The California Red Sea Urchin, *Strongylocentrotus franciscanus*, Fishery: Catch, Effort, and Management Trends

PETER E. KALVASS and JON M. HENDRIX

Introduction

Two species of strongylocentrotids are found in the nearshore coastal waters of California, the red sea urchin, *Strongylocentrotus franciscanus*, and purple sea urchin, *S. purpuratus*. While both are fished commercially for their highly valued gonads, the purple sea urchin accounted for less than 1% of the 10,086 metric ton (t) California catch in 1995.

The red sea urchin is ubiquitous in rocky habitats along the west coast of North America from Baja California to Kodiak, Alaska (Kato and Schroeter, 1985; Ebert et al., 1994). In California, the red sea urchin fishery began in the southern region of the state around 1970 and was confined to that area until about 1985 when fishermen began to harvest virgin stocks on the state's northern coast (Fig. 1). The fishery was thoroughly reviewed at the inception of the northern California fishery by Kato and Schroeter (1985). Fishermen had leapfrogged central California due to the paucity of marketable sea urchins there, largely attributable to the impact of the southern sea otter, *Enhydra lutris*, an efficient sea urchin predator (Ebert, 1968; Foster et al.[1]).

The authors are with the California Department of Fish and Game, Noyo Marine Laboratory, 19160 S. Harbor Dr., Fort Bragg, CA 95437. Views or opinions expressed or implied are those of the authors and do not necessarily reflect the position of the National Marine Fisheries Service, NOAA.

ABSTRACT—California's red sea urchin, Strongylocentrotus franciscanus, *catch peaked at 23,577 metric tons (t) in 1988. Since then, catches and CPUE have trended downward at different rates in northern and southern California, with 10,086 t landed statewide in 1995. West coast sea urchin catches and CPUE from British Columbia, Can., to Baja California, Mex., have generally declined during this period which followed a decade of rapid fishery expansion. This expansion was in response to increasing demand from Japan fueled by rising prices based largely on a more favorable export currency exchange rate. West coast stock assessment methods have been based on integrating a combination of fisheries dependent data and population surveys into models at various levels of complexity. California management policy has centered on technical measures such as size limits and seasonal closures and has been largely ineffective in stabilizing declining catches.*

[1] Foster, M. S., C. R. Agegian, R. K. Cowen, R. F. Van Wagenen, D. K. Rose, and A. C. Hurley. 1979. Toward an understanding of the effects of sea otter foraging on kelp forest communities in central California. Final Rep. to U.S. Mar. Mamm. Comm. by Moss Landing Mar. Lab., Calif.

Vessels and diving gear in the commercial sea urchin and abalone, *Haliotis* spp., fisheries are similar, with divers using surface-supplied air in their search for sea urchins and a short-handled rake to scoop them into meshed bags. Most vessels employ one or two divers and a line tender, while a relatively small percentage of boats have more than two divers.

Fishery dependent data have been the primary source of information for managing marine fisheries over the decades, owing to its relative ease of collection and availability compared to fishery independent survey data (Jamieson and Caddy, 1986). Catch statistics show that the northern California sea urchin fishery has exhibited a dramatic fishing-down effect in its relatively short history, and it has been the object of many

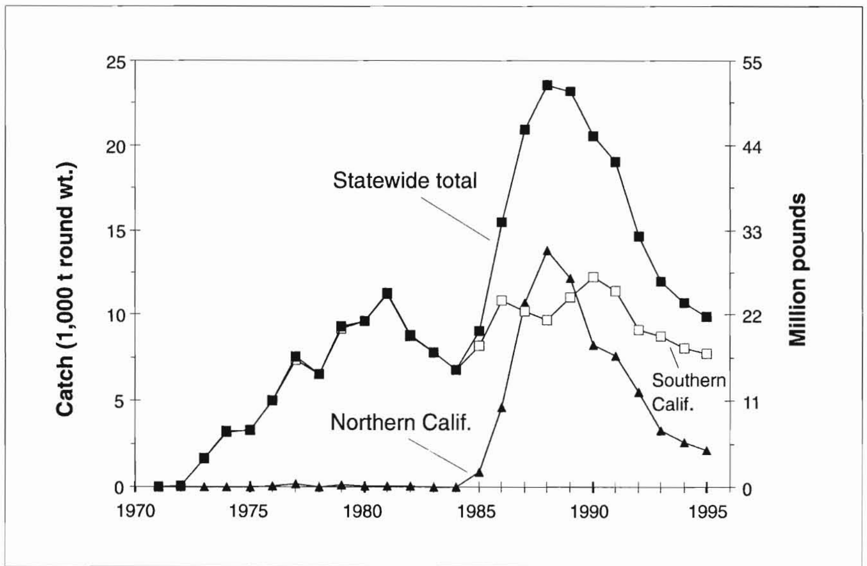

Figure 1.—California red sea urchin annual catch, 1971–95.

investigations (Kalvass, 1992; Botsford et al., 1993; Quinn et al., 1993; Rogers-Bennett et al., 1995).

Should the 84% decline in catch in northern California, from a peak of over 13,605 t (30 million pounds) in 1988 to 2,148 t (4.7 million pounds) in 1995, be termed a "fishery collapse" (Fig. 1)? Semantics aside, could this pattern have been avoided by more conservative management? These are important questions for industry members as well as fisheries managers and policy makers in that maintenance of a large adult biomass might be linked, at some level, to increased long-term yields, in part because red sea urchin fishery recruitment may involve two density-dependent mechanisms. These mechanisms, called "Allee effects," include: 1) juvenile refuge from predation under adult spines (Tegner and Dayton, 1977; Sloan et al., 1987) and 2) a minimum adult density necessary for successful spawning (Pennington, 1985; Levitan et al.,1992; Botsford et al., 1993).

Unloading sea urchins at Noyo Harbor, Fort Bragg, CA. Photo by John Mello, California Department of Fish and Game.

The principal northern California fishery area extends from Bodega Bay, including the Farallon Islands, (lat. 38° 0' N) in Sonoma County northward to northern Mendocino County (lat. 39° 50' N) (Fig. 2). The fishery primarily operates in a relatively narrow strip of the nearshore benthos from the low intertidal to about 22 m deep. In many places this band can be found entirely within 300 m of shore. A 1989 photogrammetric aerial survey of California's coastal kelp canopies estimated coverage at 14.5 km^2 on the northcoast (San Mateo County to Shelter Cove, Humboldt County) composed almost entirely of bull kelp, *Nereocystis luetkeana*. This canopy coverage can be compared with 45.3 km^2 for the southern California coast from Point Arguello, Santa Barbara County to Mexico and the Channel Islands, composed mostly of giant kelp, *Macrocystis pyrifera* (Van Wagenen[2]). Within the nearshore environment, canopy kelps are associated with hard substrate, e.g. moderate relief bedrock, reefs, pinnacles, and boulder-cobble fields (McLean, 1962) and might, therefore, serve as an index of the extent of sea urchin habitat. Northern California constitutes about 32% of the southern California kelp bed coverage based upon this survey. Unlike its northern counterpart, the southern California red sea urchin catch has been relatively stable and has averaged about 9,762 t (21.5 million pounds) since 1985.

In this analysis we examine red sea urchin catch and effort trends in both northern and southern California, and present a brief summary of northern California subtidal survey results, fishery economic factors as they influence catch and effort trends, and a survey of west coast management practices. In a future report we plan to thoroughly review our fisheries independent data, consisting primarily of size and density data in northern California, in the context of west coast red sea urchin population trends in growth, recruitment, and abundance (Kalvass and Hendrix[3]).

[2] Van Wagenen, B. 1989. California coastal kelp resources-summer 1989. Unpubl. rep. prep. for Calif. Dep. Fish Game. Ecoscan, P.O. Box 1046, Freedom, CA 95019.

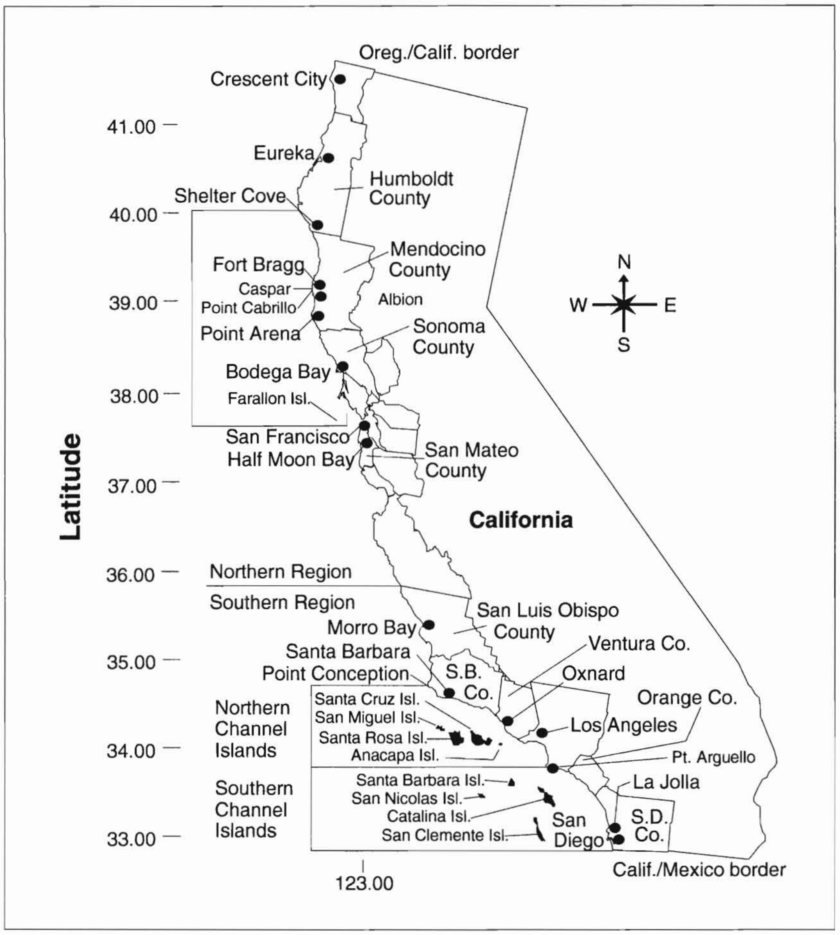

Figure 2.—Northern and southern California commercial sea urchin fishery areas.

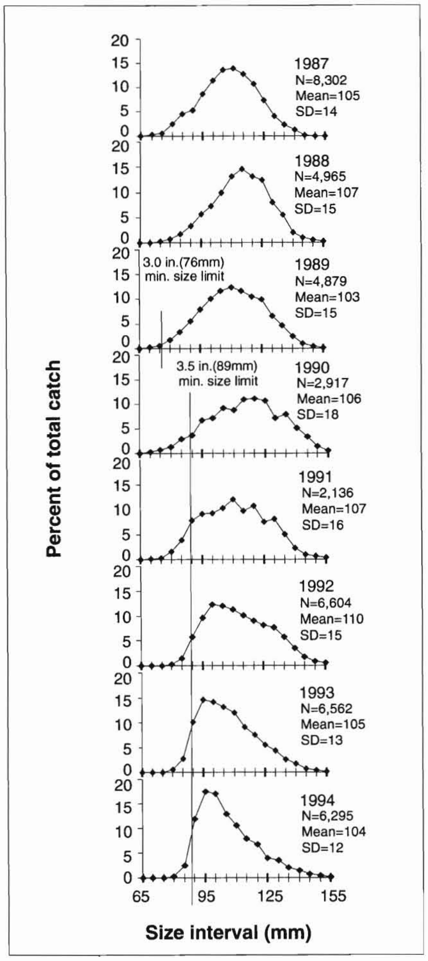

Figure 3.—Percent total catch by size interval for the northern California red sea urchin fishery, 1987–94.

Catch Patterns

In an attempt to understand the dynamics of this fishery we examined catch trends by fishery area, fishing depth strata, red sea urchin size (test diameter), and in relation to sea conditions as measured by wave height at a reference location. While the number and average size of sea urchins harvested have declined, the area and depth range fished have expanded. The declining trend in landings can be attributed to a combination of factors, including a decline in fishable stock, more restrictive management measures as a response to that decline, and a reduction or geographic shift in fishing effort which can be in part a response to the former two developments. In order to track catch-at-size trends by weight, test diameters (D) of red sea urchins from catch samples were converted to their biomass equivalents (W) (based on size-weight (drained) samples collected between 1986 and 1989 in Fort Bragg, Calif., R^2=0.87, n=2,890) using this allometric relationship: $W = 1.396 \times 10^{-3} D^{2.682}$

Northern California

The dramatic nature of the fishing-down phenomenon, whereby large individuals are removed from the stock initially, is clearly illustrated in the temporal patterns of catch-at-size distributions (Fig. 3). In 1988, an estimated 70.9% of the catch by weight consisted of sea urchins greater than 110 mm (4.3 inches), compared to 37.6% in 1994. In 1990, when the present 89 mm size limit (3.5 inches) was established, approximately 17.7% of sea urchins landed came from the 90–105 mm size band, compared to 46.6% in 1994. In 1994, 12.0% of the catch came from the 90–95 mm size interval; conversely in 1990, only about 3.7% of the catch came from this interval. There is a clear trend toward a greater reliance on a narrower band of size classes in the fishery, which appears to be independent of the imposition of minimum size limits beginning in 1989.

[3] Kalvass, P. E., and J. M. Hendrix. In Prep. Northern California sea urchin population surveys, 1988–96. Calif. Dep. Fish Game, Noyo Mar. Lab., 19160 S. Harbor Dr., Fort Bragg, CA 95437.

The twin phenomena of skewness and kurtosis are evident in the time series of estimated catch-at-size distributions from 1987 to 1994 (Fig. 4), and the shifting distribution tells the story of the fishery. At its peak in 1988, harvest of the 115–120 mm interval increased by about 33% over 1987, up to 2,028 t. By 1990, a negative (left-hand) skewness and a flattening of the catch curve developed as the largest sea urchins were removed. The platykurtotic trend continued in 1991 and 1992, reflecting declining catches. The curve asymmetry shifted to the right and became more pronounced by 1994. This greater reliance on the smallest size interval in the harvestable stock, which includes new fishery recruits, is indicative of a developing "recruitment" fishery.

Sea urchin gonad (uni) is the fishery end-product, and its quality and quantity is the principal determinant of its value. Gonad catch weights were calculated from gonadosomatic indices for each size interval based on the ratio of gonad weight to whole sea urchin drained-weight in catch samples from the Fort Bragg vicinity (1986–89). In 1988, the leading size interval was 110–115 mm yielding 352 t of uni. By 1994, this interval produced 44 t, 12.5% of the 1988 amount. In 1994, the leading size interval had dropped 15 mm to 95–100 mm and yielded 21.6% (103 t of uni) of the 477 t total.

Heavy reliance on a few localized fishery areas to support an entire fishery is a pattern reflected in the northern California fishery. Seventy percent of the 50,800 t (112 million pounds) of red sea urchin harvested from northern California waters between 1988 and 1994 originated in four fishery sectors comprising about 65 km of coastline (sectors 4, 5, 7, and 9: Fig. 5). Each of these areas is associated with one of the four major northern California ports (Fort Bragg, Albion, Point Arena, and Bodega Bay). These four areas produced about 43 t of red sea urchin harvest per minute (about 1.6 km) of nearshore latitude in 1994, vs. 142 t in 1990. An average vessel day (trip) in 1994 yielded about 500 kg, so that these areas supported about 86 vessel days per minute of latitude in 1994. Sector 7, near Point Arena, was the only sector to exceed a 500 t (1.1 million pounds) harvest in 1995 and has shown the least

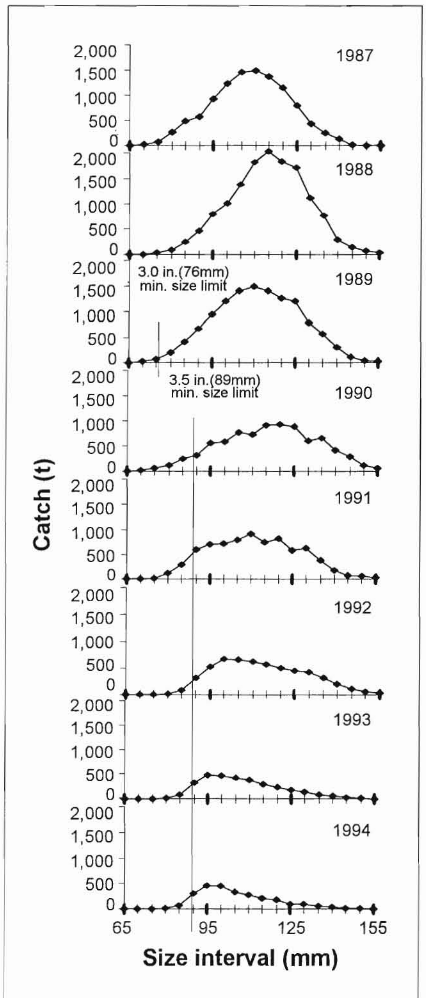

Figure 4.—Total catch (t) by size interval for the northern California red sea urchin fishery, 1987–94.

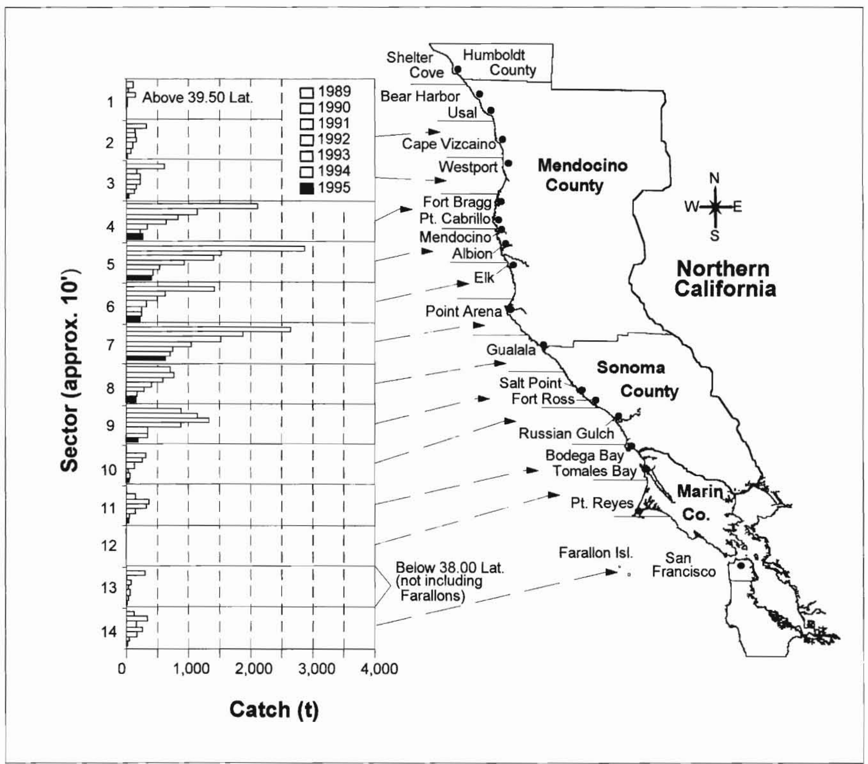

Figure 5.—Northern California red sea urchin catch by coastal sector (10' lat.) for northern California, 1989–95. Mandatory fisherman logbooks since 1988. Catch location estimates by applying logbook proportions to total regional catch.

precipitous decline of the four areas since 1990. Not surprisingly, this area contains the largest offshore reef in northern California (Saunders Reef) consisting of several square kilometers of rocky habitat ranging from about 9 to 20 m deep.

The Oregon coastal red sea urchin fishery has followed a pattern similar to that of northern California. The catch peaked at 4,218 t in 1990, then fell to 682 t in 1995. Two southern Oregon coastal areas produced over 70% of the catch during the period 1986–93 (Richmond[4]). Southern Oregon is influenced by oceanographic mechanisms that also affect northern California, most notably the California Current (Ebert and Russell, 1988). Predictably, bull kelp is abundant on shallow nearshore reefs in northern California and southern Oregon, and the marine nearshore benthic communities in southern Oregon show many other similarities to those of northern California.

The northern California catch by depth (about 3 m intervals) showed little change between 1988 and 1993. Beginning in 1994 and continuing in 1995 there was a marked shift in fishing effort from shallow (<9.1 m) to deeper (12.2–21.3 m) waters (Fig. 6). In southern California the percentage of catch from depths >18.3 m increased from 23% in 1990 to 33% in 1994. Deep-diving increases the risk of nitrogen gas bubble formation in diver tissues, "decompression sickness," and as a result reduces the amount of safe diving time available to the diver (NOAA, 1991). Taking on this added risk and reduced fishing time is probably a response to reduced sea urchin abundances at shallower depths. Alternatively, some divers have suggested that it may be in response to rougher sea conditions (which are more severe at shallower depths) in 1994 compared to previous years.

[4] Neil Richmond. 1997. Unpubl. data on file at Oreg. Dep. Fish Wildl., Mar. Field Lab, P.O. Box 5430, Charleston, OR 97420.

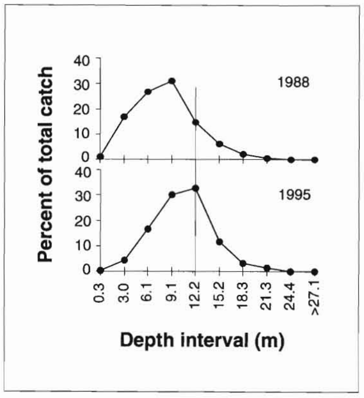

Figure 6.—Percent catch by depth interval comparison for the northern California red sea urchin fishery, 1988 and 1995. Data from logbooks.

To determine whether the 1994 shift in catch-by-depth might be the result of rougher sea conditions, we compared mean daily wave height, daily catch, and mean daily ex-vessel price per kilogram of whole red sea urchin between 1990 and in 1994 (Fig. 7) (catch and price data from the California Department of Fish and Game (CDFG) commercial market receipt database). A 2.13 m (7 ft) wave height measured at the NOAA buoy #46014 (lat. 39.2°N, long. 124.0°W) about 16 km west of Albion, Calif. was our threshold criteria for a safely fishable day based upon our own scuba diving experience. In 1990, there were 119 fishable days with less than 2.13 m wave height out of 266 legally open days (44.7%). In 1994, there were only 79 legally open days that met the fishable criteria out of 233 open days (33.9%). In 1990, 23.4% of the catch was taken in greater than 2.13 m wave height conditions. In 1994, 25.3% was harvested under these conditions. Mean wave height for the year in 1990 was 2.30 m (S.D.=0.91), and in 1994 it was 2.40 m (S.D.=0.85). Though the average difference was only about 10 cm, the graphs reveal that wave height in 1994 did not show as many extended periods of calm as in 1990 (e.g. mid-March to late April, late August to mid-September). The seasonality of ex-vessel price and the inverse relationship between catch and both price and wave height is evident, particularly in 1994.

Southern California

The southern California fishery is centered in the Southern California Bight, the area below Point Conception formed by an eastward curving coastline and consequently influenced by the California Current to a lesser degree than northern and central California waters (Fig. 2) (Ebert et al., 1994; Tegner and Barry[5]). The significant geological feature of the bight is the Channel Islands, whose nearshore zones contribute most of the area's sea urchin catch. The northern Channel Islands, consisting of three major islands (San Miguel, Santa Rosa, and Santa Cruz), have been the dominant catch area for most of the fishery's history. San Miguel is the most northwesterly of the islands which are near the northern and southern extremes of the geographic range of many invertebrate species (Morris et al., 1980). San Miguel and Santa Rosa Islands are about 14 and 27 km long, respectively, with coastlines from two to three times that distance. These two island coastlines are comparable in length to the principal northern California sea urchin fishery area between Fort Bragg and Bodega Bay.

In 1995, the northern Channel Islands contributed 1,964 t of the 7,940 t southern California catch (25%), down 50% from 3,901 t in 1994 (Fig. 8). These islands, particularly San Miguel and Santa Rosa, whose harvest peaked in 1991, accounted for 60% of the catch in 1991. In 1989, the southern Channel Islands group of Catalina and San Clemente accounted for 19% of the catch, compared to 36% in 1995. At Catalina and San Clemente Island, and the more isolated San Nicolas Island, the proportions and actual catch were greater in 1995 compared to 1994. Despite its relatively large size, Catalina Island has not been a productive sea urchin location and most of the 1995 southern Channel Island harvest originated at San Clemente Island. Here, the 1995 harvest was 78% higher than in 1994, somewhat offsetting the large reduction in the northern Channel Islands.

Throughout the 25-year history of the southern California fishery, catch patterns have been marked by periodic

[5] Tegner, M. J., and J. P. Barry. 1989. Size structure of red sea urchin (*Strongylocentrotus franciscanus*) populations in southern California: effects of growth, recruitment, predation and oceanography. Scripps Inst. Oceanogr., La Jolla, Calif., Unpubl. rep., 50 p.

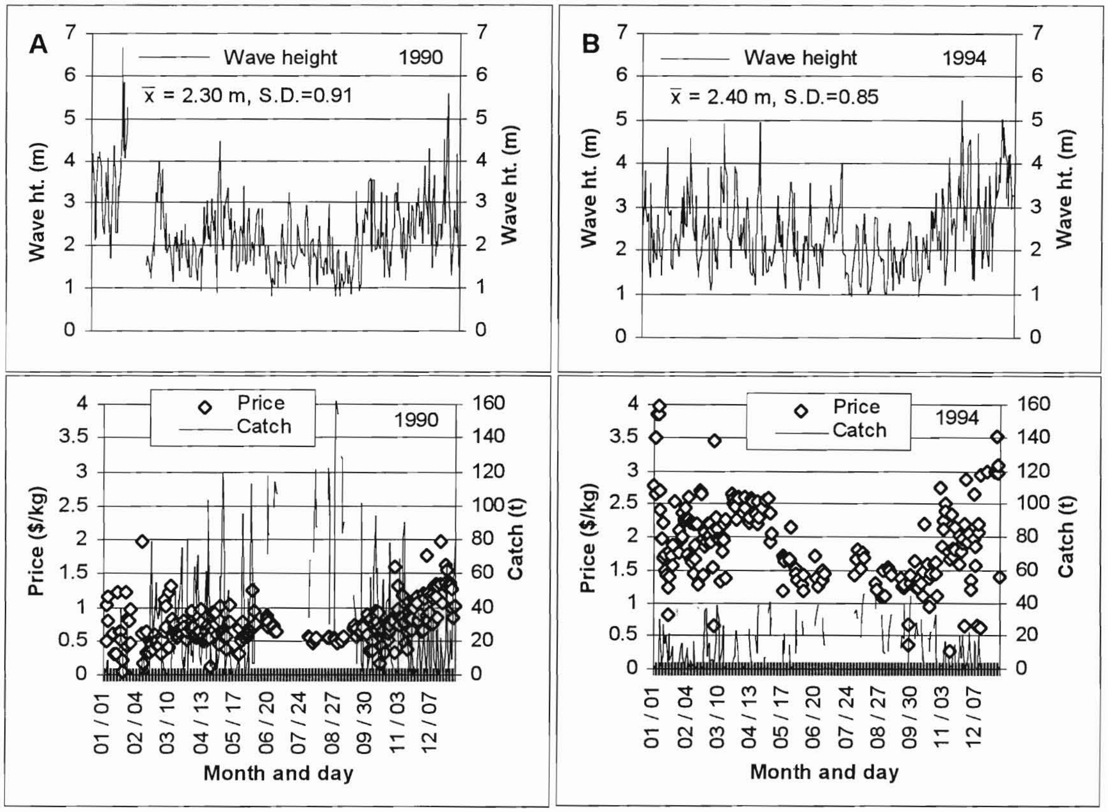

Figure 7.—Northern California 1990 (A) and 1994 (B) daily average wave height, sea urchin price, and daily catch comparison. Time in month and day. Gaps in price and catch data due to fishery closure periods.

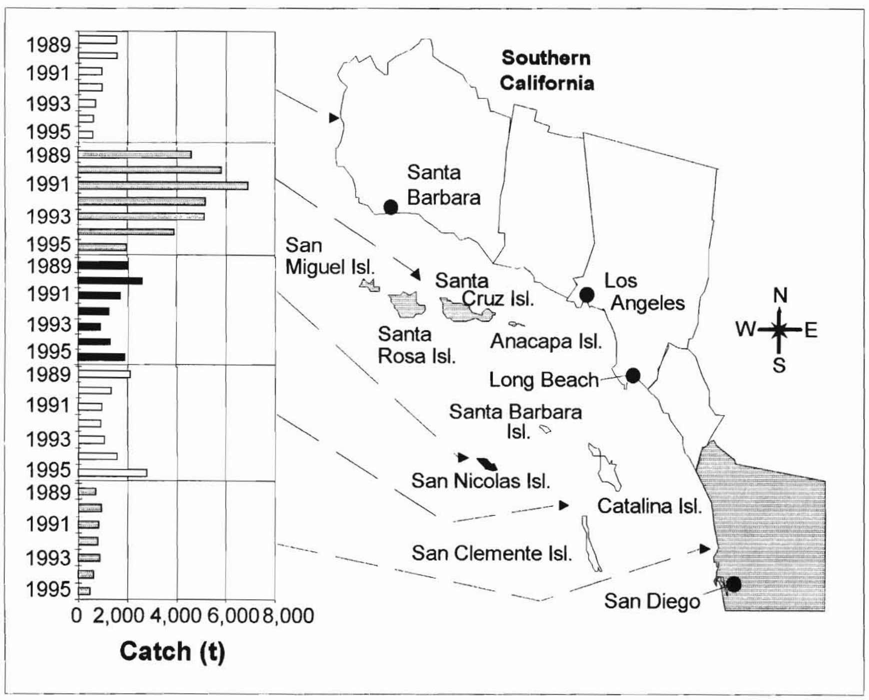

Figure 8.—Southern California red sea urchin catch by area, 1989–95. Data from logbooks.

shifts between island groups, influenced by such factors as stock abundance and gonad quality and quantity, which in turn have been influenced by oceanographic phenomena such as episodic El Niño events (Kato and Schroeter, 1985; Dayton and Tegner, 1989). These events, particularly the strong El Niño of 1982–83, greatly affected kelp abundance which impacted gonad quality and was reflected in reduced catches several years later.

Test diameter distribution in the southern California catch has exhibited an increasing positive skew that is as pronounced as that in the north. The standard deviation of catch-sampled test diameters has been decreasing since 1989, from 14 to 11 mm in 1994 when almost 26% of the sampled catch by number came from the 85–90 mm size interval. In 1994, an estimated 58% of the catch was from the 85–100 mm size band (4,679 t), compared to 36% in 1989 (Fig. 9). Because the southern Califor-

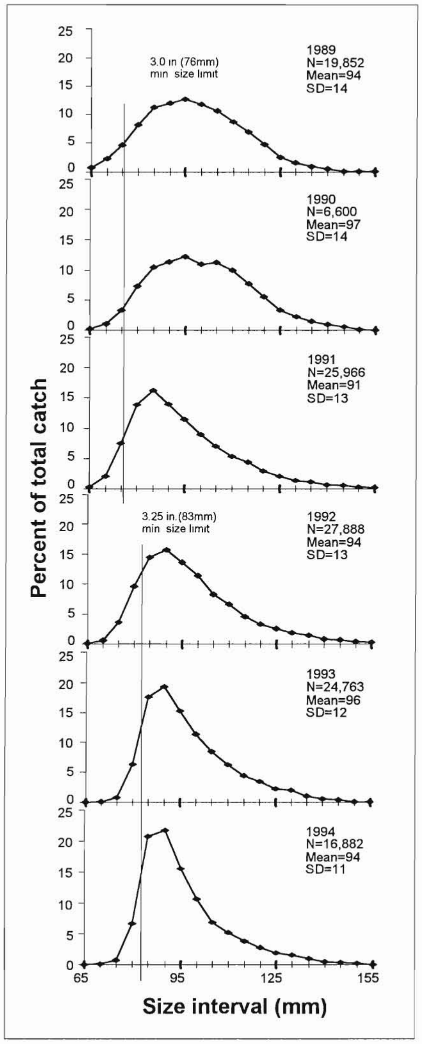

Figure 9.—Percent total catch by size interval for the southern California red sea urchin fishery, 1989–94.

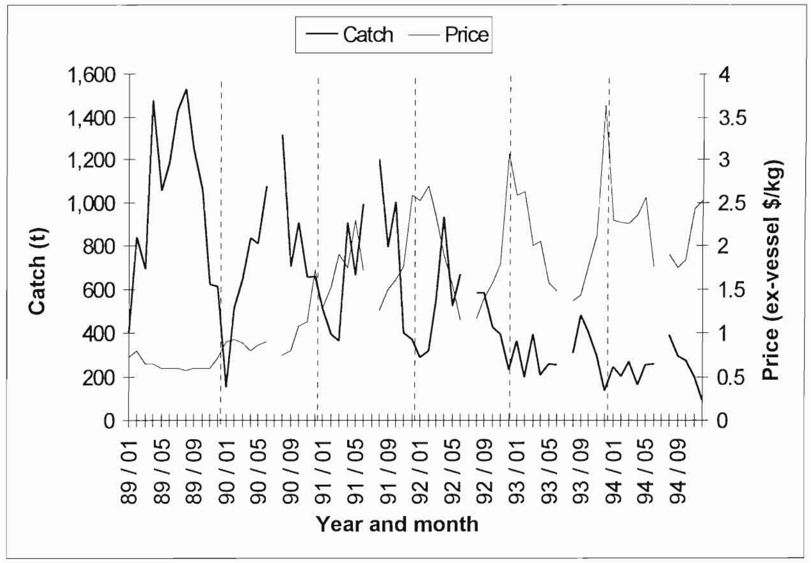

Figure 10.—Northern California sea urchin catch and average ex-vessel price by month, 1989–94. Gaps in catch and price data are due to fishery closure periods.

nia catch is not declining at the rate of the northern California catch, it may be that a strongly recruiting cohort is partly responsible for this shift. However, preliminary analysis of red sea urchin size frequency and density survey data from the National Park Service permanent transects at the northern Channel Islands from 1988–94, (Richards and Kushner, 1994; Kushner et al., 1995; Kushner[6]) does not indicate the presence of a cohort that could account for the distributional shift of catch observed over the past few years.

Effort Patterns

Catch and effort are often closely correlated, and catch expressed in terms of unit effort can be an important index of the status of a fished population (Ricker, 1975; Hilborn and Walters, 1992). In expanding fisheries, catch-per-unit-of-effort (CPUE) may be at deceptively high levels as the virgin stock is fished down. Paradoxically in declining fisheries, CPUE may stabilize or increase despite declining stocks as fishermen adapt their behavior and less efficient fishermen leave the fishery. This is particularly true with a patchily distributed species like sea urchins, and CPUE therefore may tend to overestimate stock size (Gulland, 1974; Hilborn, 1992; Pfister and Bradbury, 1996).

The California commercial sea urchin fishery is managed by limited entry, and a California sea urchin permit is valid statewide. The number of sea urchin permits sold peaked in the 1987–88 permit year at 938, but fell to 715 the following permit year. In 1995 there were 551 permittees who harvested 10,086 t of sea urchin. The distribution of the catch among permittees was as follows: 35 northern California permittees out of the 134 (26%) who fished there landed 50% of the catch in 1995, while in southern California, 103 out of 383 (27%) caught 50% of the red sea urchin harvest. In British Columbia's 1996 red sea urchin fishery there were 110 permits for a 6,624.4 t quota (Harbo[7]); in Oregon there were 38 permittees catching 682 t in 1995 (Richmond[4]).

A mass migration of divers and processors northward from southern California in the mid-1980's fueled the northern California fishery. There has been significant seasonal demographic movement between the areas, and more recently a reverse migration to southern California by many previously northern-based divers. In California in 1995, 120 permittees spent a majority of their effort (>50% landing receipts) in northern California, with 69 permittees spending all of their time in the north, landing 1,033 t (Table 1). A significant change in catch per permittee occurred in this group between the 1992 and 1993 seasons, dropping by 47% from 23,900 to 12,600 kg. This change is reflected in the total monthly catch which began a decline in September 1992 from which it has yet to recover (Fig. 10). Part of this decline is due to a

[6] David Kushner. 1992. Unpubl. data on file at Channel Islands Natl. Park, 1901 Spinnaker Dr., Ventura, CA 93001.

[7] Rick Harbo. 1995. Unpubl. data on file at Can. Dep. Fish. Oceans, S. Coast Div., 3225 Stephenson Pt. Rd., Nanaimo, B.C. V9T 1K3, Can.

Table. 1—Northern and southern California sea urchin fishery effort patterns, 1990–95.

Year	Permits	Receipts	Catch (t)	Receipts per permit	Catch (kg) per permit
Statewide permittees[1]					
1990	556	24,540	19,732	44.1	35.472
1991	594	28,790	18,392	48.5	30,981
1992	570	30,060	14,288	52.7	25,084
1993	567	29,460	11,638	52.0	20,548
1994	535	27,488	10,432	51.4	19,505
1995	484	24,491	9,774	50.6	20,194
Northern permittees[2]					
1990	112	4,860	3,910	43.4	34,927
1991	126	5,980	3,060	47.4	24,313
1992	84	4,820	2,008	57.4	23,905
1993	88	3,940	1,110	44.8	12,610
1994	85	3,845	1,122	45.2	13,200
1995	69	3,496	1,033	50.7	14,971
Majority n. permittees[3]					
1990	196	8,630	7,244	44.1	36,968
1991	225	11,160	6,864	49.6	30,527
1992	210	11,620	4,971	55.4	23,678
1993	178	8,840	2,917	49.7	16,389
1994	161	7,817	2,384	48.6	14,806
1995	120	6,087	1,984	50.7	16,533
Southern permittees[4]					
1990	294	12,330	9,077	41.6	30,890
1991	292	13,110	8,349	44.9	28,577
1992	284	13,100	6,827	46.1	24,041
1993	290	13,950	5,997	48.1	20,684
1994	328	16,189	6,680	49.4	20,367
1995	235	10,544	4,455	44.9	18,957
Majority s. permittees[5]					
1990	359	14,560	11,243	40.5	31,298
1991	368	15,910	10,223	43.2	27,760
1992	356	16,350	8,255	45.9	23,179
1993	388	18,920	8,081	48.8	20,866
1994	371	18,337	7,523	49.4	20,276
1995	363	17,468	7,410	48.1	20,413

[1] Permittees with >10 landing receipts for the year.
[2] All receipts for the year in northern ports.
[3] >50% of receipts for year in northern ports.
[4] All receipts for the year in southern ports.
[5] >50% of receipts for year in southern ports.

loss of 32 permittees in the "majority northern" category. These divers presumably returned to southern California where the "majority southern" permittees increased by 32 from 1992 to 1993. A partial explanation for the migration of permittees might be due to the regulation changes in 1992. A 3-day work week was instituted in June and August, down from 4 days, and a 4-day work-week in April and October. Though these regulations were statewide, they could have contributed to a decision by some fishermen to return to southern California, an area with greater habitat area, calmer ocean conditions, and which is home to many of them. Another factor may have been that the differential price increase for southern California sea urchins over the north also began to increase at that time (Halmay[8]). Indeed in 1991, the annual average ex-vessel red sea urchin price differential between Santa Barbara and Fort Bragg was $0.26/kg, rising to $0.42 in 1992 and $0.54 in 1993. Neither factor can, however, account for the decline in CPUE by the exclusively northern permitttees.

[8] Pete Halmay. 1996. Commercial sea urchin diver, 4738 Mt. Frissell, San Diego, CA 92117. Personal commun.

CPUE may also decline in response to "highliner" divers (high volume and efficiency) leaving the northern California area. In 1992, 51 of the top 100 divers in California fished part of their time in northern California, with 12 of them fishing there exclusively. By 1994, only 7 of the top 100 made all of their landings in the north. As with many fisheries, the California sea urchin fishery exhibits a highly skewed distribution of catch among fishermen. In 1995, 159 of the 484 permittees (33%) with at least 10 landings caught 50% of the total catch.

Northern California

CPUE, as kilograms per vessel-trip, declined from a high of 1,901 kg in 1986 to 515 kg in 1995. Confounding this pattern of general CPUE decline is the tendency to exploit remote or hazardous locations, and a greater range of depth zones which are generally bypassed during the early phases of a fishery (Pfister and Bradbury, 1996). For example, the port of Point Arena, about 70 km south of Fort Bragg, was initially overlooked by the majority of the fleet in favor of Fort Bragg partly because Point Arena lacked an all-weather port with protection from winter storm-generated southerly swells. The local stocks have subsequently benefited from this "weather refugia" which has contributed to somewhat more stable landings than at Fort Bragg. The wide variance in CPUE among locations early in the fishery has decreased over time, and the 1995 CPUE was comparable at over 100 kg/diver hour among the major fishing sectors in northern California (Fig. 11).

CPUE, as kilograms per diver-hour, also declined rapidly in Oregon to about 171 kg/h in 1995 (Richmond[4]). Washington, on the other hand, with more strictly controlled fishing effort, has had a more stable CPUE history at between 175 and 260 kg/h annually during the past decade. The number of boats was reduced by 68% in the 1989–90 season. Though even with this level of reduction, remaining vessels were able to compensate to some degree by increasing their effort (Lai and Bradbury, In Press).

Southern California

Up until the late 1980's when the northern California fishery peaked, the northern Channel Islands provided the highest share of the California sea urchin catch. With the rapid decline of the northern California fishery, the northern Channel Islands was again the dominant red sea urchin production area through 1994. Interviews with Santa Barbara area divers between 1974 and 1977 revealed that catch rates for boats with a single diver averaged about 250 kg/h, with dive time at about 3.5 h/day (Kato and Schroeter, 1985). In 1994, southern California single diver boats averaged 3.9 h/day, while overall CPUE as kg per diver-hour (from logbooks) was low, but up slightly to 100 kg from

94 kg in 1993 (Fig. 12). In 1994, San Nicolas led catch areas with 149 kg/h, though at the northern islands where most of the catch was made, CPUE was only 99 kg/h, down from over 158 kg/h in 1989. CPUE in the San Diego coastal area fell below 91 kg/h in 1993 and 1994. In contrast, most areas in northern California yielded between 91 and 113 kg/h. In the mid-1970's, single-diver boats averaged 986 kg/day, while two-diver boats averaged 2,258 kg/day (Kato and Schroeter, 1985). By 1994, southern California single-diver boats averaged 304 kg/day, while two-diver boats brought in 644 kg/day.

Because divers are paid to a large extent on the basis of the quality of their catches some divers reportedly "pick for quality" over quantity (Halmay[8]). It is difficult to determine whether the proportion of divers engaged in this practice has increased or decreased in recent years. Certainly, sea urchin diving is strenuous work, and as the diver population ages with a limited entry rate set at 10:1 (1 new entrant for every 10 departures), and gains experience, some stabilization of catch rates and an optimization of effort targeting higher valued product over catch volume might be expected.

Another factor to consider is that as stocks decline, the search component of fishing time increases relative to the actual harvest time, and delineating between these activities when recording effort in logbooks can be difficult for fishermen. The time spent searching for a fishing location, either on the surface or in the water, before the first sea urchin is collected has undoubtedly increased over the years in California as sea urchin populations have apparently decreased. Because of this ambiguity, catch per vessel or catch per diver-day is sometimes used as a measure of CPUE rather than catch per diver-hour. Conversely, these measures can mask an increasing or decreasing amount of time spent during a fishing day.

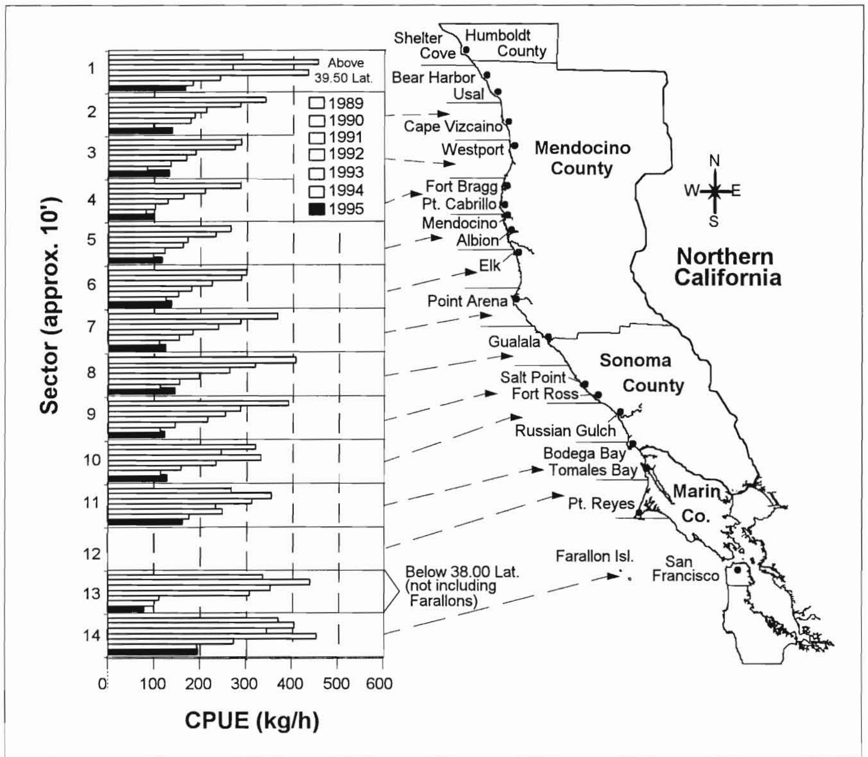

Figure 11.—Northern California red sea urchin catch per unit effort (kg/diver h) by coastal sector (10' lat.), for 1989–95. Data from logbooks.

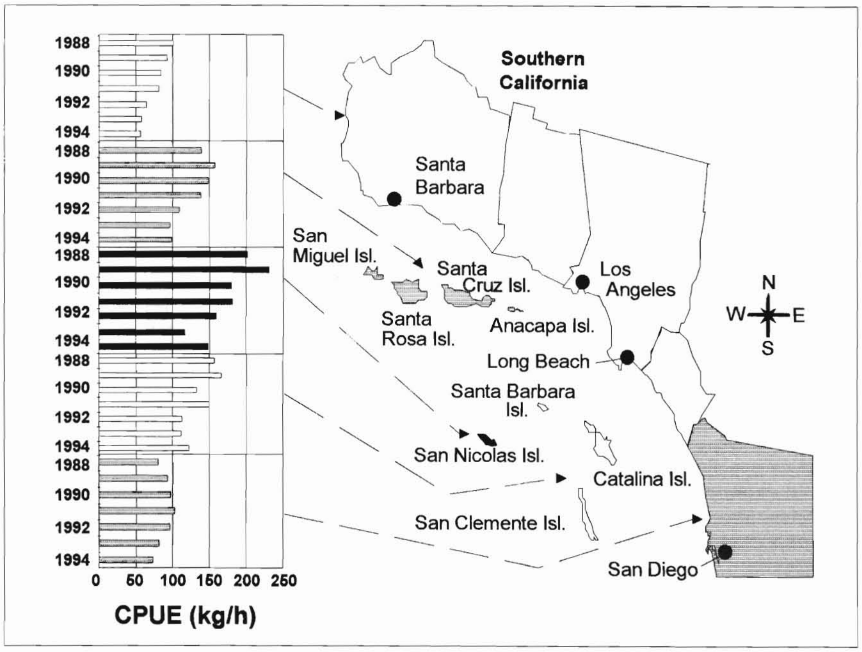

Figure 12.—Southern California red sea urchin catch per unit effort (kg/diver h) by area, 1988–94. Data from logbooks.

Economic Trends

The plunge in the Japanese Yen-to-U.S. dollar exchange rate in 1986 increased the ex-vessel sea urchin price (paid to fishermen) and launched the race to develop the northern California and southern Oregon fisheries (Fig. 13). The seasonality of gonad yield, catch, and ex-vessel price are interdependent.

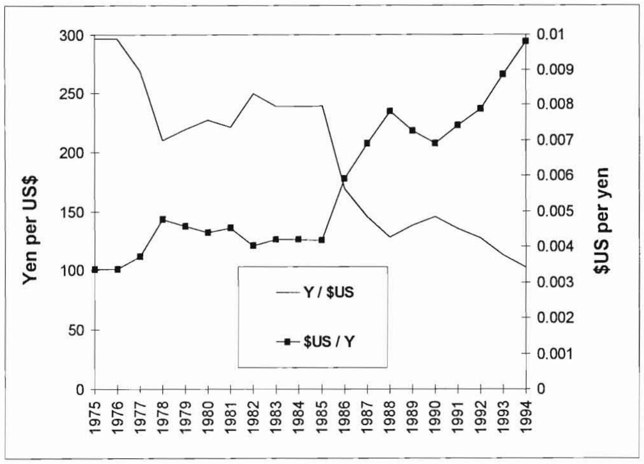

Figure 13.—Japanese Yen-to-U.S. dollar exchange rates, 1975–94 (Source: U.S. Department of Commerce).

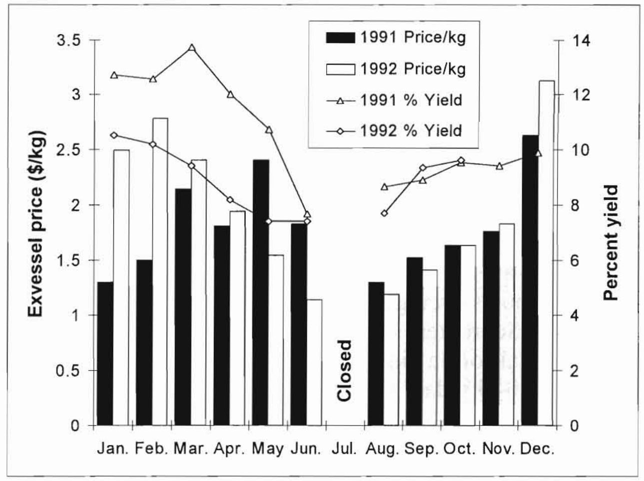

Figure 14.—Mendocino coast red sea urchin gonad yields (Fort Bragg processor data) and ex-vessel price for 1991 and 1992 (1992 Nov., Dec. yields unavailable).

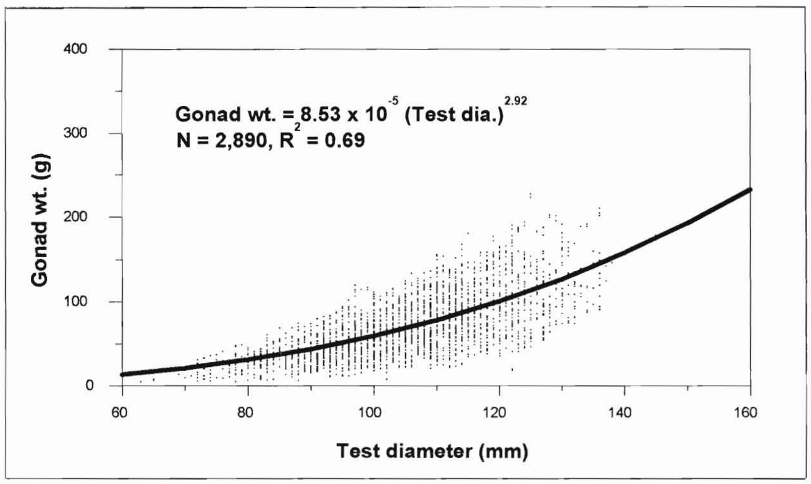

Figure 15.—Fitted regression line for red sea urchin gonad weight and test diameter data, 1986–89. Fit by nonlinear least squares process (Source: Statmost, 1995).

Catch and price are often inversely related (Fig. 10), while yield and price tend to vary together (Fig. 14). Yield is calculated as a gonadosomatic index based upon the percent recovery of gonad from whole red sea urchins, by weight. Fishermen get paid based on an industry formula incorporating yield and quality (e.g. color and texture) as measured by a grading system. The market forces of supply and demand operate on domestic ex-vessel price as well as prices at the Tokyo Central Wholesale Market where much of California uni is exported, and as a result domestic prices closely parallel wholesale Japanese prices (Sonu, 1995).

In 1994, the highest prices for imported roe at the Tokyo market occurred in February and May. Although good roe quality is the most important factor for garnering high prices, these high prices also reflect the low availability of Japanese domestic and imported roe during winter months (Sonu, 1995). Less fishable ocean conditions, more prevalent in winter months in northern California than in southern California, can impact domestic sea urchin availability. Warmer ocean conditions in California as far north as lat. 39°N in 1992 (Lynn et al., 1995) probably depressed gonad yields as well (Fig. 14). Some northern California processors have relied increasingly on reprocessing imported bulk processed Chilean sea urchin, *Loxechinus albus*, during summer closures and winter storm periods to augment declining local catches. Overall, the variability in the ex-vessel price is the result of a variable wholesale market price and a variable exchange rate (Reynolds, 1994).

Red sea urchins were sampled by CDFG personnel from catches at Fort Bragg from 1986 to 1989. Gonad weight and test diameter were related using a nonlinear curve-fitting technique based on least squares minimization (Statmost, 1995) (Fig. 15). Results show that, for example, an 89 mm red sea urchin yields an average of 42 g gonad, while a 110 mm sea urchin averages 86% more at 78 g. Clearly, despite the increasing variance in gonad weight with greater size, there is an economic advantage in avoiding smaller sea urchins with markedly lower gonad yields and curtailing the sea urchin harvest during seasonal periods of low yield.

Fishery Management

Growth and Survival

Ebert et al.[9] studied size-specific sea urchin growth along the west coast of North America using chemical tags. Mean annual total mortality rates calculated at Point Cabrillo Marine Reserve and at the Caspar Sea Urchin Closure near Fort Bragg varied from 4.8% to 14.6% during the period 1990–92, while the mean annual mortality rate from northern California to Alaska was similar at 7.0%. Mortality rates at southern California tagging sites (e.g. 30.6% to 33.0% at San Miguel Island) were clearly higher than at sites north of San Francisco. Natural mortality rates in southern California may be higher due to greater predation from such southern species as California sheepshead, *Semicossyphus pulcher,* and California spiny lobster, *Panulirus interruptus,* (Tegner and Barry[5]), but are apparently balanced by higher rates of recruitment and growth. Breen (1979) reported an average natural mortality rate of 9.5% for British Columbia populations, based upon the assumption that recruitment balances mortality in a stable population.

Recent growth and recruitment studies of red sea urchin populations at two sites about 2 km apart near Port Orford, Oreg., revealed such key findings as low recruitment and large differences in growth rates between the two study sites. Growth modeling, using the methods of Ebert et al.[9], showed high between-site variability in years (3.2–7.2) required to grow from 30 mm (1.2 in.) to 89 mm (3.5 in.). These slower-than-expected growth rates mean that resource recovery in some commercially fished areas will also be much slower than previously thought (Schroeter and Dixon[10]). This study also showed that mortality rates are strongly size-dependent for red sea urchins. Higher death rates for smaller individuals (<60 mm) and extremely low recruitment are significant impediments to recovery from fishing losses (Schroeter and Dixon[10]).

Stock Assessment

Sea urchin stock assessments rely in part on fisheries-independent data collected generally by biologist-divers (sometimes with industry assistance) and involve counting and measuring organisms along a band transect of known dimension (Sloan et al., 1987; Kalvass and Taniguchi, 1993). More recently, video methods have been used by the Washington Department of Fisheries (WDF) (Bradbury[11]). Subtidal sea urchin population surveys have been conducted at various locations along the west coast, usually in commercial sea urchin fishing zones. In some cases these have been part of an effort to obtain pre-fishery abundance estimates for quota determination (Woodby, 1992). For example, in 1991 the Alaska Department of Fish and Game (ADFG) allowed a conservative harvest rate of 3% of the estimated stock based upon a modified surplus production model in the form: $Quota = CF_1 * CF_2 * M * P_0$, where M (natural mortality) = 0.16, P_0 is the virgin population size estimate and CF_n are correction factors (Woodby, 1992). Often, however, surveys are conducted annually as part of ongoing stock assessments and quota determinations (British Columbia, Washington).

The Washington sea urchin fishery has had the most active and complex management history. From 1987 to 1996, fishery areas were managed by individual quotas on a 3-year rotation. The rationale for this system is the presumed recovery of harvestable stocks through recruitment and redistribution, and maintenance of the proportion of larger individuals by allowing undisturbed growth to the upper size limit (Lai and Bradbury, In Press). Biomass estimates are made for each fishery area using a back-calculation method. Sea urchin densities are estimated from subtidal surveys before and after annual fishery openings and the catch removed from those areas during the open periods is known. Quotas are calculated by applying a desired fishing mortality from catch-at-size-analysis model output, and estimates of total mortality from dive survey relative abundance changes, to the area biomass estimates in a standard catch equation. Recent court decisions granting 50% of the sea urchin resource to local Native American tribes have required significant changes in WDF management strategy for the 1996–97 season, including abandonment of rotational management (Bradbury[11]).

British Columbia uses "precautionary" north coast and south coast quotas based upon empirical methods, with the north coast and Queen Charlotte area having the largest quota share. The north coast quotas have no strong biological basis, though periodic sea urchin population censuses are conducted in various regions (Sloan et al., 1987; Harbo[7]; Neifer and Heizer[12]).

In southern California, sea urchin surveys have proceeded along three courses: 1) localized investigations by academic researchers in the Channel Islands, Santa Barbara and the La Jolla, San Diego County, area in which relative abundance and size frequency distribution information has been collected over a relatively limited geographic range (Tegner and Dayton, 1981, 1991; Rowley, 1989; Ebert and Russell, 1992); 2) extensive annual benthic ecological surveys by the National Park Service, which include sea urchins, around the northwest Channel Islands since 1987 at permanent transect sites (Kushner et al., 1995), and 3) CDFG has been surveying abalone and sea urchin populations at various locations in the Channel Islands since 1994 (Taniguchi[13]).

In northern California, subtidal sea urchin surveys have been conducted annually since 1988, though the geographic scope has varied each year

[9] Ebert, T. A., J. D. Dixon, S. C. Schroeter, P. E. Kalvass, N. T. Richmond, W. A. Bradbury, and D. A. Woodby. In review. Growth and mortality of red sea urchins (*Strongylocentrotus franciscanus*). Ecol. Appl.

[10] Schroeter, S. C., and J. D. Dixon. 1993. Estimating size-specific growth rates and population mortality rates for red sea urchins (*Strongylocentrotus franciscanus*) near Port Orford, Oregon. Ecometrics, 2270 Camino Vida Roble, Suite L, Carlsbad, CA 92009, 25 p.

[11] Alex Bradbury. 1996. Wash. Dep. Fish., Point Whitney Shellfish Lab., 1000 Point Whitney Road, Brinnon, WA 98320. Personal commun. and WDF sea urchin fishery management memo dated October 19, 1993, 12 p.

[12] S. Neifer and S. Heizer. 1996. Red sea urchins. Pacific Fishery Update. Can. Dep. Fish. Oceans, S. Coast Div., 3225 Stephenson Pt. Rd., Nanaimo, B.C. Can., V9T 1K3. Unpubl. rep., 9 p.

[13] Ian Taniguchi. 1996. Calif. Dep. Fish Game, 350 Golden Shore Dr., Suite 50, Long Beach, CA 90802. Personal commun.

(Kalvass et al., 1991; Kalvass and Taniguchi, 1993; Kalvass and Hendrix[3]). Standard survey methods include the careful searching of substrate, as well as the ventral surface of mature sea urchins to find clinging or canopied juveniles along a 30 m long × 2 m wide band transect, but do not include invasive techniques like crevice flashlight searches and the rolling of rocks.

Density by size class data for index sites in the Fort Bragg vicinity is shown in Figure 16. Significant trends include a strong cohort averaging about 20 mm in test diameter noted in the fall 1994 standard survey, and a dramatic drop in density on standard surveys conducted from 1989 to 1990, reflecting the steep decline in Fort Bragg area catch and CPUE during this period (Fig. 17). The increased density of red sea urchins in the 80–100 mm size class in the 1994 survey is puzzling in light of the continued trends of reduced catch and CPUE in that year, and the relatively slow growth of sea urchins. More deep transects (>15 m) were surveyed than in previous years due to poor ocean conditions, and two locations had relatively high densities which may have biased the survey results. On the other hand, the increase in smaller red sea urchins (<30 mm) was forecast by a spike of post-larval settlement in northern California in spring 1993 (Ebert et al., 1994) and noted subtidally by other researchers in 1994 (Morgan[14]). These results point out some of the problems inherent in surveying contagiously distributed nearshore invertebrate populations.

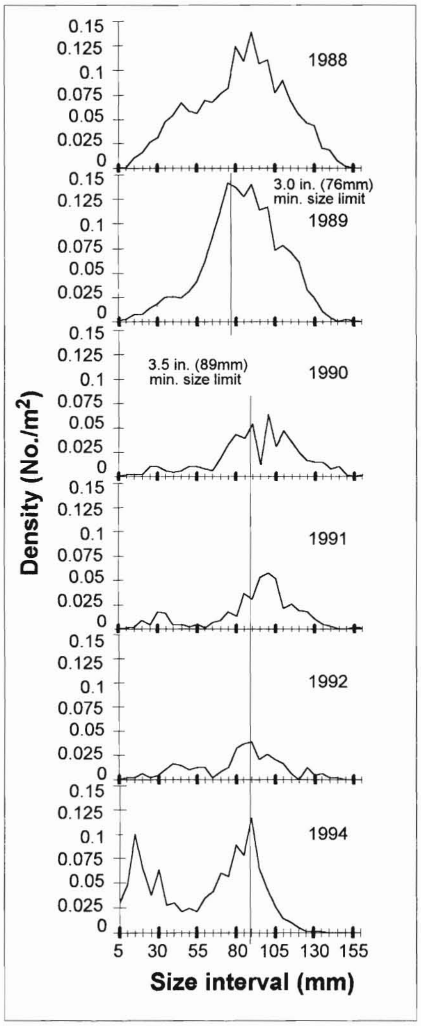

Figure 16.—Sea urchin density by size interval from subtidal surveys between Van Damme Bay and Laguna Point, Mendocino County, 1988–94.

Northern California red sea urchin populations have been examined in the theoretical context of harvest refugia and rotating spatial harvest, the management method employed by WDF. Model parameters (natural mortality and fishing mortality) were estimated using a length-based method on size frequency data from northern California population censuses and laboratory growth experiments (Botsford et al., 1993; Quinn et al., 1993).

An exploratory biomass estimate was made for northern California using a depletion estimator based on the method of Leslie (Ricker, 1975; Methot and Botsford, 1982). The Leslie model follows the general form: $C_t/f_t = qN_o - qK_t$, catch per unit of effort (C_t/f_t) is equal to the original population (N_o) minus the cumulative catch (K), where q is catchability. The technique uses a series of CPUE and associated cumulative catch values from 1988 to 1994 fitted to a regression line. The highly significant regression ($P<0.000$) predicts a pre-1988 fishable stock of 76,290 t for northern California, with a cumulative catch of 50,800 t removed during this period (Fig. 18). These preliminary results imply that the application of an 8% harvest rate, proximally equal to the natural mortality rate of an equilibrium population in northern California (Ebert et al.[9]), to the pre-1988 stock estimate of 76,290 t would have yielded a sustained harvest of about 6,103 t annually, rather than the pattern of "boom and bust" to the 2,148 t harvested in 1995.

There are a number of sources of bias in depletion estimators (Ricker, 1975; Hilborn and Walters, 1992). Variable catchability (q) can bias estimates of population size downward (e.g. in the initial phases of the sea urchin fishery, sea urchins in the more fishable mid-depths were probably more vulnerable than shallow and deep stocks, possibly resulting in CPUE declining at a faster rate than the stocks). Conversely, Hilborn and Walters (1992) obtained a "very good fit" to 14 years of catch and effort data for an Australian barramundi, *Lates calcarifer,* catadromous stock using a depletion estimator derived from the Leslie model that included parameters for growth, survival, and recruitment. They caution that depletion estimators used on open populations (e.g. oceanic) are more prone to bias due to the greater number of parameters to be estimated, and that measurement errors in catch and CPUE can lead to overestimates of initial population size.

Botsford et al.[15] compared the relative rates of decline of CPUE (as an index of abundance) and biomass-per-recruit from 1988 to 1994 for the 4 principal northern California fishing areas: Fort Bragg, Albion, Point Arena, and Bodega Bay. A statistical comparison of slopes revealed that abundance declined faster than expected at 3 of the 4 port areas, and significantly at Fort Bragg (P=0.10), indicating a decline in recruitment and possible recruitment overfishing, whereby the total reproductive capacity of the stock is impacted.

There are nearshore areas where sea urchins are the dominant benthic organ-

[14] Lance Morgan. 1997. Bodega Marine Lab, P.O. Box 247, Bodega Bay, CA 94923. Personal commun.

[15] Botsford, L. W., L. Morgan, and P. E. Kalvass. In Prep. The northern California red sea urchin: overfished or fished up? Dep. Wildl., Fish, Conserv. Biol., Univ. Calif., Davis, CA 95616.

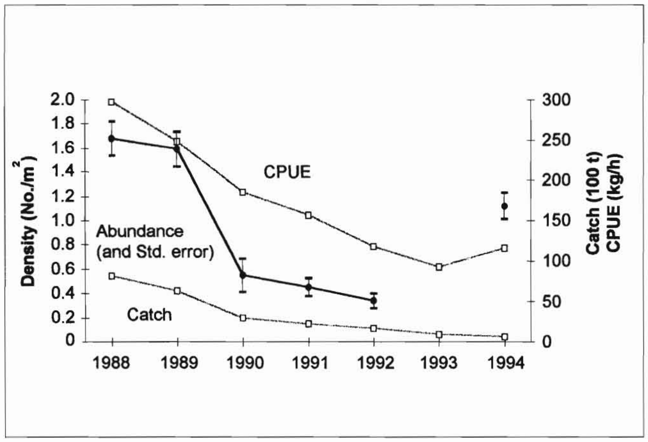

Figure 17.—Fort Bragg area red sea urchin catch, CPUE, and relative abundance, 1988–94.

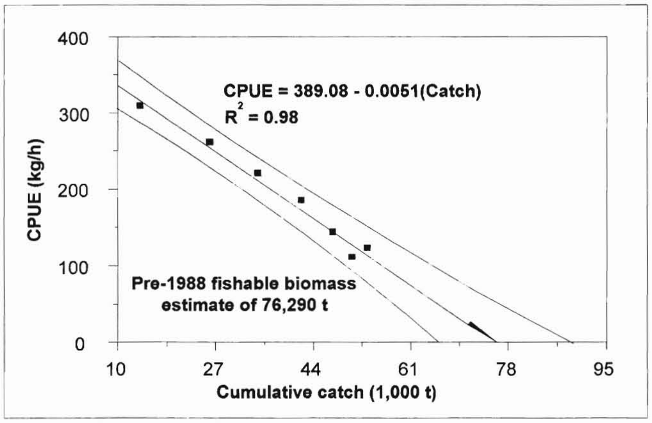

Figure 18.—Red sea urchin biomass estimate (Leslie regression method with 95% confidence boundaries) for northern California, 1988–94.

ism, decimating large fields of kelp (Harrold and Reed, 1985; Kato and Schroeter, 1985), and creating what are termed "urchin barrens." These giant patches can cover many hectares and are more prevalent in southern California than in the north. Researchers have described urchin barrens in the context of methods to increase gonad yields in these food-limited populations to enhance their marketability (Tegner, 1989; Dixon et al.[16]). Approaches involve either bringing macroalgae to the barrens or translocating sea urchins to areas of high kelp abundance. The authors have observed sea urchin dominated areas in waters deeper than about 18 m in a number of areas along the northern California coast. Conversations with divers and processors and the occasional examination of sea urchin gonads from these zones confirm that a high proportion of red sea urchins in these areas are of low market value. How this population of sea urchins should be treated in future estimates of fishable stock is an important consideration for the industry and fishery managers.

Management History

From its inception as an experimental fishery in southern California in 1971 until the late 1980's, the sea urchin fishery was not actively managed other than the requirement for a commercial fishing license and a voluntary logbook program during a period in the late 1970's. This laissez-faire approach was partly the result of the belief among many commercial and sport divers, as well as fishery managers and scientists, that sea urchins were largely valueless pests responsible in part for diminishing *Macrocystis* canopies in southern California (Kato and Schroeter, 1985). Indeed, the 7,491 t 1977 California catch averaged only about $0.22/kg, compared to $2.23/kg in 1995 (CDFG, 1990; CDFG[17]).

Beginning in 1985, permits were required to fish for sea urchins, and 2 years later a moratorium was placed on the issuance of new permits. In 1989, a statewide 76 mm (3.0-inch) minimum test diameter was implemented. In an effort to address the declining abundance in northern California, the CDFG decided in 1989 to set a target goal of reducing the sea urchin harvest by 20–30% from that of the preceding year. As a result, in 1990, the northern California minimum size limit was increased to 89 mm (3.5 inches), the month of July was closed, with open harvesting days reduced to 4 per week from May to September including a 1-week closure in each of those months. A limited entry system was established as well. The harvest reduction goal was achieved, but it soon became apparent that this level (8,027 t) did not represent a sustainable yield because of the continued decline in CPUE and other abundance indices. The last regulation change was in 1992, when the southern California size limit was raised to 83 mm (3.25 inches), 4-day work weeks were extended into April and October, and fishing days were reduced to 3 per week in June and August (Fig. 19).

Sea urchin management authority lies with the California legislature, though in 1973 the legislature authorized the commercial harvest of sea urchins to be subject to regulations set forth by the Fish and Game Commission (Commission), a five-member body appointed by the governor (CDFG[18]). Authority to levy landing taxes and establish license or individual transferable quota systems remains with the legislature. In 1987 the legislature established the Director's Sea Urchin Advisory Committee (DSUAC) consisting of CDFG-appointed industry representatives from the diver and processor communities, a California Sea Grant representative, and a CDFG member. The primary function of the DSUAC is to advise the CDFG on

[16] Dixon, J. D., S. C. Schroeter, and T. A. Ebert. 1993. The effects of supplemental feeding on the individual growth of red and purple sea urchins. Ecometrics, 2270 Camino Vida Roble, Suite L, Carlsbad, CA 92009. Final Tech. Rep., Calif. Dep. Fish Game, Contr. FG-0497, 36 p.

[17] CDFG. 1996. California commercial landings for 1995. Resour. Agency, Calif. Dep. Fish Game, 1416 Ninth St., Sacramento, CA 95814.

[18] CDFG. 1989. Final environmental document - red sea urchin commercial fishing regulations. Resour. Agency, Calif. Dep. Fish Game, 1416 Ninth St., Sacramento, CA 95814.

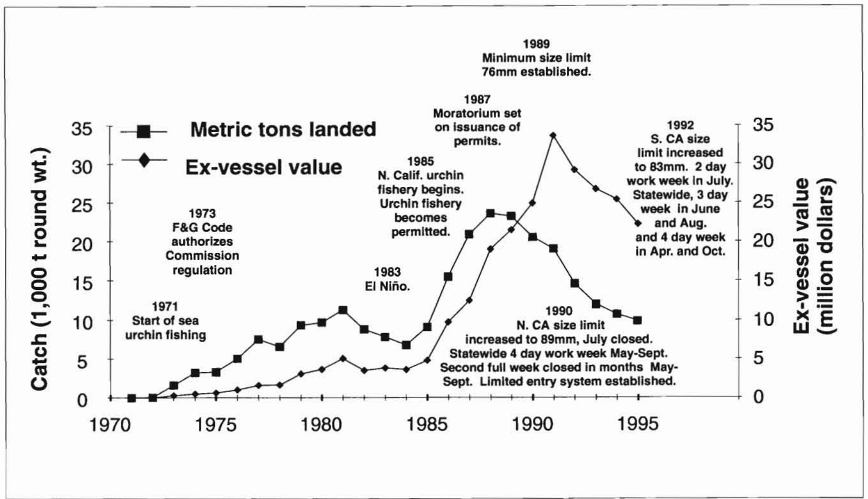

Figure 19.—California commercial red sea urchin fishery catch, ex-vessel value, and milestones, 1971–95.

project proposals funded by a special landing tax of $0.01 per pound ($0.022/kg) collected for sea urchin resource enhancement and management. The CDFG has also chosen to use the DSUAC as a forum for consensus-based management of the resource. Virtually all of the sea urchin fishery management measures to date have emerged from this forum prior to consideration by the Commission. While it is the policy of the state to give consideration to maximum sustainable yield (MSY) in its management of California's natural resources (DFG Code, Sec. 1700), there are no underlying scientific management mandates guiding the Commission. Management has, as a result, proceeded largely on a reactive "points of concern" basis (Kalvass, 1992).

Six separate government agencies in three different countries are responsible for management of commercial red sea urchin fisheries along the west coast of North America, ranging from Baja California, Mex., through British Columbia, Can., to Alaska. Though the northern and southern California fisheries are managed by the CDFG, these regions are treated separately because of their unique histories, large-scale oceanographic differences, and geographic separation. Table 2 summarizes the distribution of management techniques among the west coast entities. British Columbia adopted a pilot Individual Quota (IQ) program in 1996, replacing an industry-initiated voluntary individual vessel quota system begun in 1994. The 1996 plan features a 6,624.4 t coastwide quota evenly distributed among its 110 permittees (Harbo[7]). The ADFG initiated an experimental sea urchin fishery in 1995 in which a quota, based on a harvest rate of about 5% applied to the biomass estimate from joint industry-ADFG surveys, was auctioned to the highest bidder, a processor from northern California. The processor was responsible for hiring fishermen, without the involvement of the ADFG. The bid price was designed to pay for all costs associated with surveying and management of the fishery. Total landings for the March 1995 to April 1996 test fishery were 3 million pounds (Woodby[19]).

Oregon and California are the only entities to allow fishing without harvest quotas, though Oregon's 682 t fishery in 1995 was dwarfed by the 10,086 t 1995 California catch. All entities utilize minimum size limits and seasonal closures of varying degrees. Figure 20a, b shows catch and CPUE for the west coast fisheries (except Alaska) from 1986 to 1995 (Oregon and northern California fisheries began in the mid 1980's). All of these west coast fishery harvests have been trending downward since 1990, though in some cases the trend has been confounded by the imposition of catch quotas (Richmond[4]; Harbo[7]; Bradbury[11]; Palleiro et al.[20]; Cota[21]).

There is no doubt that some of the fishery declines are attributable to a maturation of the fisheries; however, the severity of decline in the northern California fishery, and the recent extended decline in the 25 year-old southern California fishery, are cause for concern. Interestingly, the Japanese domestic sea urchin fishery, which primarily targets strongylocentrotids, has been in decline since 1982, suffering its most dramatic decrease between 1990 and 1991. Though the Japanese government has invested millions of dollars in enhance-

[19] Doug Woodby. 1997. Alaska Dep. Fish Game, Div. Commer. Fish., Juneau. Personal commun.

[20] Palleiro, J. S., D. A. Montero, and J. M. Martinez. 1993. Informa de la temporada del perca 1992–93 erizo rojo (*S. franciscanus*) en Baja Calif. Proyecto Equinodermos CRIP Ensenada, B.C., Mex. Unpubl. rep., 16 p.

[21] Alfredo Cota. 1996. CICESE, Ecologia, P.O. Box 1306, Ensenada, B.C., Mex. Personal commun.

Table 2.—Red sea urchin management methods from British Columbia to Baja California, 1995 (Alaska fishery was experimental).

Element	B.C.	Wash.	Oreg.	N. Calif.	S. Calif.	Baja Calif.
Size limit (mm)[1]						
Lower	100	102[2]	89	89	83	80
Upper	140[3]	133				
Seasonal closures	*[4]	*	*	*	*	*
Harvest quotas	*	*				*
Limited entry	*	*	*	*	*	
Individual quotas	*					
Area closures[5]		*	*			

[1] Test diameter.
[2] Washington size limits vary by area: San Juan Islands limits are shown.
[3] Suspended in 1995–96 season.
[4] Asterisks indicate use of management method.
[5] Washington rotational fishing areas system suspended in the 1995–96 fishing season due to tribal allocation. For Oregon, no fishing in waters <3.0 m deep.

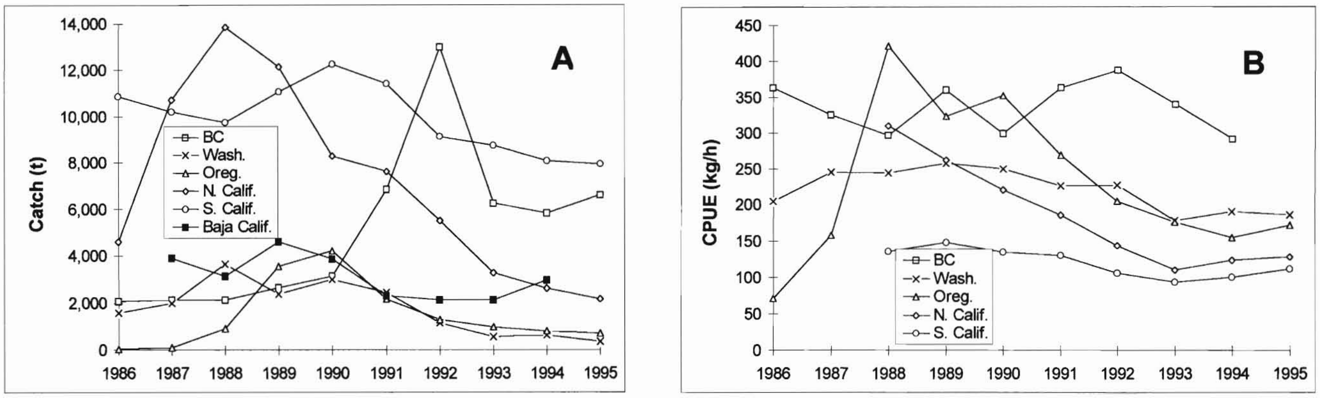

Figure 20.—West coast red sea urchin catch (A) and CPUE (B) 1986–95.

ment efforts, centering around mariculture-based juvenile sea urchin outplantings, they have yet to show visible results in increased landings (Saito, 1992; Sonu, 1995). Japanese sea uchin landings of 13,713 t in 1993 were the lowest in 35 years and less than half of the peak year of 1969 (Sonu, 1995). What makes the Japanese fishery of interest is that it is a mature fishery, targeting sea urchins of the genus *Strongylocentrotus* and exhibiting a management structure as restrictive, or more so, than the California and Oregon systems, and yet it is experiencing a decade-long decline in its principal fishery areas centered on the northern island of Hokkaido.

Discussion

Early in the development of the California fishery, the industry and CDFG focused on the benefits of reducing sea urchin densities to reduce their impact on kelp beds (Kato and Schroeter, 1985) and to increase individual sea urchin test size and gonad yield by the reduction of intraspecific competition. This process of "thinning" was welcomed as the first stage in turning a virgin stock into a more marketable one. However, both fishery-dependent and independent survey data, as well as modelling results suggest that under the fishing levels of the past decade, the population densities that are now common on the California north coast may be insufficient for fishery stock maintenance.

Researchers have found that fertilization rates are negligible in sea urchins spaced more than 1–2 m apart (Pennington, 1985; Levitan et al., 1992). Mean northern California sea urchin densities at surveyed sites in 1991 exceeded 1.0/m^2 at only 5 of 20 fished sites, while overall average density was only 0.7/m^2 (S.E.= 0.07), with abundance of reproductive sea urchins even lower. In contrast, in 1991 and 1994, red sea urchin densities at two unfished and adjacent reserves comprising about 2.5 km of coastline averaged 4.73/m^2 (S.E.= 0.30) and 4.30 (S.E.= 0.36). Notwithstanding that sea urchins exhibit patchy and clumped distributions, these behaviors do not increase the number of individuals, as smaller numbers of patches and reduced patch size can continue to limit fertilization success (Levitan et al., 1992). In monitoring since 1990, the pattern of sea urchin settlement on the north coast appears to be episodic and was dominated by several events in 1992–93 during atypical oceanographic conditions (Ebert et al., 1994; Wing et al., 1995). Despite the apparent increase in 1994 in the density of sea urchins near Fort Bragg, the harvestable portion of the stock remains greatly reduced from prefishery levels (Fig. 16). It should be further noted that relatively low urchin densities in the Fort Bragg area since 1990 did not seem to negatively impact recruitment in 1994, as one might have predicted from Allee effects. While evidence certainly points to the importance of Allee effects, sea urchin population dynamics are probably too complex over a coastal region to assign a particular threshold density level at which they are triggered.

Many researchers have characterized the red sea urchin as especially vulnerable to recruitment overfishing, whereby overfishing reduces the magnitude of recruitment (Tegner and Dayton, 1977; Botsford et al., 1993; Pfister and Bradbury, 1996; Lai and Bradbury, In Press). The northern California Dungeness crab fishery is similarly vulnerable, and over 70% of the legal-sized male crabs in the population are commonly harvested each year. The male size limit, which allows several spawning seasons prior to capture, and the prohibition on females probably prevents recruitment overfishing in this invertebrate fishery (Methot, 1986). Although red and purple sea urchins are found at sites all along the west coast, there is evidence that their population dynamics differ regionally. Recruitment of juvenile red sea urchins has been described as episodic in northern California, Oregon, Washington, and British Columbia, with long periods between significant events (Bernard and Miller, 1973; Pearse and Hines, 1987; Sloan et al., 1987; Ebert et al., 1994; Bradbury[22]), in contrast to southern California and Mexico where average annual recruitment rates appear to be higher (Tegner and Dayton, 1981;

[22] Bradbury, A. 1989. Management and stock assessment of the red sea urchin (*Strongylocentrotus franciscanus*) in Washington State. Wash. Dep. Fish., Pt. Whitney Shellfish Lab., Brinnon, WA 98320. Draft rep., 38 p.

Ebert et al., 1994; Tegner and Barry[5]). Most of these results are based on size distribution analysis and collections from artificial sea urchin settlement monitoring devices.

There are several identified mechanisms that link physical oceanographic conditions to benthic invertebrate larval settlement and subsequent recruitment. These have to do with relaxation of upwelling and its associated cross-shelf movement of water masses (Roughgarden et al., 1988; Ebert et al., 1994; Wing et al., 1995). Given the spatiotemporal variability of recruitment, the potential influence of density-dependent Allee effects, and model simulation results which suggest that the levels of recruitment seen in most west coast red sea urchin populations can greatly increase the probability of severe stock depletion (Pfister and Bradbury, 1996), fishery managers need to structure management strategies to compensate for these factors.

Red sea urchin population survey data from northern California and the stock depletion model estimates strongly suggest that northern California stocks are below 50% of pre-fishery levels and that some stocks are in a recruitment overfished condition (Botsford et al.[15]). A 1987 CDFG report (Heimann et al.[23]), written when both the northern and southern California fisheries were rapidly accelerating, cautioned that the northern California fishery "will not be able to sustain present catch levels." Goals outlined in the report included ensuring:

1) a sustained yield harvest over the long term,

2) the economic viability of the industry, and

3) that the ecology of the sea urchin beds are not drastically altered.

The uncertainty inherent in marine ecosystems warrants a cautious approach to resource exploitation. Managers must often act before scientific consensus is achieved and use common sense in their decision-making, favoring management actions that are "reversible" in their resource impacts (Ludwig et al., 1993). Several researchers have discussed the dangers of relying on the concept of MSY or a bioeconomic equilibrium in managing resources (Ludwig et al., 1993; Shepherd, 1993). They describe a "ratchet effect" whereby, during relatively stable periods in a fishery, caused perhaps by a temporary stock increase from a successful recruitment episode, harvest rates may appear to stabilize at levels predicted by steady-state bioeconomic theory, but which in fact are often extreme levels. A sequence of these good years can encourage additional effort leading to a risk of stock collapse when the stock returns to a more normal state. The "latent" effort available, as temporarily unused fishing power, should markets change or stocks increase in the California sea urchin fishery, is considerable and could be a serious threat to the future of the resource (Jamieson and Caddy, 1986). In northern California in 1995, 26% of the 134 permittees with significant landings for the year accounted for 50% of the catch.

The present California sea urchin management scheme based on size limits and effort control has not been sufficient to meet the goals outlined in 1987 and cannot be expected to prevent effort increases brought on by any temporary stock increases or in response to stock decreases elsewhere on the west coast. Size limits alone will not sustain a commercial sea urchin fishery, particularly when fishing effort is high and recruitment is highly variable (Shepherd, 1993; Lai and Bradbury, In Press). The adoption of some form of catch-based control or periodic harvest system similar to other west coast jurisdictions seems prudent. Time will tell whether the northern California fishery will take a path of recovery, equilibrate at its present level, or continue the recent downward trend (Fig. 21). At this critical stage in the fishery, it should be realized that calls for additional research without confronting the present problem may be mere delaying tactics (Ludwig et al., 1993).

Acknowledgments

This work was supported in part by funds from the CDFG Director's Sea Urchin Advisory Committee. Catch samples were collected and summarized, and fishermen logbooks were keypunched, edited, and summarized by I. Taniguchi, C. Talbot, J. Kwiecien, J. Mello, J. Hendrix, J. Hernandez, H. McIntyre, and C. Bill. Thanks also to P. Haaker, F. Henry, and two anonymous

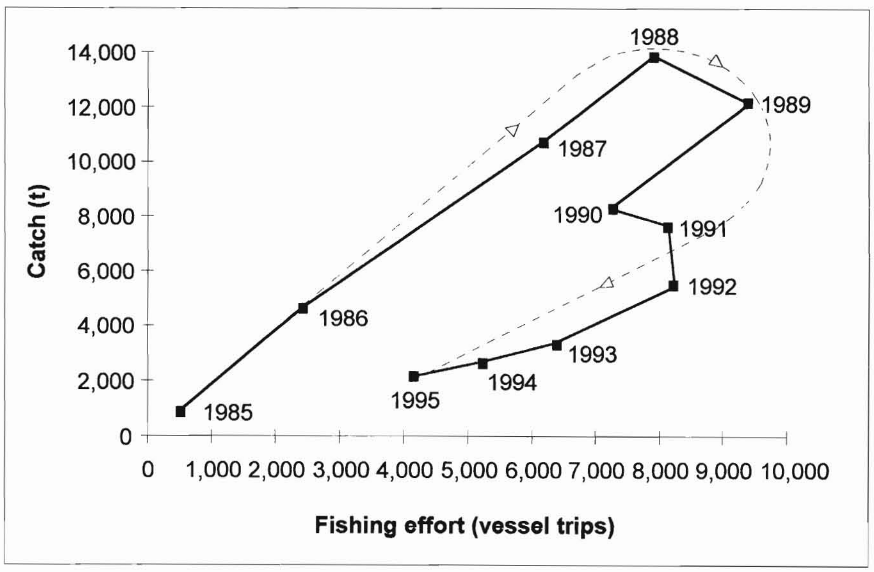

Figure 21.—Northern California red sea urchin catch (t) and effort (vessel trips), 1985–95 (dotted line fitted by hand), (after Shepherd's (1993) dynamic response pattern).

[23] Heimann, R. F. G., D. O. Parker, and P. Kalvass. 1987. Recommendations for the management of red sea urchins in California. Calif. Fish Game, 19160 S. Harbor Dr., Fort Bragg, CA 95437. Unpubl. rep., 7 p.

reviewers for their comments on the manuscript. The final manuscript benefited greatly from the constructive comments of S. Schroeter and J. Dixon. We also thank those fishermen who faithfully fill out their logbooks.

Literature Cited

Bernard, F. R., and D. C. Miller. 1973. Preliminary investigation on the red sea urchin resources of British Columbia [*Strongylocentrotus franciscanus* (Agassiz)]. Fish Res. Board Can., Tech. Rep. 400:1–35.

Botsford, L. W., J. F. Quinn, S. R. Wing, and J. G. Brittnacher. 1993. Rotating spatial harvest of a benthic invertebrate, the red sea urchin, *Strongylocentrotus franciscanus*. *In* D. M. Eggers, G. Kruse, R. J. Marasco, C. Pautzke and J. T. Quinn (Editors), Proc. Int. Symp. Management Strategies of Exploited Fish Populations, p. 409–428. Univ. Alaska Sea Grant Program Rep. AK-SG-93-02.

Breen, P. A. 1979. The ecology of red sea urchins in British Columbia. *In* Int. Symp. Coastal Pac. Mar. Life, p. 3–12. West. Wash. Univ., Bellingham, 73 p.

CDFG. 1990. California marine fish landings for 1977–1986. Resour. Agency, Calif. Dep. Fish Game, Sacramento, Fish Bull. 173, 52 p.

Dayton, P. K., and M. J. Tegner. 1989. Bottoms beneath troubled waters: benthic impacts of the 1982–84 El Niño in the temperate zone. *In* P. W. Glynn (Editor), Global ecolological consequencies of the 1982–83 ENSO, p. 433–472. Elsevier Oceanogr. Ser. (Amst.), No. 52.

Ebert, E. E. 1968. California sea otter - census and habitat survey. Underwater Nat. 5(3):20–22.

Ebert, T. A., and M. P. Russell. 1988. Latitudinal variation in size structure of the west coast purple sea urchin: A correlation with headlands. Limnol. Oceanogr. 33(2):286–294.

________ and ________ . 1992. Growth and mortality estimates for red sea urchin *Strongylocentrotus franciscanus* from San Nicolas Island, California. Mar. Ecol. Prog. Ser. 81:31–41.

________, S. C. Schroeter, J. D. Dixon, and P. Kalvass. 1994. Settlement patterns of red and purple sea urchins (*Strongylocentrotus fransciscanus* and *S. purpuratus*) in California, USA. Mar. Ecol. Prog. Ser. 111:41–52.

Gulland, J. 1974. The management of marine fisheries. Univ. Wash. Press, Seattle, 198 p.

Harrold, O., and D. C. Reed. 1985. Food availability, sea urchin grazing, and kelp forest community structure. Ecology 66(4):1160–1169.

Hilborn, R. 1992. Current and future management trends in fisheries stock assessment and management. S. Afr. J. Mar. Sci. 12:975–980.

________ and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, N.Y., 570 p.

Jamieson, G. S., and J. F. Caddy. 1986. Research advice and its application to management of invertebrate resources: an overview. *In* G.S. Jamieson and N. Bourne (Editors), North Pacific workshop on stock assessment and management of invertebrates, p. 416–424. Can. Spec. Publ. Fish. Aquat. Sci. 92.

Kalvass, P. 1992. The northern California commercial sea urchin fishery-a case study. *In* The management and enhancement of sea urchins and other kelp bed resources: A Pacific rim perspective, p. 1–14. Calif. Sea Grant Rep. T-CSGCP-028. Univ. Calif., La Jolla.

________ and I. Taniguchi. 1993. Relative abundance and size composition of red sea urchin, *Strongylocentrotus franciscanus*, populations along the Mendocino and Sonoma county coasts, 1991. Resour. Agency, Calif. Dep. Fish Game, Mar. Res. Admin. Rep. 93-1, 70 p.

________ , ________ , P. Buttolph, and J. DeMartini. 1991. Relative abundance and size composition of red sea urchin, *Strongylocentrotus franciscanus*, populations along the Mendocino and Sonoma county coasts, 1989. Resour. Agency, Calif. Dep. Fish Game, Mar. Res. Admin. Rep. 91-3, 103 p.

Kato, S., and S. C. Schroeter. 1985. Biology of the red sea urchin, *Strongylocentrotus fransciscanus*, and its fishery in California. Mar. Fish. Rev. 47(3):1–20.

Kushner, D., D. Lerma, and D. Richards. 1995. Kelp forest monitoring, 1994 annual report. U.S. Dep. Inter., Natl. Park Serv., Channel Isl. Natl. Park Tech. Rep. CHIS-95-03, 124 p.

Lai, H. L., and A. Bradbury. In Press. Exploitation dynamics and management strategies for a red sea urchin (*Strongylocentrotus franciscanus)* population. Can. Spec. Publ. Fish. Aquat. Sci.

Levitan, D. R., M. R. Sewell, and F. Chia. 1992. How distribution and abundance influence fertilization success in the sea urchin *Strongylocentrotus franciscanus*. Ecology 73(1):248–254.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science 260:235–241.

Lynn, R. J., F. B. Schwing, and T. L. Hayward. 1995. The effect of the 1991-93 ENSO on the California current system. CalCOFI Rep. 36:57–71.

McLean, J. G. 1962. Sublittoral ecology of kelp beds of the open coast area near Carmel, California. Biol. Bull. 122(1):95–114.

Methot, R. D., Jr. 1986. Management of Dungeness crab fisheries. *In* G. S. Jamieson and N. Bourne (Editors), North Pacific workshop on stock assessment and management of invertebrates, p. 326–334. Can. Spec. Publ. Fish. Aquat. Sci. 92.

________ and L. W. Botsford. 1982. Estimated preseason abundance in the California Dungeness crab (*Cancer magister*) fisheries. Can. J. Fish. Aquat. Sci. 39:1077–1083.

Morris, R. H., D. P. Abbott, and E. C. Haderlie. 1980. Intertidal invertebrates of California. Stanford Univ. Press, Stanford, Calif., 690 p.

NOAA. 1991. NOAA diving manual. U.S. Dep. Commer., NOAA, Rockville, Md., 400 p.

Pearse, J. S., and A. H. Hines. 1987. Long-term population dynamics of sea urchins in a central California kelp forest: rare recruitment and rapid decline. Mar. Ecol. Prog. Ser. 39:275–283.

Pennington, J. T. 1985. The ecology of fertilization of echinoid eggs: the consequences of sperm dilution, adult aggregation and synchronous spawning. Biol. Bull. 169:417–430.

Pfister, C. A., and A. Bradbury. 1996. Harvesting red sea urchins: Recent effects and future predictions. Ecol. Appl. 6:298–310.

Quinn, J. F., S. R. Wing, and L.W. Botsford. 1993. Harvest refugia in marine invertebrate fisheries: models and applications to the red sea urchin, *Strongylocentrotus franciscanus*. Am. Zool. 33:537–550.

Reynolds, J. A. 1994. Economic analysis of factors affecting prices and costs in the California sea urchin fishery. Univ. Calif., Davis, M.S. thesis, 86 p.

Richards, D., and D. Kushner. 1994. Kelp forest monitoring, 1992 annual report. U.S. Dep. Inter., Natl. Park Serv., Channel Isl. Natl. Park. Tech. Rep. CHIS-94-01, 127 p.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Can. Fish. Res. Board 191:1–382.

Rogers-Bennett, L., W. A. Bennett, H. C. Fastenau, and C. M. Dewees. 1995. Spatial variation in red sea urchin reproduction and morphology: implications for harvest refugia. Ecol. Appl. 5(4):1171–1180.

Roughgarden, J., S. Gaines, and H. Possingham. 1988. Recruitment dynamics in complex life cycles. Science 241:1460–1466.

Rowley, R. J. 1989. Settlement and recruitment of sea urchins (*Strongylocentrotus* spp.) in a sea urchin barren ground and a kelp bed: are populations regulated by settlement or post-settlement processes? Mar. Biol. 100:485–494.

Saito, K. 1992. Japan's sea urchin enhancement experience. *In* The management and enhancement of sea urchins and other kelp bed resources: A Pacific rim perspective, p. 50–61. Calif. Sea Grant Rep. T-CSGCP-028. Univ. Calif., La Jolla.

Shepherd, J. G. 1993. Why fisheries need to be managed and why technical conservation measures on their own are not enough. Minist. Agric. Fish Food Lab. Leafl. 71:5–15.

Sloan, N. A., C. P. Lauridsen, and R. M. Harbo. 1987. Recruitment characteristics of the commercially harvested red sea urchin *Strongylocentrotus franciscanus* in southern British Columbia, Canada. Fish. Res. 5:55–69.

Sonu, S. C. 1995. The Japanese sea urchin market. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-SWR-030, 33 p.

Statmost. 1995. Statmost statistical analysis and graphics. DataMost Corp., Salt Lake City, Utah, 851 p.

Tegner, M. J. 1989. The feasibility of enhancing red sea urchin *Strongylocentrotus franciscanus* stocks in California; an analysis of the options. Mar. Fish. Rev. 51(2):1–22.

________ and P. K. Dayton. 1977. Sea urchin recruitment patterns and implications of commercial fishing. Science 196:324–326.

________ and ________ . 1981. Population structure, recruitment and mortality of two sea urchins (*Strongylocentrotus franciscanus* and *S. purpuratus*) in a kelp forest. Mar. Ecol. Prog. Ser. 5:255–268.

________ and ________ . 1991. Sea urchins, El Niños, and the long term stability of southern California kelp forest communities. Mar. Ecol. Prog. Ser. 77:49–63.

Wing, S. R., J. L. Largier, L. W. Botsford, and J. F. Quinn. 1995. Settlement and transport of benthic invertebrates in an intermittent upwelling region. Limnol. Oceanogr. 40:316–329.

Woodby, D. 1992. Red sea urchins in southeast Alaska:status of research and management.In:The management and enhancement of sea urchins and other kelp bed resources: A Pacific rim perspective, p. 70–81. Calif. Sea Grant Rep. T-CSGCP-028. Univ. Calif., La Jolla.