winter and twice as much in summer).

2) Salted roe (shio uni): Methods of salting vary, depending on the requirements of buyers. Generally, the steps are as follows.

A) Layers of cheesecloth are placed on a wire rack.

B) A layer of roe is placed on the cheesecloth and covered thoroughly with salt; about 25 percent salt to weight of roe is used.

C) More layers of roe and salt are placed on the rack, sometimes with cheesecloth between layers, until the thickness reaches about 5 cm.

D) The roe is allowed to drain for several hours or overnight; about 40-50 percent of moisture is removed, and salt uptake is 10-15 percent.

E) The salted roe is packed in plastic-lined wooden kegs or plastic containers, sometimes with the addition of 10 percent by weight of ethyl alcohol (95 percent).

Recently a new type of shio uni has been produced using less salt but requiring freezing for preservation. This product apparently brings a high price if good quality roe is used[12].

3) Steamed roe (mushi uni):

A) Fresh roe is placed in wood or screen containers of various sizes.

B) The containers are stacked and

[12]K. Yanagita, California Uni Co., Los Angeles, Calif. Personal commun.

Figure 18.—Showcase in a sushi shop. A wood tray filled with red sea urchin roe is seen to the left; two pieces of "uni sushi" are on the counter on the right.

placed in a large steamer.

C) The roe is steamed for about 30 minutes; about 20-30 percent of moisture is removed during the process. Some processors steam roe under pressure, reducing cooking time to 15 minutes or less.

D) The roe is bulk-packed or packed in small wooden or plastic trays, and frozen.

4) Baked roe (yaki uni):

A) Fresh roe is placed in shallow oven-proof dishes.

B) The roe is baked in an oven at 190°C for 30 minutes. About 30-40 percent of moisture is removed in the process.

C) The cooked roe is then packed in small wooden trays (around 30 g) or in plastic imitation "scallop shells" and frozen.

5) Frozen roe (reito uni):

A) Fresh roe of good quality is packed in standard wood trays or bulk plastic trays.

B) The trays are stacked and inserted in a plastic bag, then frozen at −17°C.

C) The frozen roe, still in the plastic bag, is stored in insulated master cartons in the freezer.

This method is used when the product is to be sold later as raw-thawed sea urchin roe, and only good roe is acceptable. If the roe is destined to be salted or processed further, second-grade roe may be used, and it is often simply placed in plastic bags and frozen in bulk.

California firms have experimented with other processing methods in attempts to service specialty markets. Two such items produced were canned roe and freeze-dried roe. In addition, sea urchin roe has been used as feed for aquarium animals, particularly for sea anemones and other invertebrates.

The best quality roe is reserved for the fresh product, which brings the best prices. Secondary products are made from broken roe, or roe that is off-color, too large, or leaking fluids excessively. Salted roe is usually produced in the summer, when the price of fresh roe is low in Japan.

Because appearance is important to the Japanese, who are said to "eat with their eyes," the packing process is critical. In Japan as well as in the United States, most of the roe is bought by "sushi" shops, which are Japanese seafood restaurants specializing in fresh seafood. Customers in sushi shops usually sit at a counter in front of refrigerated showcases which contain many seafoods, mostly raw, in plain view (Fig. 18). Sea urchin roe is displayed in the same wooden trays used by the processor. To maintain good appearance, broken pieces of roe are placed on the bottom, and only whole, firm roe is placed on the top layers of wood trays. The best size is 40-50 mm, but California sea urchin roe is usually larger. Skeins of roe are separated according to their color. Very large skeins are used in other than fresh products, or broken up into smaller pieces and packed on the bottom of trays. Bright yellow roe was historically considered the highest quality in Tokyo, although consumers in different areas of Japan often prefer bright orange roe. Since the late 1970's, orange roe has equalled yellow roe in price in Tokyo.

Trays used for the Japanese market were formerly imported from Japan because only certain types of wood are ac-

Figure 19.—Sea urchin roe packed for the domestic retail market in an "oyster tray".

ceptable, as they impart some odor or flavor to the roe. Now, however, a firm in Los Angeles manufactures nearly all wood trays used by the U.S. industry[13].

Sanitation is important because sea urchin roe, which is usually sold fresh out of the shell, can easily pick up bacterial and fungal contamination. To counteract bacteria, some processors use ultraviolet-treated water in all phases of processing, and disinfectants are used by all to maintain a sanitary environment. Good refrigeration is also critical, especially during summer.

Labor costs are rather high in an operation which calls for meticulous cleaning, sorting, and packing. Thus several processors turned to bulk-packing methods. In addition to savings in labor costs, bulk-packing also offered lower costs for trays (plastic instead of wood), as well as lower shipping costs, because the plastic trays were considerably lighter, and only a few were needed compared to wood trays. Once in Japan, the roe is repacked in the traditional wood trays and marketed through normal channels.

The proximity of the markets and the use of experienced labor ensured that the appearance of the repacked product was good. The only drawback was the extra time and cost needed to transport and repack the roe. Presently, fresh red sea urchin roe is being shipped to Japan primarily in wood trays, but some foam bulk trays are also used. The product form is largely determined by the current prices of both, and, recently, roe packed in wood trays has generally yielded higher profits.

For the domestic market, wood trays and plastic "oyster" trays (Fig. 19), which are partitioned, have 5 or 10 depressions, and hold 100 or 200 g of roe, are used for sale through retail markets. Nearly all sushi restaurants prefer the wood trays, however.

Several attempts have been made to process sea urchins aboard vessels at sea. The principal advantages are proximity to the sea urchin supply, access to clean salt water, and easy disposal of waste products. Apparently the cost of maintaining crews and workers aboard the vessels for extended periods proved uneconomical.

In the early days of the fishery, processing plants were concentrated in Santa Barbara, but by 1984 plants were located in Los Angeles (four), Long Beach (two), Ventura (one), and Oxnard (one). Several plants stopped processing recently in San Diego, Los Angeles, Oxnard, and Santa Barbara. These are likely to resume processing when conditions are favorable. Periodically, red sea urchins are harvested in northern California near Fort Bragg and trucked to central and southern California for processing.

Several attempts have been made to process sea urchins in northern California, but none has proved successful for a sustained period. The chief problem appears to be inclement weather during winter when the market is most favorable. In addition to high seas, visibility is extremely poor during and after winter storms, making diving for sea urchins rather difficult and hazardous. Nevertheless, some small-scale processing is being carried out with sea urchins from Half Moon Bay to Fort Bragg to supply local sushi shops.

Processors indicate that about 35-45 experienced workers are needed to clean and pack 10 t of whole red sea urchins in wood trays in an 8-hour work day. When larger foam trays are used, the same amount can be processed by 25 workers if the roe need not be aligned in the trays. If careful packing is required, however, only a slight savings in labor is realized.

The plants process sea urchins around 200 days annually. In a typical operation, 4 persons crack the shells open, 12 remove the roe and do preliminary cleaning, 6 do the final cleaning, and 16 pack the roe in wood trays[6]. During periods of full production, some plants have 80 persons working 10-12 hours per day.

The quantity and quality of roe contained in sea urchins is vital to processors. Quantity is by and large a seasonal phenomenon, as the amount of roe depends in part on the reproductive state of the sea urchins. However, nutritional state is important, and areas devoid of preferred algae produce sea urchins with poor yield or poor color.

We were fortunate in being allowed to examine the production log of a southern California processor, and we have constructed a graph (Fig. 20) of the yield of premium roe processed in 1975-76. The figure includes only roe packed in trays for the fresh roe market.

[13]The only known domestic tray maker is Matsumoto, Inc., 411 E. 5th St., Los Angeles, Calif.

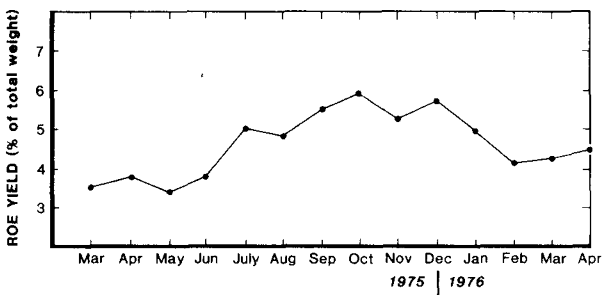

Figure 20.—Yield of sea urchin roe at a commercial processing plant. Only good quality roe sold fresh is included in the yield.

The production curve is similar to the reproductive cycle of red sea urchins (Fig. 4). The yield is lower because off-colored roe is discarded, some roe is inevitably lost during processing, and cooked and salted roe are not included in the data. Further, the gonad index given in Figure 4 is based on drained weight of sea urchins, while the production yield is based on total weight at dockside.

Roe color is exceedingly important in marketing. Clear, bright yellow or orange roe is best for the fresh market. As many as eight color grades are used by California processors, and all dark or discolored roe is discarded. For salted roe, the preferred color is orange, which is the color of high quality bottled salted roe made with Japanese sea urchins.

In the California fishery we noted that orange roe was exclusively from male red sea urchins while yellow roe was usually found in females. Bernard (1977) and Kramer and Nordin (1975) found the same relationship in red sea urchins from British Columbia, and the latter found no cyclic changes in color of the roe. Dark brown roe represents gonads degenerated because of starvation.

In addition to having good color and appearance, best quality roe is firm, small (less than 5 cm), and free of leaking fluids. Some processors feel that poor quality roe tends to occur in greater frequency in large (old) urchins, and for this reason they discourage harvest of the very large red sea urchins.

Persons in California wishing to buy and process sea urchins must obtain a wholesale fish dealers and preservers license ($65) from the Department of Fish and Game. In addition, the wholesaler is responsible for keeping records of all sea urchins purchased, and for paying a tax of $2.87/t of whole sea urchins bought.

Shipping and Marketing

Fresh roe is shipped to Japan by air freight, principally from Los Angeles International Airport. A freight forwarder consolidates products from several firms to take advantage of lower bulk-rate charges for air freight. Since carriers do not use refrigerated containers, each processor must include adequate artificial coolant in individual shipping cartons. Unit cost for air freight depends on the quantity shipped. Amounts under 100 kg are charged $5.08/kg; between 100 and 200 kg, $4.40/kg; 200-300 kg, $2.85/kg; and over 300 kg, $2.16/kg. To this are added handling charges of $17 to $45 per shipment, depending on the number of cases of roe shipped[14].

Steamed roe is often air-shipped to Japan, but it can also be frozen and sent by sea, as are all salted and frozen products. The basic shipping charge is presently $388/t. Other charges (insurance, labor, overland freight, etc.) are additional costs, as are surcharges for adjustments based on current fuel and currency rates[15].

[14]Mr. Kagawa, "K" Line Air Service, Inc., Redondo Beach, Calif. Personal commun.
[15]T. Saito, Pacific Marine Products Corporation, Ventura, Calif. Personal commun.

Sea urchin roe for the domestic market is shipped in insulated cartons containing coolants similar to those used in overseas shipment. Both truck and air transport are used, depending on distance.

The short shelf life of fresh sea urchin roe makes it imperative that the product be handled expeditiously. Fresh roe is usually shipped by air freight to Japan within 30 hours after delivery of the sea urchins at dockside by divers. Shipment timing is important because all imported food undergoes agricultural inspection and customs clearance at the receiving airport in Japan. Spot checks are also made by health officials to monitor levels of bacterial contamination. It is best to ship sea urchins from Los Angeles on flights that depart around midnight, as they arrive before dawn in Tokyo after 11-12 hours. Shipments that arrive late in the day are held over for inspection the following day. Shipments are not made on Fridays, because arrival date is Sunday in Japan, or on Sundays, when most U.S. processors suspend operations.

After official clearance, the roe is held overnight in refrigerators until early the next morning when auctions are held at the Metropolitan Central Wholesale Fish Market, located in Tsukiji, Tokyo. Bulk-packed roe is trucked directly from the airport to outlying regions, particularly to Miyagi Prefecture, about 325 km from Tokyo. There the roe is repacked in standard wood trays before being marketed.

Most of the sea urchin roe produced in California is marketed fresh in Japan, but an increasing amount of fresh roe is being packed in wood trays for the growing domestic sushi trade. Small amounts packed in plastic oyster trays are also sold in U.S. retail outlets. The total amount sold in the United States is unknown, but is thought to be on the order of 30-40,000 wood trays per month, which we estimate to be about 25 percent of the average amount sent to Japan.

In Japan, fresh U.S. roe packed in wood trays is sold primarily at the Tsukiji Market through auction. The roe is sold in lots (bundles) of 11-13 trays. In other cities, sea urchin roe is sold through auction or directly to major wholesalers. Bulk-pack fresh roe, repacked in Japan in traditional wood trays, is sold in many cities through auction and direct sales. Salted, steamed, or baked roe is usually sold through brokers to manufacturers that specialize in preserved sea urchin roe products.

Several American processors sell sea urchin roe to Japanese trading firms at a fixed price so they are not subjected to the vagaries of auctioning. Some processors sell their own products at auction through brokers, however. These brokers receive about 5 percent of the sales price for their services. The auctioneers, called primary wholesalers, receive 5.5 percent of the auction price for handling the product. In addition, an import customs duty of 10 percent is assessed on fresh roe, and 7 percent on salted roe. These duties are paid on the basis of the bill of sale if the roe has been sold outright. If not, a small down payment is required, and the balance of the duty is paid after the primary wholesaler reports the selling price to the customs office.

As of 1984, divers were paid about $400-500/t for red sea urchins. The prices usually correspond to the high demand in winter, low yield during spring, and low demand in summer. To encourage harvesting of good quality sea urchins, some processors offer bonuses when high roe yields are achieved.

As mentioned, the prices paid at the auctions in Japan are based on supply and demand. Of course, quality is always of primary importance, and domestic roe always brings the highest prices. As the Japanese sea urchin fishery is mainly a spring-summer fishery, prices are generally lower during those months because of high domestic production (Mottet, 1976). Around the middle of August, seasonal monsoons depress fishing effort; at the same time, several species of sea urchins start reproductive activity, and fisheries for those species are curtailed. Then imports need to be increased to fill the demand.

The United States and the Republic of South Korea are presently the largest exporters of sea urchin roe to Japan. The demand and price are especially high during the holiday season near the end of the year. Thus the average catch by month in the California sea urchin fishery (Fig. 21) reflects the price structure. But the lower catches from March through July are also related to low gonad yields after the spawning season.

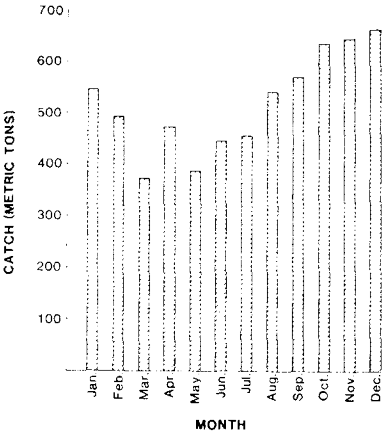

Figure 21.—Average California catch, by month, of red sea urchins, 1973-83. Source: California Department of Fish and Game.

Processors in the United States sometimes sell their products to Japanese brokers at a flat annual price which reflects the value at both the high and low demand periods. Often by agreement the volume is kept minimal in the spring and summer to avoid big losses. However, the plants have to operate even during unprofitable periods, because of the need to keep key personnel employed.

Processors and buyers sometimes resort to freezing roe during the summer when Japanese prices are low. The frozen roe is held several months until prices are better, and though premium prices are never paid for frozen roe, the profits are a bit better than selling fresh roe in summer.

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