History and Trends in Oregon's Red Sea Urchin, *Mesocentrotus franciscanus,* and Purple Sea Urchin, *Strongylocentrotus purpuratus,* Fisheries, 1986–2022

SCOTT GROTH

Introduction

Biology

The red sea urchin, *Mesocentrotus franciscanus,* is the largest species of sea urchin (up to 211 mm test diameter (TD)) common to the rocky nearshore of the U.S. west coast (Ebert et al., 2018). It ranges from Baja Mexico to Kodiak, Alaska (Ebert et al., 1999) where the species is common in shallow (i.e., 3–35 m depth) rocky reef habitats and most abundant within kelp beds (Rogers-Bennett, 2007). They eat marine vegetation, such as drifting kelp. When well fed their gonads become robust in winter months in preparation for spring spawning (Dean et al., 1984).

Reproduction is episodic, affected by coastal circulation and upwelling conditions (Morgan et al., 2001), and consequently they have evolved life spans greater than 100 years (Ebert and Southon, 2003). Reproduction may also be affected by high water temperatures which shorten their larval period (Cameron and Schroeter, 1980) and may lead to conditions of higher predation and greater stress (Russell, 1987). While their larvae may travel great distances during their 62–131 day larval period (Strathmann, 1978), once settled, they only travel short distances, mostly when food is scarce (Mattison et al., 1977).

The red sea urchin's complex biological characteristics demand skillful fishing since the fishery product is their gonads, the quality of which depends heavily on seasonal, environmental, and demographic conditions. Sea urchin gonads are marketed as "uni," typically combined with rice to make a popular sushi item.

Fishery History

Red sea urchin commercial fishing along the U.S. west coast is relatively recent and has undergone major shifts. The fishery began in the 1970's in southern California, and by the 1980's market demand accelerated and exploration for unexploited stocks extended throughout their range (Kato and Schroeter, 1985). Between the late 1980's and early 1990's Japan's economy expanded which increased demand for uni and stimulated the fishery (Kalvass and Hendrix, 1997). Broadly, the west coast red sea urchin fishery was characterized by a rapid increase in landings, then an equally rapid decrease as stocks were depleted (mid-1990's), followed by a long period (1995–2022) of fishery stability (Fig. 1). State-specific red sea urchin fishing histories along the U.S. west coast were reviewed for northern California by Kalvass and Hendrix (1997), for Washington by Pfister and Bradbury (1996), and for Oregon in this paper. Little recreational catch of sea urchins occurs on the U.S. west coast (personal observ.).

In 1986, the search for unexploited red sea urchin stocks reached Oregon. At that time, the red sea urchin's primary predator, the sea otter, *Enhydra lutris,* had been extirpated by fur traders from Oregon more than a century prior (Jameson et al., 1982). Lacking a predator or fishery pressure, red sea urchin densities were likely at a historic peak. High-density stocks were indeed discovered and infrastructure (e.g., vessels, processing plants,

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ABSTRACT—The red sea urchin, Mesocentrotus franciscanus*, is a large echinoid common to the rocky vegetated nearshore areas throughout the U.S. west coast. Red sea urchin fisheries are among the U.S. west coast's most valuable dive fisheries. These fisheries are broadly characterized as "boom and bust," where a virgin stock is quickly removed without much replacement via recruitment. The unique life history of red sea urchin (long lived, episodic recruitment, etc.) deeply affected the patterns of the stock and consequently the fishery.*

Oregon's red sea urchin fishery also experienced a boom and bust, like many similar fisheries. Fishing began in 1986 and boomed to total catches greater than 4,200 t in 1990. By 1993, the catch dropped below 1,000 t per year where it has remained. Between 1997 and 2017, catch remained low but value was steady, characterized by a low number of participants fully involved in the fishery. During 2018–22, catch has remained steady; however, unit price grew five times the previous era. For years, Oregon's (previously unfished) stock of red sea urchin was removed by the fishery without new recruitment and did not operate in a way consistent with classic definitions of "sustainable." While stock levels were the lowest on record in 2014, ensuing episodic recruitment events were so great that densities of red sea urchin returned to unfished levels. The future of Oregon's red sea urchin fishery likely depends heavily on episodic recruitment events which occur infrequently. Managing the stock and fishery then is complicated and complex and may depend on long-term monitoring combined with a high degree of management flexibility.

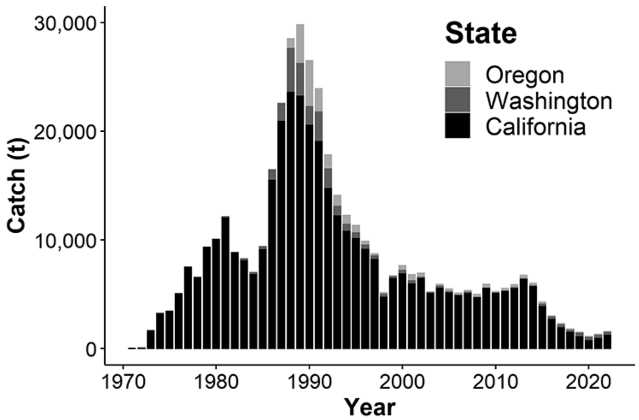


Figure 1.—Red sea urchin landings in Oregon, Washington, and California by year, 1972–2022 (Pacific States Marine Fisheries Commission, 2022).

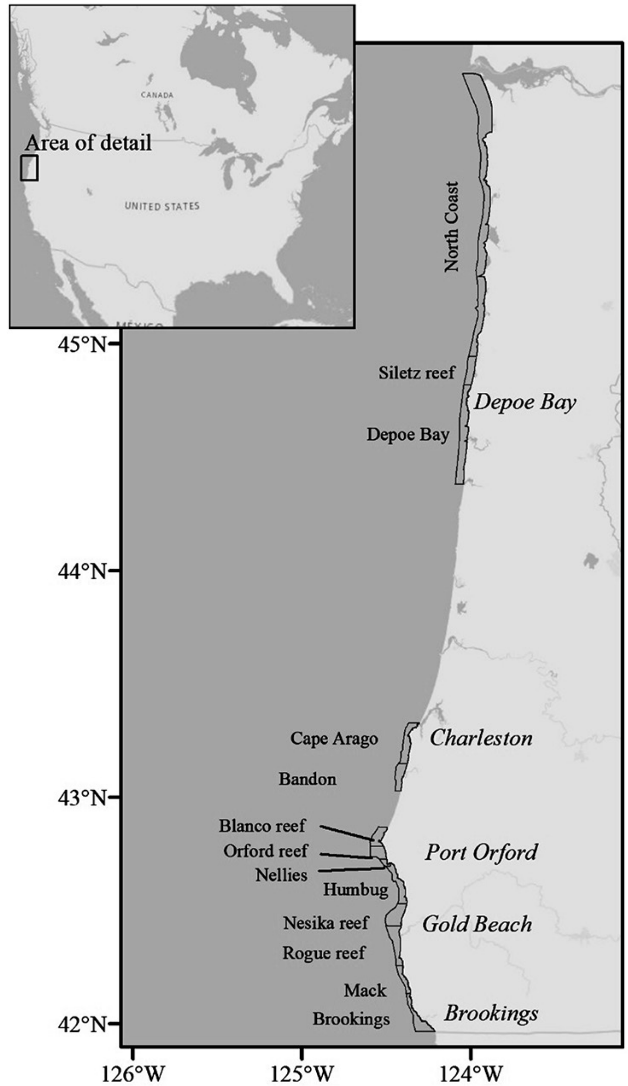


Figure 2.—Sea urchin "ODFW areas" (defined by continuous reef) in relation to ports important to sea urchin deliveries along the Oregon coast.

etc.) were developed around this budding industry. The stock was fished down; efficiency and then effort both declined. By 1996, the last remaining Oregon sea urchin processing facility closed (Richmond et al., 1997), and since that time, sea urchins have been trucked to adjacent states for processing. Since the late 1990's catch and effort has remained steady, albeit at a lower level.

Fishery Scope

Oregon's red sea urchin fishery is an important component of the states' fishery profile with connections to the broader region. California has the most extensive kelp beds (thus fishing area) and consequently is the largest and most valuable component of the U.S. west coast fishery cumulatively totaling, 387,412 t from 1971 to 2022. Washington State has limited coastal kelp beds but extensive kelp beds within Puget Sound. Landings in Washington have totaled 23,366 t between 1981 and 2022. Oregon's fishery is similarly sized to Washington, totaling 20,587 t from 1986 to 2022 (Pacific States Marine Fisheries Commission, 2022). Overall, the U.S. west coast red sea urchin fishery had a strong peak centered around 1990, when factors such as strong markets and exploration of previously unexploited stocks caused the fishery to boom (Fig. 1).

Oregon's coastline measures 362 miles (636 km) and is characterized by rocky shores in southern portions, while the northern portions of the state tend to be sandy. Given the predominance of rocky shorelines in the southern portion of Oregon, kelp beds (mostly *Nereocystis luetkeana*) occur most prominently. Importantly, two large offshore rocky reefs account for most of Oregon's kelp beds: Orford Reef and Rogue Reef hold most of Oregon's kelp beds (Merems and Donnellan, 2011), and consequently the majority of the red sea urchin catch (71%) has occurred at those areas (Fig. 2).

Purple and Green Sea Urchins

The Oregon sea urchin fishery focuses on red sea urchin; however, the purple sea urchin, *Strongylocentrotus purpuratus,* is a minor component of landings, accounting for less than 1% of historic catch (Pacific States Marine Fisheries Commission, 2022). Green sea urchin, *Strongylocentrotus*

Sea urchin diver jumping in the water while tender prepares gear. Photo: Scott Groth.

droebachiensis, a target of fisheries north of Oregon (Washington, Canada, and Alaska) are uncommon in Oregon; however, they have been found to be present in extremely small numbers for the first time in 2015, near Port Orford (personal observ.).

Methods and Materials

Fishery Methods

The fishery for red sea urchin is artisanal in nature, requiring specialized diving gear and a high degree of skill to take quality products. Divers use a surface supplied air system, referred to as "hookah," which allows them an unlimited supply of air. Divers pick individual sea urchins off the reef using a hand rake and place them in suspended mesh bags, made neutrally buoyant with the aid of a buoy of lift bag system. This enables divers to move their catch and mesh bag along as they swim the reef. Since sea urchin are individually collected, there is no bycatch.

Dive tenders (non-diving crewmembers) keep lines clear, assist getting divers and catch on and off the vessel, and assure that things are running smoothly while divers are underwater. Most sea urchin divers begin their careers as dive tenders to gain experience on the water because commercial diving requires more skill and knowledge compared to most other fisheries and has a higher degree of danger.

Sea urchin vessels make single-day trips, returning to port each day for processing. Vessels in the fleet are mostly small boats (<35 ft long) with a shallow draft for fishing tight and shallow areas. During a single day trip, each diver (usually 1–4 individuals) makes multiple dives, constrained by sunlight and safe diving time. Live catch is returned to port daily and then trucked to remote processing facilities. Processing requires cracking the sea urchin's test and removing the five skeins of gonad (erroneously called "roe") (Kato and Schroeter, 1985). Less frequently they are sold whole in live markets. The quality and quantity of sea urchin gonads in each landing determines the value, not strictly the whole wet weight landed at port as in other fisheries.

Catch, Effort, and Stock Metrics

Landing receipts and fishery logbooks for 1986–2022 were used to assess catch and effort. Buyers fill out a receipt for each landing of sea urchins and must record diver name, date, port landed, total pounds for each species, and the unit price. To assess catch by reef, logbooks from 1986 to 2022 were used. Logbooks require the recording of catch area (e.g., reef name), depth, diving time, and estimated weight of catch. From 1986 to 2011 divers recorded logbook information as a daily summary, consisting of a coarse description of area and estimated weight of catch. Beginning in 2012 divers recorded logbook information for individual dives, including GPS data combined with estimated catch weight from each dive. To measure stock metrics, we used market sampling and population surveys.

Market Sampling

To understand changes in the size distribution of red sea urchin caught in the fishery, market sampling was employed. During opportunistically selected deliveries, biologists measured the TD of 50 randomly selected red sea urchin using 300 mm Vernier calipers. Data were pooled according to catch area and by year, (Fig. 2 shows the areas). Occasionally, divers targeted only the largest red sea urchins to satisfy specific markets; those deliveries were not sampled. Market sampling at Orford Reef was robust and continuous, while other areas were fished and sampled less frequently (Table 1).

Population Surveys

Index sites were used to measure the abundance and size distribution of red sea urchin populations in areas critical to the fishery. Survey areas were selected based on three criteria: 1) relevance to the fishery (e.g., prime catch areas, reserve areas, etc.), 2) expected presence of commercial quantities of red sea urchin, and 3) depths were generally shallower than 20 m. Surveys were performed periodically from the early 1990's to 2019, though earlier survey data by Oregon State University (OSU) from 1983 and 1984 was also incorporated (Washburn, 1984). Red sea urchin population surveys were conducted at three ports (Port Orford, Depoe Bay, and Charleston) important to the fishery, and, in each, fished and reserve areas were surveyed over time (Table 2).

Surveys were performed using subtidal belt transects. At each transect, two divers worked together to extend a 30 or 40 m line, then identify and count sea urchin species within 1 m perpendicular to each side of the transect line (Fig. 3). Survey methodology focused on emergent sea urchins, rocks were not moved, and lighting was not used.

For size distribution, two methods were used. For surveys from the 1990's, the first 50 red sea urchins in each transect were measured in situ, when fewer than 50 were found, those areas adjacent to the transect were searched until 50 were measured. For surveys from the 2010's, all sea urchins were collected and brought to the surface for measurement, when sea urchins were too numerous for this to

Sea urchin diver with a deckload of red sea urchins. Photo: Scott Groth.

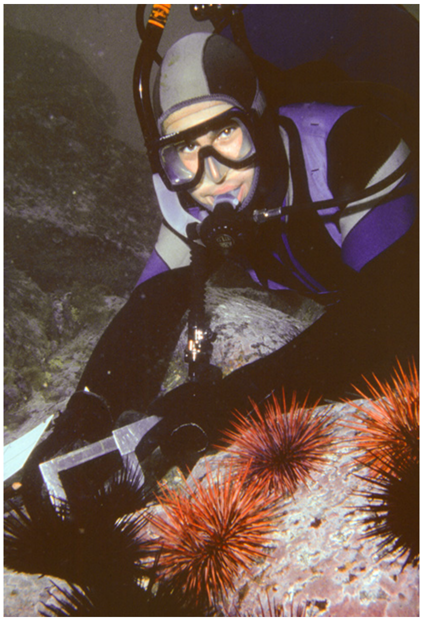
be practical the first 50 of each sea urchin species were collected, when less than 50 sea urchins (per species) were found, no extra efforts to measure sea urchins at the site were made. Importantly, population survey siting focused on the red sea urchin, not the purple sea urchin, which is found at highest densities shallower than these surveys occur.

Survey Areas

Three ports were selected to index red sea urchin populations in Oregon: Port Orford, Depoe Bay, and Charleston. Selection was based on importance to the fishery, accessibility, and geographical separation. Transect sites were repeated as geographically exactly as possible in each sampling event. The number of sites surveyed at each area in a year was constrained by budget.

Table 1.—Mean test diameter size (mm) and number of red sea urchin from market samples, by ODFW area, 1987–2022.

	Rogue		Humbug		Orford		Arago		Depoe			
Year	*n*	Mean size (mm)	*n*	Mean size (mm)	*n*	Mean size (mm)	*n*	Mean size (mm)	*n*	Mean size (mm)	Total *n*	Mean size (mm)
1987					50	131.40					50	131.40
1988	30	120.60	55	120.96	763	108.05	125	120.45			973	110.76
1989	678	128.60	86	107.65	2,381	124.05	150	122.89	33	113.64	3,328	124.40
1990	1,761	126.83	2,190	120.79	7,420	128.34	350	123.81	367	130.41	12,088	126.68
1991	975	122.56	150	106.43	2,570	116.20	75	111.77	330	113.53	4,400	117.49
1992	150	119.66	250	113.16	2,567	113.93	125	114.81	350	118.97	3,492	114.86
1993					1,205	110.53	474	110.88	1,149	105.12	2,828	108.39
1994	100	134.85	100	110.67	1,656	111.83	50	114.92	290	110.46	2,196	112.71
1995	200	114.25			600	112.11					800	112.65
1996	450	110.32			600	108.36			50	101.12	1,100	108.83
1997	50	106.82			950	106.81					1,000	106.81
1999					1,052	106.73					1,052	106.73
2000					1,600	107.49					1,600	107.49
2001					1,248	106.74					1,248	106.74
2002					150	104.67					150	104.67
2004					149	110.14					149	110.14
2005			107	116.03	320	117.14	243	114.05			670	115.84
2006	207	123.08	50	105.32	203	122.81					460	121.03
2007					183	116.15					183	116.15
2008					634	113.54			200	115.61	834	114.04
2009					1,592	111.54					1,592	111.54
2010			250	118.14	896	120.27	309	119.58			1,455	119.76
2011			50	120.21	3,029	120.27					3,079	120.27
2012					499	117.23	872	115.92	500	115.03	1,871	116.03
2013					1,100	119.83					1,100	119.83
2014					900	126.24					900	126.24
2015					550	128.05					550	128.05
2016					100	127.93					100	127.93
2017	100	100.46	50	116.82	399	109.24					549	108.33
2018	142	95.56									142	95.56
2019	54	94.21									54	94.21
Total	4,897		3,338		35,366		2,773		3,269		49,993	
Average		121.93		118.28		117.78		116.70		112.95		117.89



ODFW biologist measuring red sea urchin in situ during fishery independent survey. Photo: ODFW Archives.

Port Orford

Three areas were selected to index red sea urchin populations near Port Orford on Oregon's south coast (Fig. 4). Two fished areas were surveyed: 1) Orford Reef, a 1,367 hectare (ha) area 10 km northwest of the port of Port Orford and 2) Humbug Mountain, a 200 ha area 9 km south of Port Orford. One reserve area was also surveyed, Redfish Rocks Marine Reserve (MR), a no-take marine reserve, 5 km south of Port Orford. Prior to its establishment as a marine reserve in 2012 the Redfish Rocks area was an important sea urchin fishing area.

Depoe Bay

Five areas were selected to index red sea urchin populations near Depoe Bay, on Oregon's central coast (Fig. 5). Three fished areas were surveyed: 1) Government Point, a 160 ha area 1.6 km northwest of Depoe Bay, 2) Depoe Bay, a 240 ha area adjacent to Depoe Bay, and 3) Cape Foulweather, a 200 ha area south of Depoe Bay. Pirates Cove Research Reserve (RR) is a small (3 ha) no-take research reserve 1.1 km north of Depoe Bay, established

Table 2.—Summary of red and purple sea urchin densities (per m²) by year and reef in Oregon, 1991–2019.

Port	Reef	Year	*n*	Mean red sea urchin density	Mean purple sea urchin density
Charleston	Gregory Point	1996	2	1.40	0.70
		1997	1	1.20	1.60
		2013	6	0.48	0.21
		2015	6	0.45	4.02
	Lighthouse	2013	5	1.24	0.00
		2015	5	1.47	1.00
	Simpson Reef	1993	1	0.20	0.00
		1996	1	0.20	0.00
		1997	1	0.40	0.00
		1999	1	0.60	0.00
		2013	18	0.19	0.01
		2015	17	0.22	0.11
Depoe Bay	Cape Foulweather	1991	2	0.08	0.00
		1994	10	0.67	0.01
		1996	10	1.11	0.05
		1998	9	0.58	0.00
		2012	11	0.27	0.01
		2015	12	0.21	0.23
	Depoe Bay	1991	4	0.85	0.10
		1994	6	1.62	0.62
		1996	6	2.62	0.02
		1998	3	1.97	0.00
		2012	7	1.49	1.13
		2015	7	0.72	0.48
	Government Point	1991	2	0.36	0.00
		1994	9	1.77	0.77
		1996	5	2.83	0.69
		1998	6	1.92	0.43
		2012	5	0.90	0.01
		2015	4	1.17	0.00
	Pirates Cove	2012	4	0.26	0.00
		2015	4	0.20	0.05
	Whale Cove	1996	1	0.53	0.01
		1997	1	0.80	0.00
		1998	1	1.80	0.00
		2012	6	0.42	0.00
		2015	6	0.50	0.01
Port Orford	Humbug	1992	5	0.41	0.01
		2011	15	0.09	0.00
		2014	9	0.13	0.00
		2016	17	0.29	0.53
		2019	9	1.54	3.89
	Island Rock	1984	1	1.70	0.00
		1992	4	0.73	0.01
	Nellies Cove	1984	4	3.07	0.00
		1992	3	0.88	0.04
		1993	1	0.96	0.01
		2015	19	1.52	2.57
		2019	11	2.02	14.93
	Orford Reef	1984	6	2.71	0.00
		1991	37	0.88	0.00
		1993	39	0.90	0.05
		1995	41	0.68	0.08
		1997	15	0.65	0.07
		2011	39	0.27	0.00
		2014	36	0.52	0.06
		2016	30	3.29	2.52
		2019	24	4.66	6.24
	Redfish Rocks	1984	4	2.60	0.00
		1992	2	2.28	0.03
		2011	16	0.42	0.00
		2014	8	0.74	0.00
		2016	15	1.13	0.28
		2019	9	1.87	0.66

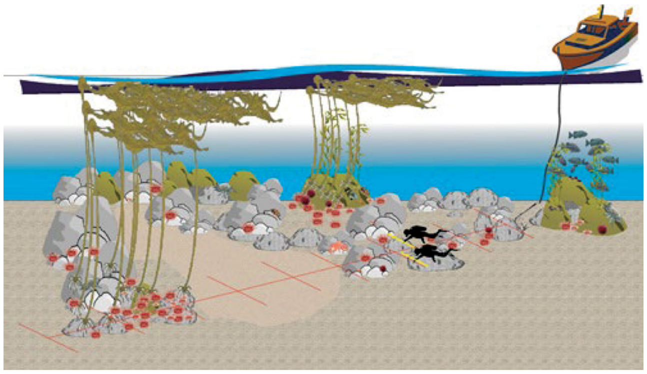


Figure 3.—Illustration of methodology for subtidal belt transects used in ODFW sea urchin population surveys (illustration by Scott Groth).

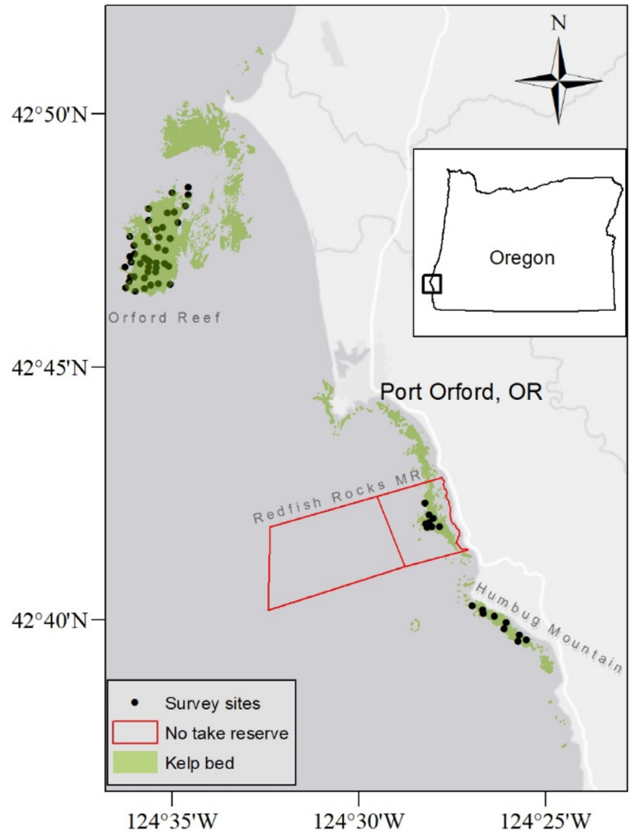


Figure 4.—Sea urchin population index survey sites near Port Orford.

in 1999. Whale Cove Habitat Reserve (HR) is a small (13 ha) no-take reserve established in 1963, 2.5 km south of Depoe Bay. Otter Rock MR is a small no-take marine reserve, 7 km south of Depoe Bay established in 2012; however, data from this area was combined with Cape Foulweather since its adoption was recent and long-term fishing pressure has been minimal.

Charleston

Three areas were selected to index red sea urchin populations near Charleston, a port on Oregon's south-central coast (Fig. 6): 1) Simpson Reef, an expansive fishing area (300 ha) surrounding Cape Arago and 7 km southwest of Charleston; 2) Gregory Point RR, a 24 ha no-take reserve, established in 1993 and 4 km west of Charleston; and 3) Lighthouse Beach, a small (13 ha) but geographically separate area 13 km south of Charleston and adjacent to the north edge of Gregory Point RR.

Results

Catch, Effort, and Value

Red sea urchin fishery landings in Oregon developed quickly (1986–88), expanded and then decreased dramatically (1989–1995). Finally, they were reduced to a stable level from 1996 to 2022. The fishery began in 1986, and by 1990, 4,228 t were landed. By 1996, landings had dropped dramatically, averaging 217 t (annually) from 1996 to 2022. Effort (measured number of individual trips) closely mirrors total landings, with some lag as the stocks were depleted, going from 31 in 1986 to 4,435 in 1991. In the most recent 10-yr period (2013–22), effort has been stable, averaging 325 trips per year (Fig. 7).

Similar to catch and effort, the value of the fishery experienced rapid expansion, then became stable at a lower level. Value of the fishery peaked in 1990 with an ex-vessel value of $3.4 million in 1990; at that time, markets were excellent and Oregon was able to develop processing infrastructure, further elevating ex-vessel value. Fishery stock and markets quickly declined, and the fishery became smaller but stable. From 1996 to 2017, value averaged $284,000 per year. Recent years (2018 to 2022) have seen highly increased prices and values consequent with low kelp conditions along the U.S. west coast. Fishery value from 2018 to 2022 averaged $673,400 annually.

Price per pound of red sea urchin has been variable, with recent sudden changes (Fig. 8). Mean price per pound in the early years was high (e.g., $1.93/kg in 1993) as markets were lucrative. At that time, the Japanese economy (the primary market) was booming and previously unexploited U.S. west coast stocks provided a robust source. As the stock was depleted and the Japanese economy turned down, prices declined. As the fishery matured and stock levels remained low, domestic markets were used more frequently. Beginning around 2016, U.S. west coast kelp beds decreased, reducing the amount of high quality uni, leaving just a few areas of Oregon still viable for markets causing the price to elevate, and from 2018 to

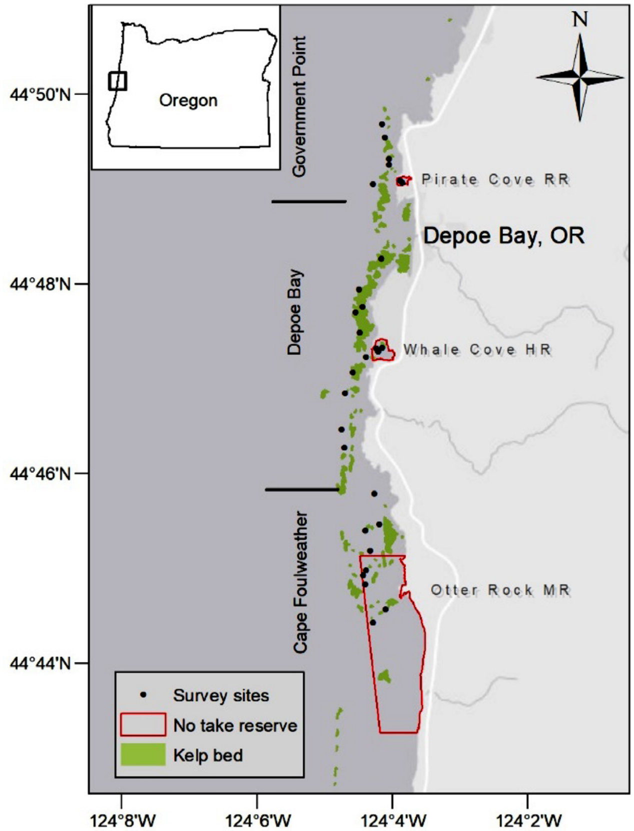


Figure 5.—Sea urchin population index survey sites near Depoe Bay.

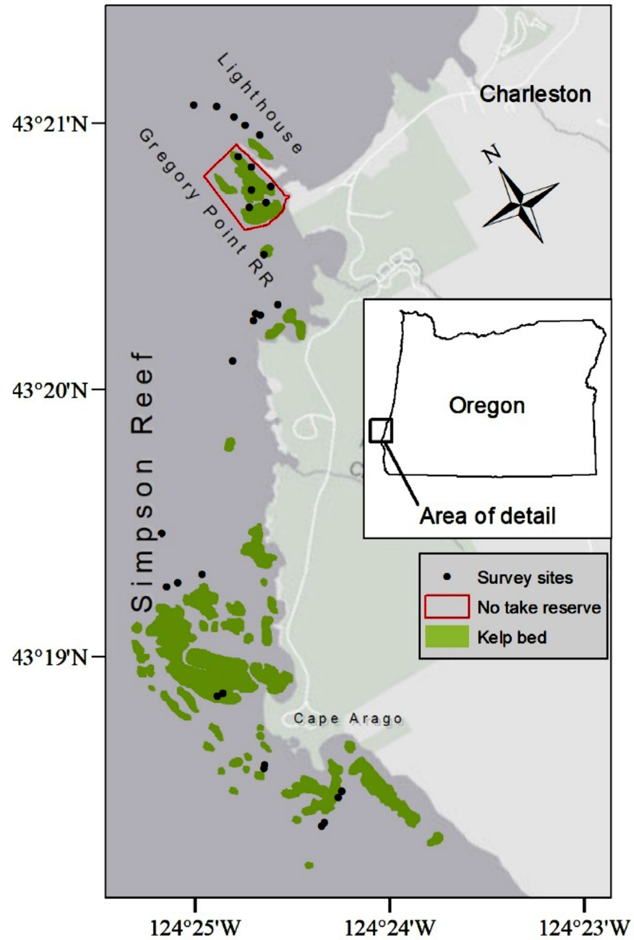


Figure 6.—Sea urchin population index survey sites near Charleston.

2022 prices were at all-time highs (averaging $6.10/kg).

Catch by Port

Oregon's red sea urchin fishery catch is focused on the southern portion of the state. In total 20,587 t have been caught across the 1986–2022 period. By port, Port Orford has had the highest landings (11,733 t) followed distantly by Gold Beach (4,779 t), then Depoe Bay (1,820 t), Charleston (979 t), Brookings (724 t), and Newport (517 t), while other ports including Garibaldi and Pacific City (combined) added 35 t (Table 3).

Catch by Fishing Area

Most of the Oregon red sea urchin landings originate from the south coast at Orford Reef and Rogue Reef. On average, these two areas account for 71% of the landings from years 1986 through 2022 (Fig. 9). Fishery logbooks also validate this fact as diver-based accounts show that most landings are occurring here, and that they are strongly associated with the presence of surface canopy kelp (Fig. 10). This strong correlation has not been evaluated thoroughly, but future analysis may include modeling or statistical analyses showing that kelp canopy can be a strong predictor of sea urchin catch.

Catch by Depth

Time at depth constrains fishing (dive) time in this fishery. As a diver descends, the amount of time one may stay underwater declines, due to increased nitrogen absorption. Typically, sea urchin divers attempt to stay as shallow as possible (for increased dive time), while considering sea state conditions (swell, current, etc.). The mean diving depth of fishing was 14.6 m, deeper at offshore reefs (Orford Reef (16.7 m), Rogue Reef (14.8 m)), and shallower at nearshore areas (Depoe Bay (9.3 m), Charleston (8.7 m), and Brookings (10.4 m)).

Stock Metrics

Market Sampling

Catch at Orford Reef shows a pattern familiar to the "boom and bust" of a virgin stock. Initial market sampling showed catch of primarily large, older animals in the first years of the fishery (1986–90). From 1991 to 2002, a period of "recruitment fishing" occurred, where catch was dominated by red sea

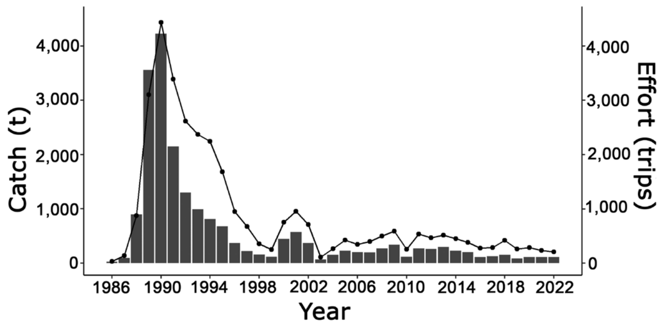


Figure 7.—Catch (t, bar chart) and effort (number of trips, line chart) in Oregon's commercial red sea urchin fishery, 1986–2022.

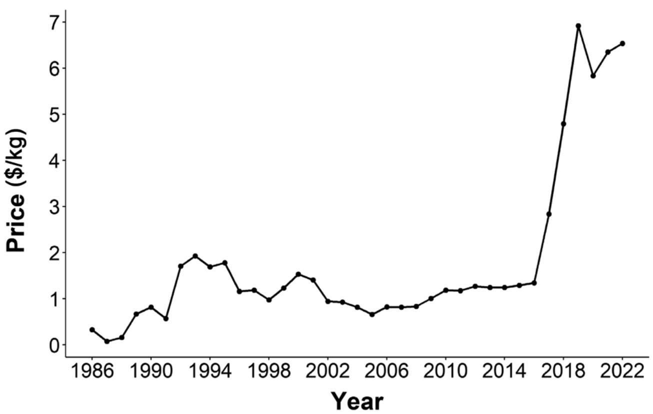


Figure 8.—Nominal price $/kg for red sea urchin in Oregon, 1986–2022.

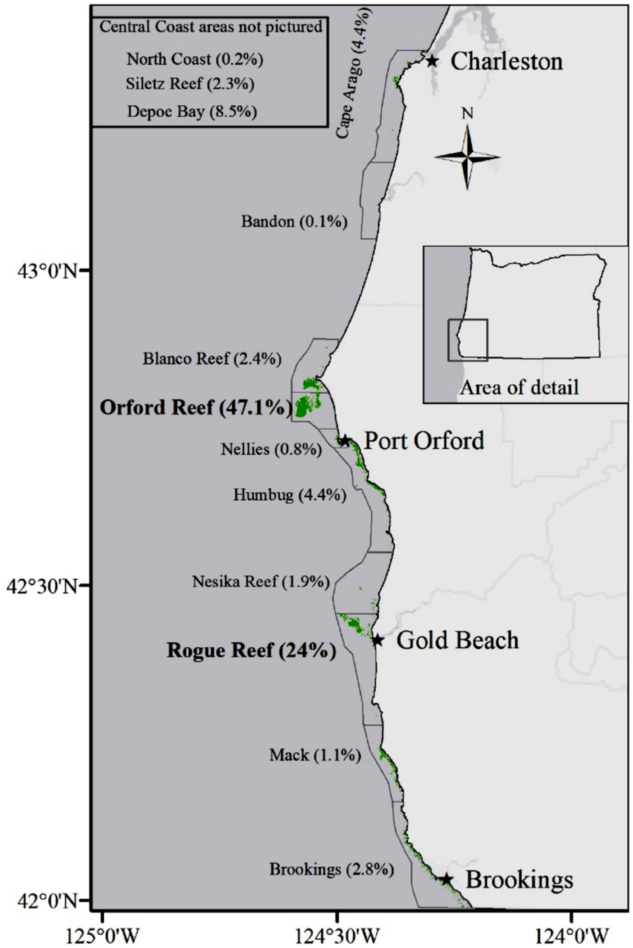


Figure 9.—Catch of red sea urchin by ODFW area, in Oregon, 1986-2022. Note emphasis on south coast areas particularly, Orford Reef and Rogue Reef.

urchin, simply recruiting to minimum legal size (MLS). From 2004 to 2016 when red sea urchin fishing pressure was lower, larger and older individuals again became a substantial component of catch. Sampling during 2017–18 shows smaller individuals in the catch again, probably due to incoming cohorts of fast-growing red sea urchin from recent episodic events recruiting to MLS (Fig. 11).

The early years of market sampling show many large and old red sea urchin caught at Orford Reef. Several individuals measuring >180 mm TD were caught in the first years of the fishery, including a maximum size of 197 mm found in a 1989 market sample. No red sea urchin of this size has been found after this initial fish-down of the stock; however, they have been found at this size in population survey samples of Whale Cove HR, the only area of the state established as a no-take reserve prior to the inception of the fishery. This is evidence of the intensity of the fishery and the long lives of the red sea urchin.

Population Surveys

Together, abundance (i.e., number of sea urchins per m^2) and size distribution (i.e., sizes (expressed in TD)) provide insight into the population dynamics of the red sea urchin stock.

Port Orford The areas of Port Orford are most important to Oregon's red sea urchin fishery. Population surveys have focused primarily on Orford Reef, where a majority of Oregon's kelp bed area and fishery catch occur. Prior to the beginning of the fishery, stocks were robust but then were quickly fished down, to the extent that fishing interest dropped sharply. In recent years densities abruptly increased to pre-fishing levels.

Orford Reef Given its extent of shallow rocky grounds and kelp beds, Orford Reef is the highest value fishing area. Hence, it is a critical area to understand red sea urchin population abundance, size distribution, and recruitment in Oregon. Prior to fishery inception, red sea urchin densities were high (2.71/m^2 in 1984) and composed of large, old individuals (Washburn, 1984). From 1988 to 1997, fishery effort and landings were high. During this period, densities of red sea urchin were substantially reduced, and

Table 3.—Landed weight (mt) and nominal value ($) for red sea urchin in Oregon, 1986–2022.

	Port								Totals	
Year	Brooking	Gold Beach	Port Orford	Charleston	Newport	Depoe Bay	Garibaldi	Pacific City	Landings (t)	Value ($)
1986	0	0	25	0	0	0	0	0	25	8,313
1987	22	0	70	0	0	0	0	0	92	7,025
1988	24	102	681	81	1	4	0	0	894	141,731
1989	29	719	2,736	29	40	4	0	0	3,557	2,377,331
1990	52	1,174	2,230	132	100	523	9	9	4,228	3,447,461
1991	154	545	1,079	146	0	220	0	4	2,149	1,225,653
1992	65	174	769	39	25	224	0	0	1,296	2,212,784
1993	58	118	499	67	175	74	0	0	990	1,908,848
1994	26	229	480	16	6	55	0	0	812	1,372,999
1995	59	223	316	9	20	51	0	0	678	1,205,142
1996	15	136	202	11	4	3	0	0	372	431,388
1997	17	49	137	0	1	18	0	0	222	263,634
1998	21	56	49	20	2	8	0	0	156	152,164
1999	14	27	52	5	7	7	0	0	113	138,851
2000	3	123	168	85	9	58	0	0	446	682,484
2001	62	5	155	47	126	173	2	0	571	803,287
2002	62	42	97	55	0	112	0	0	368	347,879
2003	1	0	34	16	0	14	0	0	65	60,501
2004	0	3	69	41	0	37	0	0	151	122,670
2005	0	6	127	70	1	18	2	0	224	147,883
2006	0	48	91	12	0	50	2	0	203	166,185
2007	0	52	115	28	0	0	0	0	195	159,404
2008	0	13	182	20	0	51	2	0	268	223,168
2009	0	111	224	2	0	0	3	0	341	341,907
2010	5	15	93	2	0	0	0	0	114	134,711
2011	3	116	140	1	0	7	0	0	267	313,488
2012	1	29	131	12	0	85	0	0	258	327,982
2013	0	59	225	2	0	10	0	0	296	367,116
2014	0	25	204	0	0	0	0	0	229	284,508
2015	9	20	164	4	0	6	0	0	202	260,307
2016	0	9	102	0	0	0	0	0	112	149,518
2017	21	28	56	16	0	7	0	0	128	362,362
2018	0	138	13	0	0	0	0	0	151	725,445
2019	0	61	16	5	0	0	0	0	82	570,331
2020	0	105	1	5	0	0	0	0	111	652,044
2021	0	111	0	0	0	0	0	0	111	702,791
2022	0	109	0	0	0	0	0	0	109	716,266
Total	724	4,779	11,733	979	517	1,820	21	14	20,587	23,515,560

by 1997 densities were low (0.65/m²), when compared to "commercial quantities" (conventionally, one red sea urchin/m²). Across this period, effort and landings dropped sharply (Fig. 7). By 2011, after years of lower effort and landings, stocks had still not rebounded and were at their lowest levels found in this study. Strong recruitment events occurred throughout the mid-2010's, driving densities to their highest level (4.66/m² in 2019), fully recovering from the long and exploitive fishing effort (Fig. 12a).

In 1991, ODFW performed the first robust red sea urchin population survey of Orford Reef. Red sea urchin populations were dominated by very old, large individuals, combined with many smaller individuals, likely from a recruitment event in the late 1980's. The standing stock of old individuals was quickly removed (by the fishery) and the population was dominated by recruits from the 1980's episodic recruitment event until the mid-2010's. First detected in 2014, another strong episodic recruitment event occurred and has become the primary component of the recent stock (Fig. 12b).

Purple sea urchin populations at Orford Reef were nearly absent (in the deeper waters of these surveys), but they increased suddenly, beginning in 2014. Few purple sea urchins were found in early surveys (e.g., <0.01/m² in 1991), when suddenly in 2016, high abundances were found (2.52/m²), then increasing further in the most recent 2019 surveys (6.24/m²) (Fig. 13). The size of individual purple sea urchins at Orford Reef is generally small, with mean size at about 43.7 mm in 2019 (Fig. 14).

Humbug Mountain The rocky reefs adjacent to Humbug Mountain are less expansive than at Orford Reef, though they are geographically separated, allowing a good comparison area. The first surveys were conducted on Humbug Mountain in 1992. At that time, the fishery had already operated at this area for several years. Survey results from 1992 showed substantial densities (0.41/m²) of red sea urchin and few purple sea urchin (0.01/m²). Like Orford Reef, Humbug Mountain was fished down substantially by 2011. By 2019, red sea urchin populations recovered beyond the virgin stock conditions (Fig. 14a). Size distribution also showed a similar pattern as Orford Reef, where 1992 sur-

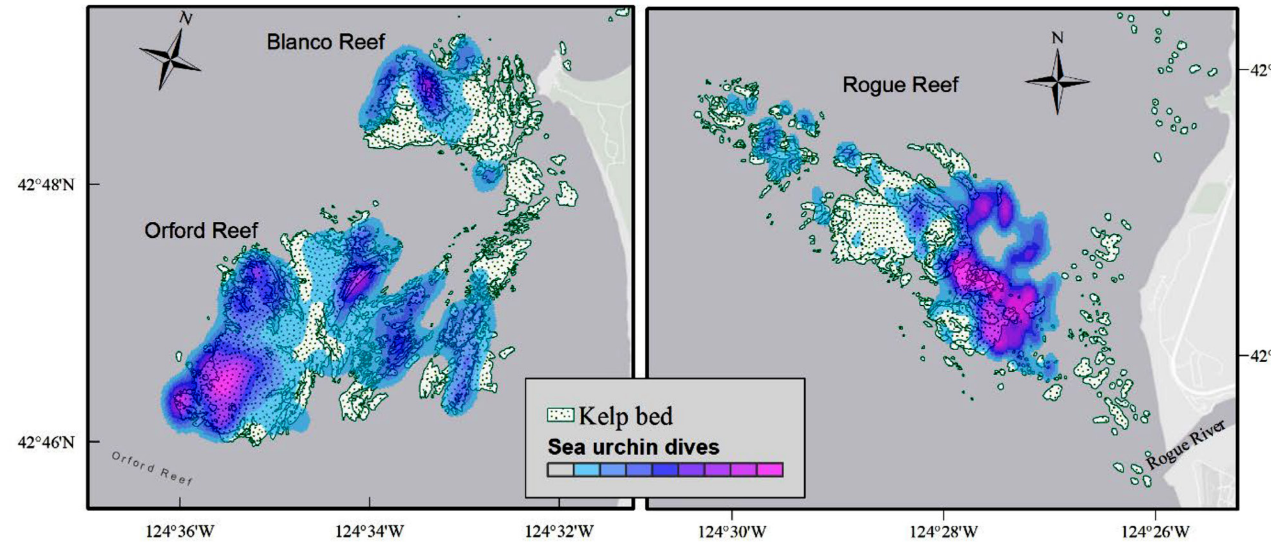


Figure 10.—Heat map of red sea urchin dives in relation to kelp bed extents (from Merems and Donnellan, 2011) at Orford Reef and Rogue Reef, 1986–2022.

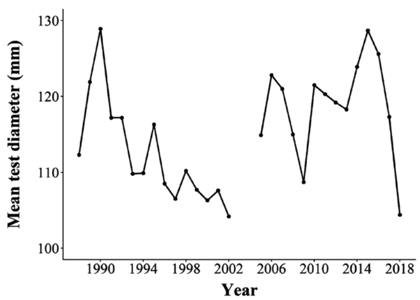


Figure 11.—Mean test diameter (mm) of red sea urchin caught in the commercial fishery at Orford Reef, 1986–2018 (no sampling since 2018).

veys showed dominance by a ~90 mm TD size class, then a large (~135 mm TD), old population in the mid-2010's followed by a late 2010 large recruitment event, where the population became dominated by ~40 mm red sea urchin (Fig. 14b).

Redfish Rocks MR The rocky reefs of Redfish Rocks MR were designated a no-take reserve in 2012; kelp beds in the rocky nearshore area are abundant. Red sea urchin surveys have occurred at regular intervals in the 2010's, but only two historic surveys (1984 and 1992) exist. Although early surveys show a high density of red sea urchin (e.g., 2.28/m² in 1991), by 2011 densities were lower (0.42/m²); however, since that time, recruitment there has been consistent, and densities have increased steadily (Fig. 14c). Like Orford Reef and Humbug Mountain, size distribution at Redfish Rocks MR show that 1992 populations were dominated by a ~90 mm TD size class, then a large, old population in the mid-2010's, followed by a late 2010's large recruitment event, where the population became dominated by ~40 mm individuals (Fig. 14d).

Humbug Mountain and Redfish Rocks have both experienced dramatic increases in purple sea urchin densities which were low from 1992 to 2014 (0.01 and 0.03/m², respectively). Then densities became very high by 2019 (3.89 and 1.87/m², respectively) (Fig. 14a, c).

Depoe Bay The Port of Depoe Bay is located on Oregon's central coast, and it accounts for 9% of Oregon's red sea urchin fishery catch; kelp beds are small and disconnected from primary area in the south coast. Survey areas encompassed nearly all the ports' kelp beds and included three no-take reserve areas.

Red sea urchin populations within the fished areas of Government Point, Depoe Bay, and Cape Foulweather are situated north to south, respectively. Throughout the areas, the larger and older individuals were removed from the population in the early years of the fishery; afterward, a strong recruit class settled in this region. Red sea urchin populations at all fished areas near the Port of Depoe Bay were dominated by a single year class which likely settled around 1992. Anecdotally, kelp beds within this region were more persistent in the southern areas than those in the north, and this appears to reflect the growth of red sea urchins which has been faster in the south than the north but is also coupled with greater densities in northern areas (Fig. 15b, d, f).

At Government Point and Depoe Bay, population densities of red sea urchin have been high. Densities peaked in 1996 at 2.83 and 2.62/m², respectively, driven by the single recruit class of ~1992 (Fig. 15a, c). Despite high populations, individual sizes have just barely reached the fishery MLS of 89 mm TD, despite at least 26 yr to grow. It seems likely their very slow growth could be caused by low amounts of kelp and high densities of red sea urchin throughout the era. Densities have declined substantially through the years, probably through natural mortality with some contribution from fishery mortality.

At Cape Foulweather, red sea urchin densities have been persistent-

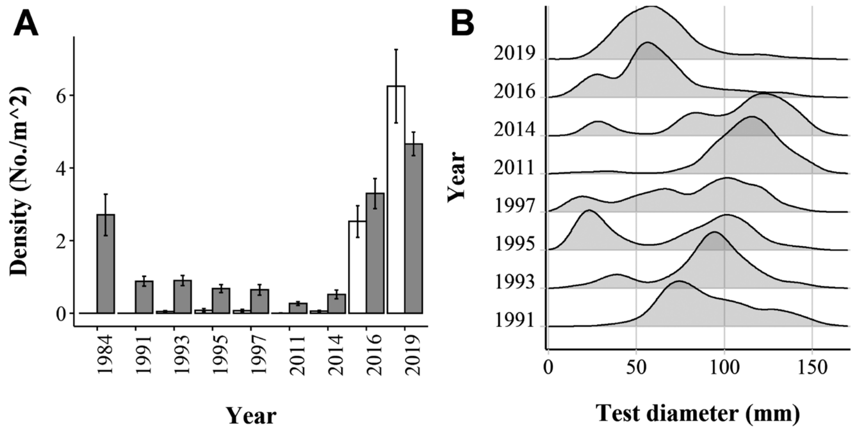


Figure 12.—Sea urchin stock dynamics at Orford Reef, 1984–2019, A) densities of red sea urchin (shaded bars) and purple sea urchin (white bars) by year (error bar indicates SE), and B) relative size distribution of red sea urchin by year, from survey data.

ly low (Fig. 15e); however, they have grown more quickly than other areas (Fig. 15f). The low densities combined with shallow depths and related higher kelp availability at these areas have likely contributed to the faster growth.

Depoe Bay features two longstanding marine reserves: Whale Cove HR (est. 1963), the only area in the state designated a reserve prior to the inception of the red sea urchin fishery and Pirates Cove RR (est. 1993). In addition, Otter Rocks MR (est. 2012) is a newer no-take reserve, since only a few sites were surveyed and the short time span since its designation, data from this area was pooled with previously described Cape Foulweather for this analysis.

Both Pirates Cove RR and Whale Cove HR had populations of large, old red sea urchins; however, densities at Whale Cove HR were higher and their mean sizes were the highest in the state (143.8 mm TD in 2015) (Fig. 16). In addition, the largest red sea urchin ever found in an Oregon survey was collected at Whale Cove HR in 2015, measuring 185.5 mm TD.

As of 2015, purple sea urchin densities were low near the Port of Depoe Bay. However, those surveys occurred just prior to the population booms

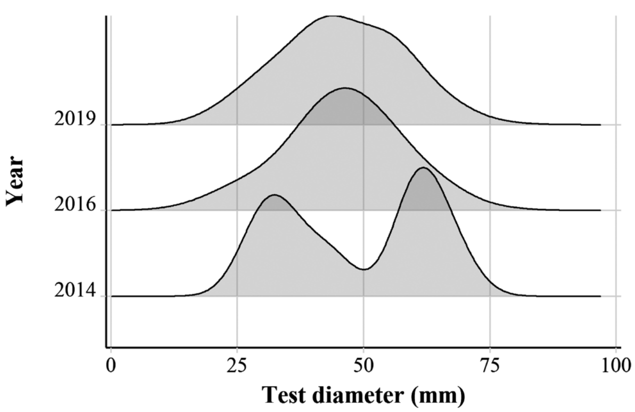


Figure 13.—Purple sea urchin size distribution at Orford Reef, 2014–2019, from survey data.

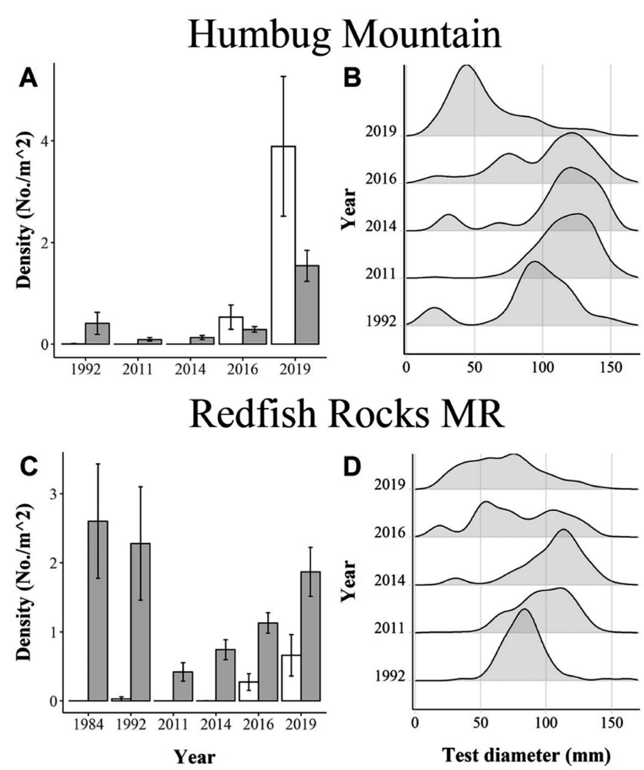


Figure 14.—Sea urchin stock dynamics at Humbug Mountain and Redfish Rocks Marine Reserve, 1984-2019. A and C) densities of red sea urchin, (shaded bars) and purple sea urchin (white bars) by year (error bar indicates SE), and B and D) relative size distribution of red sea urchin by year, from survey data.

found in 2016 and 2019 surveys of the Port Orford region.

Charleston The Port of Charleston accounts for 5% of Oregon's red sea urchin fishery catch. However, these populations are geographically separate from Port Orford and Depoe Bay and include a no-take reserve.

At Charleston, Simpson Reef is the primary sea urchin fishing area and the most expansive. Red sea urchin populations have been at a low level since surveys began (e.g., 0.20/m² in 1993) which was after initial, robust fishery removals. Little recruitment appears to have occurred at this area, and in the most recent surveys, densities were similar (e.g., 0.22/m² in 2015). Red sea urchin densities within Gregory Point RR have been higher than neighboring Simpson Reef, and mean sizes have been larger than other areas of Charleston (117.4 mm compared to 109.8 mm at Simpson Reef in 2015). Lighthouse Beach is a small area and is geographically separate from Simpson Reef and adjacent to Gregory Point RR. At Lighthouse Beach densities have been high recently (e.g., 1.47/m² in 2015); however, mean size has been smaller (e.g., 95.7 mm in 2015) and are presumably younger (Fig. 17).

As of 2015, the purple sea urchin boom found in southern ports just became noticeable in Charleston. While historic surveys showed low populations around Charleston (e.g., <0.01/m² in 1993 at Simpson Reef, 0.70/m² in 1996 at Gregory Point RR, and 0.20/m² in 2012 at Lighthouse Beach), many more were found in 2015 surveys. Purple sea urchin densities of 0.11/m², 4.02/m², and 1.00/m² at those same areas, respectively, were found in 2015 (Fig. 17a, c, e).

Management

Oregon's red sea urchin fishery management has focused on increasing sustainability, despite a massive boom then adjusting to a small fishery. Historical management actions are listed in Table 4. Key tenets of Oregon's red sea urchin fishery management include:

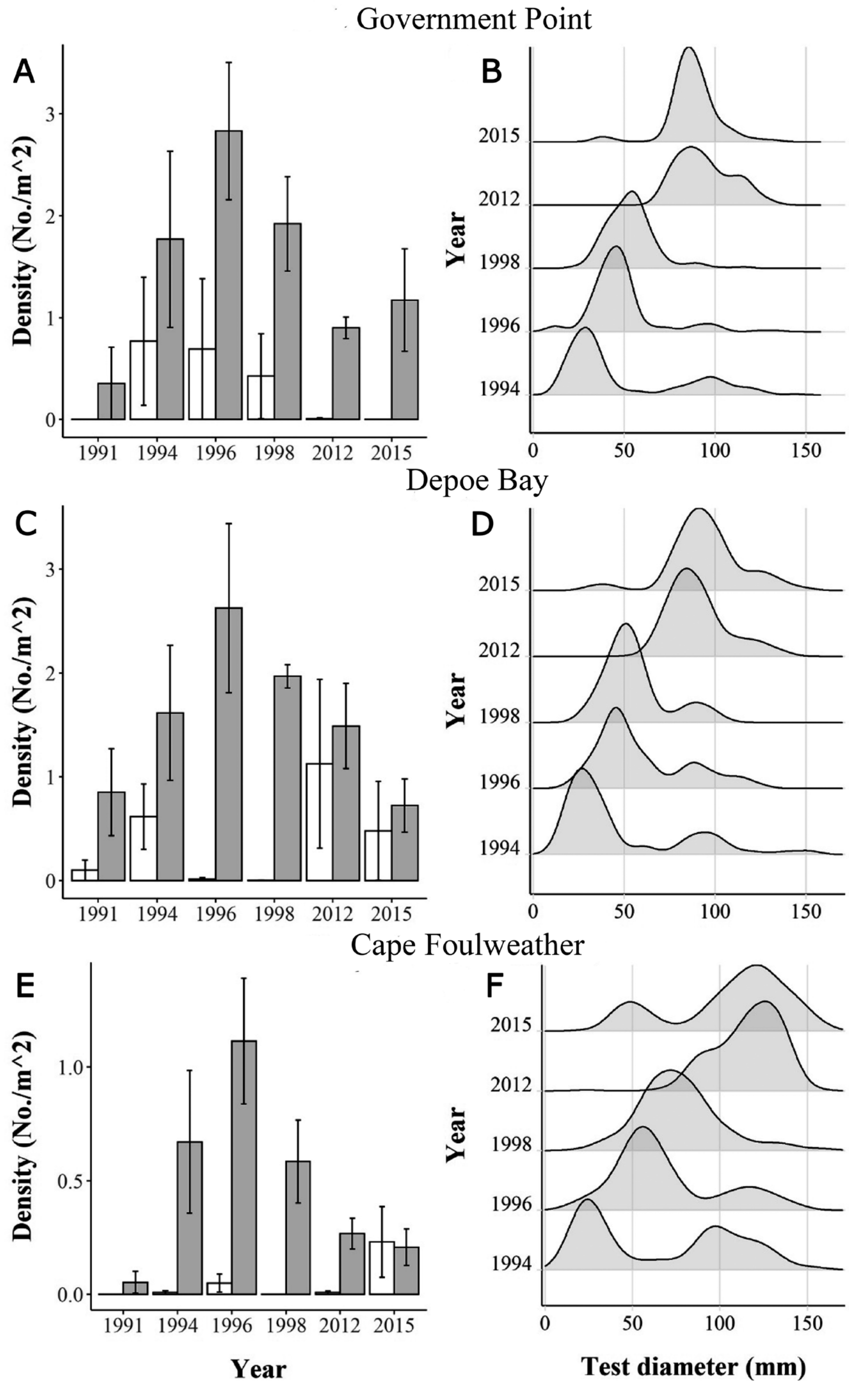


Figure 15.—Sea urchin stock dynamics at fished areas near Depoe Bay (Government Point, Depoe Bay, and Cape Foulweather) 1991–2015. A, C, and E) densities of red sea urchin (shaded bars) and purple sea urchin (white bars) by year (error bar indicates SE), and B, D, and F) relative size distribution of red sea urchin by year, from survey data.

1) Effort limitation: Limiting effort is a key to stabilizing fisheries. Limited entry allows managers to control pressure on the stock and reduces competition, increasing participant investment in sustainability. The sea urchin fishery boomed so quickly that limited entry was adopted soon after its inception (1987, 92 permits), to 46 permits in 1986, 30 in 1995, and 12 in 2016. The current level of 12 permits is designed to provide stability to the fishery and was reduced based on past levels of fishing that did not allow consistent fishery catch.

2) Area restrictions: Reserve areas, whether they be no-take reserves or de facto reserves, provide sites for the stock to persist without fishery pressure, enhancing source populations for the stock. Oregon red sea urchin fishery regulations include designated no-take reserves (e.g., Redfish Rocks RR, Whale Cove HR, etc.), which may be used as stock reserves and allow assessment of the stock absent fishery pressure.

Additionally, regulations creating de facto reserves may be easy to adopt. In Oregon's red sea urchin fishery, rules explicitly disallow fishing in very shallow zones (<3.3m water depth), but also practical limitations (e.g., depth and dive time) create additional de facto stock reserve in deep zones. In 2016, a regulation was adopted which disallows the use of mixed gas diving, increasing deepwater refugia.

3) Minimum legal size: Minimum size limits are used commonly in fisheries to protect immature stock and allow a period of reproductive viability prior to recruitment into the fishery. In Oregon's red sea urchin fishery, a minimum legal size was first adopted in 1988 (76.2 mm TD (3 inches)) then increased to 88.9 mm TD (3.5 inches) in 1991.

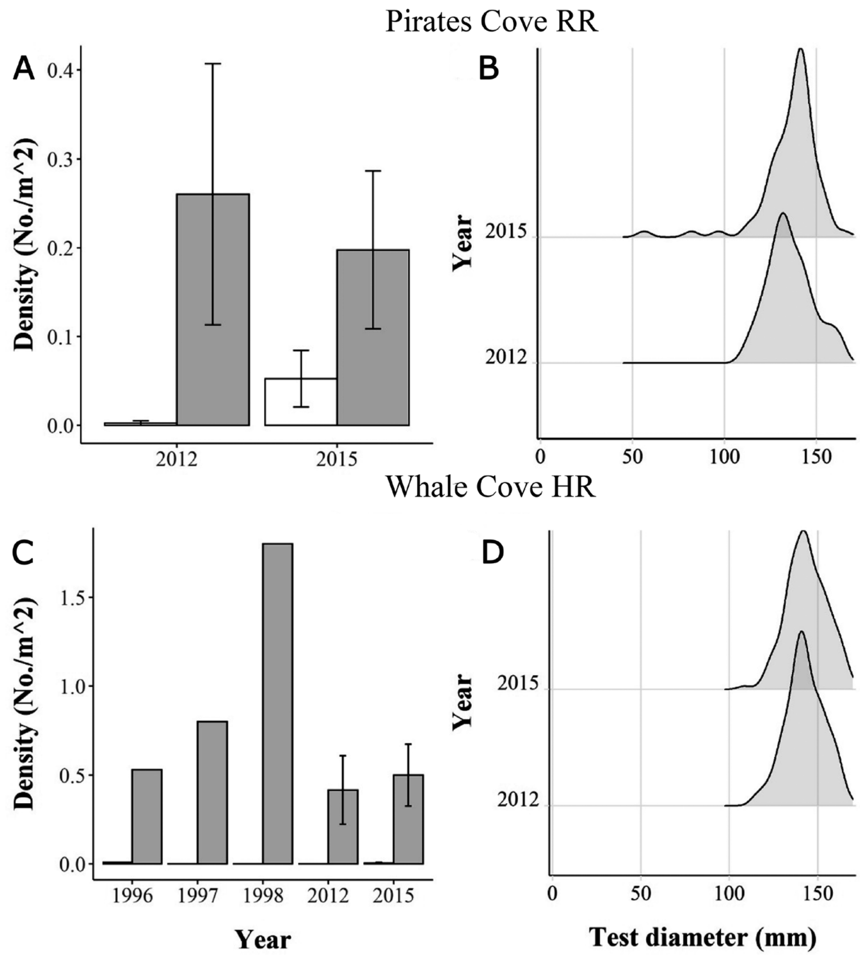


Figure 16.—Sea urchin stock dynamics at two subtidal reserve sites near Depoe Bay (Pirates Cove Research Reserve and Whale Cove Habitat Reserve) 1996-2015. A and C) densities of red sea urchin (shaded bars) and purple sea urchin (white bars) by year (error bar indicates SE), and B and D) relative size distribution of red sea urchin by year, from survey data.

Discussion

Stock Trends

Oregon's red sea urchin fishery exemplifies a "boom and bust" fishery, where a large virgin stock is fished out with only weak annual recruitment events. Soon after its inception the new fishery escalated, effort and landings rose quickly and then just as quickly fell (Fig. 7). Red sea urchin densities went from high to minimal in a few years (Fig. 12a). As the fishery progressed, it relied on the remnants of that very old population, and little recruitment input. By the early 2010's, the remaining stock was only large sizes in sparse populations (Fig. 12b). Recently however, densities have fully recovered from more than 30 years of fishing down.

Red sea urchin recruitment occurs episodically. During this study period (1983–2019), three large recruitment events have occurred in Oregon. A late 1980's recruitment event occurred throughout Oregon, which aided in fueling the robust fishery of the early 1990's. In the Depoe Bay region, an episodic event occurred around 1992 (Fig. 15). In 2014–16, another massive recruitment event was detected in the Port Orford region, though these red sea urchins have not reached fishery MLS (Fig. 12, 14). These events demonstrate their importance to the fishery where stocks may be severely depleted or overly abundant at times; however, it may not necessarily imply that the stock is over or underfished. It is clear that populations of sea urchins in Ore-

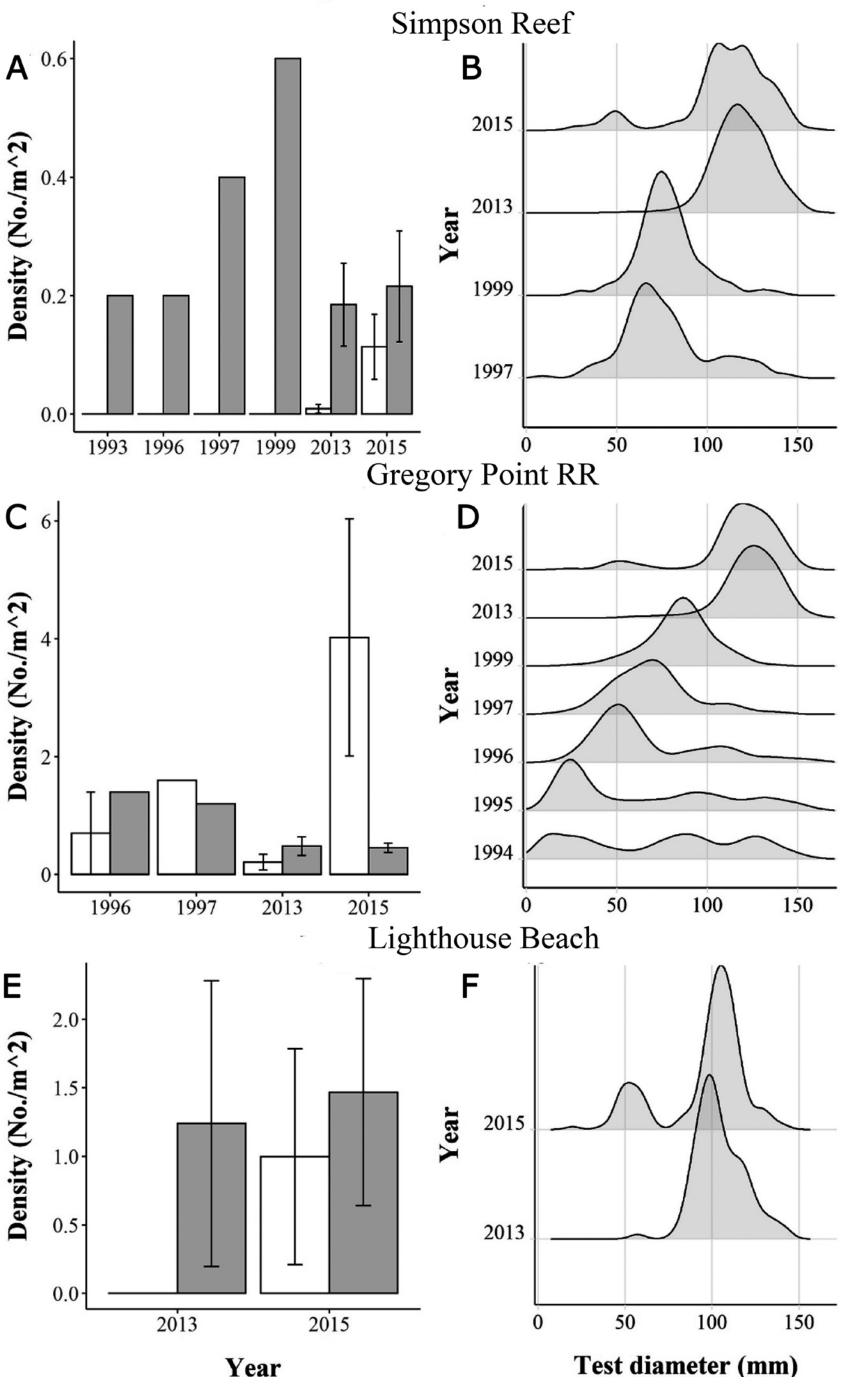


Figure 17.—Sea urchin stock dynamics at areas near Charleston (Simpson Reef, Gregory Point Research Reserve, and Lighthouse Beach) 1993–2015. A, C, and E) densities of red sea urchin (shaded bars) and purple sea urchin (white bars) by year (error bar indicates SE), and B, D, and F) relative size distribution of red sea urchin, from survey data.

gon are not temporally stable, and evidence of consistent annual fishery recruitment was not found in the years covered by this work.

Fishery Trends

In their 1997 analysis of California's red sea urchin fishery, Kalvass and Hendrix (1997) observed a dynamic response pattern, where the fished stock responds to fishing effort and vice versa, per Shepherd (1993) (Fig. 21 in Kalvass and Hendrix, 1997) and they were curious if this downward trend would continue.

Oregon's red sea urchin fishery exhibited a nearly identical "dynamic response" pattern through the early years of the fishery. Further, the longer time-series presented here, shows this pattern moved to stabilization following a level threshold fishery effort for many years (Fig. 18). Similar to the Kalvass and Hendrix (1997) analysis, the data presented here show a fluctuating pattern in the relationship between stock and fishing effort; however, these data show that a somewhat stable pattern has emerged (see years 1996 to 2022: Fig. 18). Recent increases of red sea urchin densities appear likely to make a near-term shift in the pattern of this relationship.

Value of Market Sampling

When evaluating size structure of red sea urchin stocks, managers employ two methods: 1) market sampling and 2) population surveys. While population abundance surveys are costly, the cost is acute and the data provides a fishery independent assessment of stocks. Market sampling is easily executed (e.g., can be performed dockside by a single individual); however, the resulting data is fishery dependent. The primary difference between these two datasets is that the fishery independent data is unbiased by fishery selectivity about the stock.

Comparing synchronized market sampling and population survey size structures shows that modes of legal sized red sea urchins are congruent; however (expectedly), only the population survey data gives an indication of pre-fishery recruitment, a key component of evaluating stock status. Understanding pre-fishery recruitment is especially important to understanding contemporary stock conditions in cases (such as red sea urchin) where it may take many years prior to settlement to reach MLS. While market sampling may provide a good indication of size distribution of the stock in years when recruitment hasn't occurred recently (1993, 2011, 2014), when there are recent recruitment events that have not recruited into the fishery, size structure from the two methods is drastically different (2016, 2019) (Fig. 19).

Overall, market sampling data has provided some value. Detection rates of large, old sea urchins in market samples can provide insight to the size structure of the overall population. In addition, working with and communicating with industry is highly valued. Consideration should be given to the comparative costs of surveys vs. market sampling.

Fishery Management

Worldwide, fisheries for sea urchins have a poor record of sustainability and have generally followed a trend of quick expansion followed by an equally rapid decline (Andrew et al., 2002). Oregon's red sea urchin fishery is well characterized by this assessment for most of its history. The recent massive episodic recruitment of red sea urchin occurred while populations were at historically low levels, reducing Oregon's future management prioritization of maintaining threshold densities at fishing areas.

The three key methods of Oregon's red sea urchin fishery management (effort limitation, reserve areas, and MLS) have variable levels of efficacy. Effort limitation has worked well to assure investment and encourages consistency of fishery catch. Reserve areas (direct and de facto) enhance accurate stock assessment and set aside some areas to promote conditions of reproduction (by providing high density stocks absent of fishery pressure). Minimum size limits in this fishery create a size reserve; however, I suspect that the efficacy is limited (as a method of assuring stock sustainability) given the long lives and episodic nature of recruitment.

Table 4.—Key management actions for sea urchin in Oregon, thru 2022.

Year	Management action
Prior to 1988	No specific permit required.
1988	Permit system adopted by Oregon Fish and Wildlife Commission (OFWC). Number of permits set at 92, issued to individual divers, 9.07 t (20,000 lb) landing requirement over previous two years.
	Adopted minimum size (76.2 mm (3 in) test diameter), minimum harvest depth (3.3 m (10 ft MLLW)), maximum number of divers in water per boat (2), and a logbook requirement.
1989	OFWC reduced the number of permits to 46, through attrition (failure to renew). Changed the 9.07 t (20,000 lb) landing requirement from a 2 yr to a 1 yr requirement.
	Restricted the maximum number of non-permitted people on a urchin boat to two.
	Medical transfer rule, allowing permitees to temporarily transfer their permit if an injury or illness was suffered, made permanent.
1990	OFWC established buffer zones around three key Steller sea lion pupping rocks (Seal Rock and Long Brown Rock on Orford Reef and Pyramid Rock on Rogue Reef).
	Amended medical transfers to:
	The greater of either the lb taken the previous year or 9.07 t (20,000 lb).
	A limit on each medical transfer to 90 days
	No limit on the number of transfers
1991	OFWC raised the minimum size to 88.9 mm (3.5 in) test diameter and reduced the allowable number of undersized urchins to 50 per landing.
	OFWC adopted a 50.8 mm (2 in) minimum size limit on purple sea urchins, and a special harvest permit, requiring pre-harvest surveys
1992	Due to Steller sea lion interactions coupled with poor market quality of sea urchins during the summer OFWC established a sea urchin season at Orford Reef (May–October).
1993	OFWC established subtidal reserves at Gregory Pt. and Pirates Cove.
1994	OFWC closed urchin harvest on Orford Reef from May 1 to October 31.
1995	New permit system adopted by OFWC including:
	New target level number of permits (30)
	New annual renewal poundage (2.27 t (5,000 lb))
	Reinstated 2 yr continuous medical transfer limit
2014	Permit lottery suspended for two years while fishery is reviewed.
2016	Permits reduced to 12, mixed gas diving disallowed, sea cucumbers included to permit

The Future of Oregon's Sea Urchin Fisheries

Unlike conventional "recruitment fisheries" where a surplus of new fishery recruits are somewhat reliably available on an annual basis, the red sea urchin stock and fishery appears to depend on a longer time scale. Oregon's red sea urchin fishery has been fueled by only a few recruitment events over its 36-yr history. This key temporal difference from conventional fisheries must be considered in management. Management actions such as use of reserves, effort limitation (despite stock surpluses), and periodic fishery independent population monitoring (using index sites rather than fully randomized designs) appear more appropriate than annual quotas for Oregon's red sea urchin fishery.

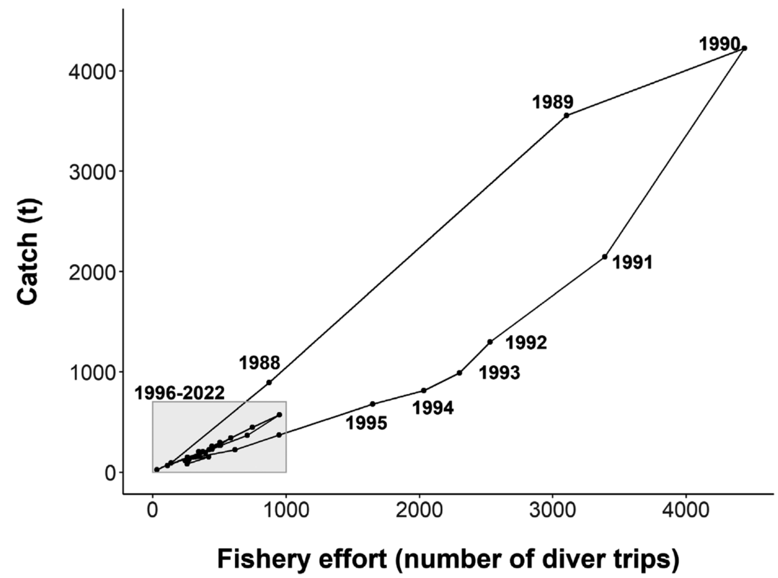


Figure 18.—Red sea urchin, catch (t) compared with effort (vessel trips) in Oregon, 1986–2019, exhibiting Shepherd's (1993) dynamic response pattern. Note rapid acceleration of both catch and effort in early years of fishery (1986–90), rapid decline for both (1991–96), then stability at relatively low levels (1996–2022). This pattern is characteristic of boom-bust fisheries.

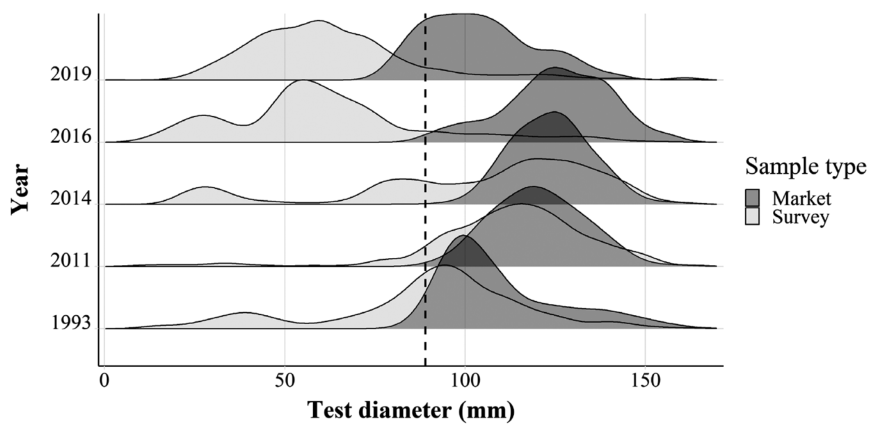


Figure 19.—Size distribution of red sea urchin, from fishery market samples (dark shaded) and population surveys (light shaded) at Orford Reef.

The future of Oregon's red sea urchin fishery is unclear. As of 2019, stocks were at all-time highs while kelp abundances were at low points (Hamilton et al., 2020). It seems likely that the recent episodic recruitment events may fuel the fishery for many years to come, given that the previous event sustained the fishery for more than 30 years.

Ecologically, there are serious concerns of the population boom of both red and purple sea urchins along the U.S. west coast. The boom is particularly acute, given the absence of sea urchins' primary predator at both adult (sea otters, *Enhydra lutris*) (Jameson et al., 1982) and juvenile life stages (sunflower sea stars, *Pycnopodia helianthoides*) (Harvell et al., 2019). Particularly, there are concerns of how the robust sea urchin population may depress kelp beds and possible conversion from a "healthy kelp bed" state to an "urchin barren" state. The restoration of sea otter and sunflower sea star populations is currently being considered and may serve as an effective and natural method of stabilizing nearshore ecosystems (Rogers-Bennett and Catton, 2019).

Lastly, purple sea urchin populations have boomed on the U.S. west coast and managing these massive populations is challenging. Populations at Orford Reef survey sites (which were not designed to assess purple sea urchin since they are typically in shallower zones) have gone from barely detectable (<0.01–0.10/m² 1984–2014) to very high (6.24/m² in 2019), to estimates in the neighborhood of 350 million individual purple sea urchin (Groth[1]). While this surplus may be inviting to consider new fishery options, history has shown low market appeal, despite high abundance. The biological need of reducing these populations is unclear, but most stakeholders encourage active management, such as direct removal or destruction. Given their long life history and persistence, it seems unlikely this will resolve quickly by natural means.

Acknowledgments

Data and accounts in this manuscript consists of many generations of biologists and sea urchin divers' careers, and this author was only a small part.

To this point, I thank prior generations for their hard work surveying and documenting the many aspects involved including: N. Richmond, J. Golden, J. McCrae, J. Schafer, C. Wood, N. Wilsman, A. Merems, J. Heinrich, and B. Miller. I thank my collaborator and friend Steven Rumrill for his help in working for and guiding this research. Kendall Smith, Dave Fox, and Bob Hannah helped shape this manuscript. This journal's editors and two anonymous reviewers provided helpful comments.

[1]Groth, S. D. 2019. Sea urchins, sea stars, abalone and kelp beds. Unpubl. rep., Oreg. Dep. Fish. Wildl., Charleston, OR, 2 p.

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