History and trends in Oregon's red sea urchin fishery

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Abstract

The red sea urchin (*Mesocentrotus franciscanus)* is a large echinoid common to the rocky vegetated nearshore areas throughout the West Coast of North America. Fisheries for red sea urchin are the US West Coasts most valuable dive fisheries. Results of these fisheries are broadly characterized as "boom and bust" where a virgin stock was 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 experienced a boom and bust, like many similar fisheries. Fishing began in 1986 and boomed to total catches greater than 4,200 metric tons (t) in 1990, by 1993 catch reduced below 1,000 t per year where it has remained. In the era between 1997 and 2017, catch remained low, but value was steady, characterized by a low number of participants fully involved in the fishery. 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 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.

Introduction

Biology

The red sea urchin (*Mesocentrotus franciscanus)* are ubiquitous to the rocky nearshore of the West Coast of North America. They are a large sea urchin reaching sizes up to 211 millimeter (mm) test diameter (TD) (Ebert, Barr et al. 2018). Reproduction is episodic, affected by coastal circulation and upwelling conditions (Morgan, Wing et al. 2001), and consequently they have evolved life spans greater than 100 years (Ebert and Southon 2003). High water temperatures shortens sea urchins larval period (Cameron and Schroeter 1980), but also tends to create 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, Trent et al. 1977). The red sea urchin range from Baja Mexico to Kodiak, Alaska (Ebert, Dixon et al. 1999) where they are common to shallow (i.e., 3-35 meter (m) depth) rocky reef habitats and most abundantly within kelp beds (Rogers-Bennett 2007). The red sea urchin eats marine vegetation, primarily drifting kelp; when well fed their gonads become robust in winter months in preparation for spring spawning (Dean, Schroeter et al. 1984). Sea urchin gonads are a fishery product known as “uni” and are of high value, making them an important fishery target.

Fishery history

Red sea urchin commercial fishing along the United States (US) West Coast began in the 1970s in Southern California. By the 1980s market demand accelerated and exploration for unexploited stocks extended throughout their range (Kato and Schroeter 1985). Between the late 1980s and early 1990s Japan’s economy expanded, furtherer increasing demand for uni and raised ex-vessel pricing, allowing the fishery to expand (Kalvass and Hendrix 1997). During that time the US

West Coast red sea urchin fishery experienced a rapid increase in landings, then an equally rapid decrease as stocks were depleted (mid 1990s), a long period of fishery stability followed (1995-2019), Figure 1. State specific history of red sea urchin fishing along the US West Coast is reviewed for Northern California by (Kalvass & Hendrix 1997), in Washington by (Pfister and Bradbury 1996) and in Oregon here. Little recreational catch of sea urchins occurs on the US West Coast (pers obs).

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, Kenyon et al. 1982). Lacking a predator or fishery pressure, red sea urchin densities were likely at a historic peak at that time. High-density stocks were indeed discovered and infrastructure (e.g., vessels, processing plants, etc.) were developed around this budding industry. As the stock was fished down, efficiency, then effort both declined. By 1996, the last remaining Oregon sea urchin processing facility closed (Richmond, Schaefer et al. 1997). In subsequent years, catch and effort has remained steady, albeit at a lower level.

Fishery scope

Red sea urchin fisheries have been robust in each of the US West Coast states. California has the most extensive kelp beds (thus fishing area) and consequently is the largest and most valuable component of the US fishery totaling, 384,214 metric tons (t) from 1971 to 2019. Washington state has limited coastal kelp beds, but extensive kelp beds within Puget Sound. Landings in Washington have totaled 22,905 t between 1981 and 2019. Oregon's fishery is similarly sized to Washington, totaling 20,256 t from 1986-2019 (Pacific States Marine Fisheries Commission 2020). Overall, the US 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 (Figure 1).

Oregon's coastline measures 636 kilometers (km) and is arranged approximately parallel to longitudinal lines. Oregon's nearshore habitats are 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 2011), consequently the majority of the red sea urchin catch (71%) has occurred at those areas (Figure 2).

Purple and green sea urchins

The Oregon sea urchin fishery focuses on red sea urchin; however, purple sea urchin (*Strongylocentrotus purpuratus)* are a minor component of landings, accounting for less than 1% of historic catch (Pacific States Marine Fisheries Commission 2020). Green sea urchin (*Strongylocentrotus droebachiensis*), a target of fisheries north of Oregon (Washington, Canada, and Alaska) are uncommon in Oregon; however, have been found to be present in extremely small numbers for the first time in 2015 (pers obs).

Here I describe the fishery and stock trends of sea urchins, most specifically, the red sea urchin within Oregon.

Methods and materials

Fishery methods

The fishery for red sea urchin is artisanal; specialized diving gear and a high degree of skill is required. Small, shallow draft vessels equipped with surface supplied air (aka "hooka") systems are employed to access shallow, rocky nearshore areas. Hand rakes are used to collect sea urchins individually then are placed in mesh bags suspended off the bottom by the use of an inflatable buoy. Since sea urchin are individually collected, there is no bycatch. Dive tenders (vessel crew members not diving) keep lines clear, assist getting divers and catch on and off the vessel, and assure things are running smoothly while divers are underwater. Most sea urchin divers begin their careers as dive tenders to gain experience. Individual experience and skill are more critical than many other fisheries; not only is diving in the Northeast Pacific inherently dangerous (currents, swell, depths, etc.), knowledge of identifying sea urchins with quality uni is also necessary. Single day trips including multiple dives where live catch is returned to port daily then trucked to remote facilities for processing are most common. Sea urchins are processed by cracking their shell (test) and placing each of the five skeins of gonad (erroneously called "roe") in wooden boxes (Kato and Schroeter 1985), less frequently they are sold whole in live markets. The quality and quantity of sea urchin gonads determines the value, not strictly their whole weight.

Catch and effort metrics

Landing receipts and fishery logbooks from 1986-2019 were used to assess catch and effort. Landing receipts are issued for each day of catch by each individual; date, port, pounds (by species), and value are recorded for each. To assess catch by reef, logbooks from 1986-2019 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 logbooks recorded a daily summary, consisting of a coarse description of area and estimated weight of catch. Beginning in 2012, logbooks recorded information for individual dives, where exact positions were attributed and estimated catch weight from each dive was recorded.

Stock metrics

To measure stock metrics, two methods were employed, 1) market sampling and 2) 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, (see Figure 2 for areas). Occasionally, larger sized sea urchin are targeted, based on market demand (e.g., live market) or small sized sea urchins based on seasonal gonad conditions, 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

To measure the abundance and size distribution of red sea urchin populations at sites critical to the fishery, index surveys were employed. 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) for safety, depths were generally shallower than 20 m. Surveys were performed periodically from the early 1990s 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; 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 identified and enumerated sea urchin species within one meter perpendicular to each side of the transect line (Figure 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 1990s the first 50 red sea urchin 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 2010s, all sea urchins were collected and brought to the surface for measurement, when sea urchins were too numerous for this to 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 red sea urchin, not purple sea urchin, which are found at their 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.

Port Orford

Three areas were selected to index red sea urchin populations near Port Orford on Oregon's South Coast (Figure 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 (Figure 5). Three fished areas were surveyed: Government Point a 160 ha area 1.6 km northwest of Depoe Bay, Depoe Bay a 240 ha adjacent to Depoe Bay and Cape Foulweather a 200 ha 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 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 Marine Reserve (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 (Figure 6). Simpson Reef is an expansive fishing area (300 ha) surrounding Cape Arago, 7 km southwest of Charleston. Gregory Point Research Reserve (RR) is a 24 ha no-take reserve, established in 1993, 4 km west of Charleston. Lighthouse beach is a small (13 ha), but geographically separate area, 13 km south of Charleston, adjacent to the north edge of Gregory Point RR.

Results

Catch, effort and value

Red sea urchin fishery landings in Oregon developed quickly (1986-1988), expanded then decreased dramatically (1989-1995), and finally reduced to a stable level from 1996-2019. The fishery began in 1986, and by 1990, 4,228 tons were landed. By 1996 landings had reduced dramatically, averaging 231 tons (annually) from 1996-2019. 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-year period (2010-2019) effort has been stable, averaging 384 trips per year (Figure 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 ex-vessel value of 3.4 million USD 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 reduced, the fishery became smaller but stable; from 1996-2017, averaging 284k USD per year. Recent years (2018 and 2019) have seen highly increased prices and values consequent to low kelp conditions along the US West Coast. Fishery value in 2018 and 2019 was 725k and 570k respectively.

Price per pound of red sea urchin has been variable, with recent sudden change (Figure 8). Mean price per pound in the early years was high (e.g., $1.93 USD/KG in 1993) as markets were lucrative, at that time the Japanese economy (primary market at that time) was booming and previously unexploited US West Coast stocks provided a robust source. As the stock was depleted and the Japanese economy turned down, price reduced. As the fishery matured and stock levels remained low, domestic markets were used more frequently. Beginning around 2016, US West Coast kelp beds decreased, reducing the amount of high quality uni, leaving just a few areas of Oregon still viable for markets; the price elevated and by 2019 was at an all-time high ($6.95 USD/KG).

Catch by Port

Oregon's red sea urchin fishery catch is focused on the southern portion of the state. In total 20,256 t have been caught across the 1986-2019 period. By port, Port Orford has had the highest landings (11,733 t) followed distantly by Gold Beach (4,454 t). Landings at other ports included Depoe Bay (1,820 t), Charleston (973 t), Brookings (724 t), Newport (517 t), while other ports including Garibaldi and Pacific City (combined) added 35 t (Table 3). Purple sea urchin landings combined to 175 t, along similar distributions by port .

Catch by fishing area

Catch was focused on the South Coast (Figure 9). Seventy one percent of Oregon's red sea urchin catch occurred at two large offshore rocky reefs, (Orford Reef and Rogue Reef). As such, position data from fishery logbooks are robust at these two areas. These data show a strong association between fishing sites and kelp beds, where nearly all fishing occurs within or directly nearby kelp beds (Figure 10). The importance of kelp beds to the fishery cannot be mistaken and may allow kelp bed maximum extent area to be a good predictor of fishing viability.

Catch by depth

As a dive fishery, fishing depth has obvious constraints regarding dive time related to safety. As a diver descends deeper, the amount of time one may stay underwater reduces, 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), Brookings (10.4 m)).

Stock metrics

Market sampling

Orford Reef market sampling showed a pattern of large, older animals in the catch in the first years of the fishery (1986-1990). Soon after, a period of "recruitment fishing" occurred, where catch was dominated by red sea urchin simply recruiting to minimum legal size (MLS), 1991-2002. From 2004-2016 when red sea urchin fishing pressure was lower; larger and older individuals again became a substantial component of catch. 2017-2018 sampling 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 (Figure 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 have 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 m²) 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 the Oregon's kelp bed area and fishery catch occur. Prior to the beginning of the fishery, stocks were robust but then quickly fished down. 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 a critical area to understand abundance, size distribution and recruitment events of red sea urchin populations 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 1988-1997 fishery effort and landings were high. During this period, densities of red sea urchin were substantially reduced, by 1997 densities were low 0.65/ m^2, when compared to "commercial quantities" (conventionally, 1 red sea urchin/ m^2). Across this period, effort and landings reduced sharply (Figure 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 2010s, driving densities to their highest level (4.66/ m^2 in 2019), fully recovering from the long and exploitive fishing effort (Figure 12a).

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

Purple sea urchin

Purple sea urchin populations at Orford Reef, were nearly absent (in the deeper waters of these surveys), then have increased suddenly, beginning in 2014. Few purple sea urchins were found in early surveys (e.g., 0.00/ m^2 in 1991) when suddenly in 2016, high abundances were found (2.52/ m^2), then increasing further in the most recent 2019 surveys (6.24/ m^2), Figure 13. The size of individual purple sea urchins at Orford Reef is generally small, with mean size at about 43.7 mm in 2019 (Figure 14).

Humbug Mtn

The rocky reefs adjacent to Humbug Mountain are less expansive than Orford Reef, though geographically separated, allowing a good comparison area. The first surveys conducted on Humbug Mountain occurred in 1992 when the fishery had already operated at this area for several years. Survey results from 1992 showed substantial densities (0.41/ m^2) of red sea urchin and few purple sea urchin (0.01/ m^2). Like Orford Reef, Humbug Mountain was fished down substantially by 2011, then populations recovered beyond the virgin stock conditions by 2019 (Figure 14a). Size distribution also showed a similar pattern as Orford Reef, where 1992 surveys showed dominance by a ~90 mm TD size class, then a large (~135 mm TD), old population in the mid 2010s followed by a late 2010s large recruitment event, where the population became dominated by ~40 mm red sea urchin (Figure 14b).

Redfish Rocks MR

The rocky reefs of Redfish Rocks MR were designated a no-take reserve in 2012; kelp beds and rocky nearshore are abundant. Red sea urchin surveys have occurred at regular intervals in the 2010s, but only two historic surveys (1984 and 1992) exist. Although early surveys show a high density of red sea urchin (e.g., 2.28/ m^2 in 1991), by 2011 densities were lower (0.42/ m^2); however since that time recruitment there has been consistent and densities have increased steadily (Figure 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 2010s followed by a late 2010s large recruitment event, where the population became dominated by ~40 mm individuals (Figure 14d).

Purple sea urchin

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/ m^2 respectively), then became very high by 2019 (3.89 and 1.87/ m^2 respectively), Figures 14a and 14c.

Depoe Bay

The port of Depoe Bay is located on Oregon’s Central Coast, 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 include three no-take reserve areas.

Depoe Bay Fished 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, larger, 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, this appears reflective in the growth of red sea urchins which has been faster in the South than the North but is also coupled with greater densities in North areas (Figure 15 b, d and 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/m^2 respectively, driven by the single recruit class of ~1992 (Figure 15 a and c). These densities may have been even higher than measured in 1994 surveys however were likely affected by detection rates given their small (~25 mm TD) size during those surveys. Despite high populations, individual sizes have just barely reached the fishery MLS of 89 mm TD, despite at least 26 years of time 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 lowered substantially through the years, probably through natural mortality, with some contribution from fishery mortality.

At Cape Foulweather, red sea urchin densities have been persistently low (Figure 15e); however they have grown more quickly than other areas (Figure 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 Reserve Areas

Depoe Bay features two long standing 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 urchin, however densities at Whale Cove HR were higher and their mean sizes were the highest in the state (143.8 mm TD in 2015), Figure 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.

Purple sea urchin:

As of 2015, purple sea urchin densities were low near the Port of Depoe Bay, though those surveys occurred just prior to the population booms found at 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 most expansive. Red sea urchin populations have been at a low level since surveys began (e.g., 0.20/ m^2 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/ m^2 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, 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/ m^2 in 2015); however, mean size has been smaller (e.g., 95.7 mm in 2015) and are presumably younger (Figure 17).

Purple sea urchin:

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., 0.00/ m^2 in 1993 at Simpson Reef, 0.70/ m^2 in 1996 at Gregory Point RR, and 0.20/ m^2 in 2012 at Lighthouse Beach), many more were found in 2015 surveys. Purple sea urchin densities of 0.11/ m^2, 4.02/ m^2, and 1.00/ m^2 at those same areas, respectively, were found in 2015, Figures 17 a, c and e. It seems likely that current densities are higher.

Management

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

1) Effort limitation: Limiting effort is a key to stabilizing fisheries. Benefits include the control of pressure on the stock, but also to fishery participants by reducing fishing costs and increasing participant investment. The sea urchin fishery boomed so quickly that limited entry was adopted soon after its inception (1987, 92 permits), permits were reduced in 1986 to 46, then in 1995 to 30, then last in 2016 to 12. The current level of

permits (12) is designed to provide stability to the fishery and is reduced based on past levels of fishing that did not allow consistent fishery catch.

2) <u>Area restrictions</u>: Reserve areas, whether they be no-take reserves or de facto reserves, allow places 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 directly used as stock reserves and allow assessment a part of the stock absent of 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 deep-water refugia.

3) <u>Minimum legal size</u>: 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.

Discussion

Stock trends

From its beginning to recent times, Oregon's red sea urchin fishery exemplified a "boom and bust" fishery, where a large virgin stock was mined out with only weak annual recruitment events. Soon after its inception the new fishery escalated, effort and landings elevated quickly and then just as quickly reduced (Figure 7). Red sea urchin densities went from high to minimal in a few years (Figure 12a). As the fishery progressed, it relied on the remnants of that very old population, and little recruitment occurred. By the early 2010s, the remaining stock was only large individual sized, sparse populations (Figure 12b). Recently, densities have fully recovered from more than 30 years of fishing down.

Episodic recruitment events

Red sea urchin recruitment occurs episodically. During this study period (1983-2019), three large recruitment events have occurred in Oregon. A late 1980s recruitment event occurred throughout Oregon, which aided in fueling the robust fishery of the early 1990s. In the Depoe Bay region, an episodic event occurred around 1992 (Figure 15). In 2014-2016, another massive recruitment event was detected in the Port Orford region, though these red sea urchins have not reached fishery MLS (Figure 12 and 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 Oregon 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 observed a dynamic response pattern, per Shephard 1993 (Figure 21, in Kalvass, Hendrix 1997) and was curious if this downward trend would continue.

Oregon's red sea urchin fishery exhibited a nearly identical 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 (Figure 18). Similar to the Kalvass and Hendrix analysis, the data presented here show a situation (recent, rapid stock changes) where a change to recent patterns should be imminent. High red sea urchin densities soon to recruit to the fishery are likely to make major shifts to catch and efficiency.

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 provides data 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, and 2014), when there are recent recruitment events that have not recruited into the fishery, size structure from the two methods is drastically different (2016 and 2019), Figure 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 versus 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, Agatsuma 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.

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 33-year 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.

The future of Oregon's red sea urchin fishery is unclear. As of 2019, stocks are at all-time highs while kelp abundances are at low points (Hamilton, Bell 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 US West Coast. The boom is particularly acute, given the absence of sea urchins' primary predator at both adult (Sea otters, *Enhydra lutris*) (Jameson, Kenyon et al. 1982) and juvenile life stages (Sunflower sea stars, *Pycnopodia helianthoides*) (Harvell, Montecino-Latorre 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 Pycnopodia 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 US 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 (0.00- 0.10/ m^2 1984-2014) to very high (6.24/ m^2 in 2019), to estimates in the neighborhood of 350 million individual purple sea urchins (Groth 2019). 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.

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Table 1: Mean test diameter size (mm) and number of red sea urchin (*Mesocentrotus franciscanus*) from market samples, by ODFW area, 1987-2019.

Year	ROGUE		HUMBUG		ORFORD		ARAGO		DI
	n	Mean size (mm)	n	Mean size (mm)	n	Mean size (mm)	n	Mean size (mm)	n
1987					50	131.40			
1988	30	120.60	55	120.96	763	108.05	125	120.45	
1989	678	128.60	86	107.65	2381	124.05	150	122.89	33
1990	1761	126.83	2190	120.79	7420	128.34	350	123.81	367
1991	975	122.56	150	106.43	2570	116.20	75	111.77	330
1992	150	119.66	250	113.16	2567	113.93	125	114.81	350
1993					1205	110.53	474	110.88	1149
1994	100	134.85	100	110.67	1656	111.83	50	114.92	290
1995	200	114.25			600	112.11			
1996	450	110.32			600	108.36			50
1997	50	106.82			950	106.81			
1999					1052	106.73			
2000					1600	107.49			
2001					1248	106.74			
2002					150	104.67			
2004					149	110.14			
2005			107	116.03	320	117.14	243	114.05	
2006	207	123.08	50	105.32	203	122.81			
2007					183	116.15			
2008					634	113.54			200
2009					1592	111.54			
2010			250	118.14	896	120.27	309	119.58	
2011			50	120.21	3029	120.27			
2012					499	117.23	872	115.92	500
2013					1100	119.83			
2014					900	126.24			
2015					550	128.05			
2016					100	127.93			
2017	100	100.46	50	116.82	399	109.24			
2018	142	95.56							
2019	54	94.21							
Totals	4897	121.93	3338	118.28	35366	117.78	2773	116.70	3269

Table 2- Summary of red and purple sea urchin (*Strongylocentrotus purpuratus*) 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

Table 3: Landed weight (t) and nominal value (USD) for red sea urchin in Oregon, 1986-2019.

Year	Port								Tota
	Brookings	Gold Beach	Port Orford	Charleston	Newport	Depoe Bay	Garibaldi	Pacific City	Landings (t)
1986	0	0	25	0	0	0	0	0	25
1987	22	0	70	0	0	0	0	0	92
1988	24	102	681	81	1	4	0	0	894
1989	29	719	2,736	29	40	4	0	0	3,557
1990	52	1,174	2,230	132	100	523	9	9	4,228
1991	154	545	1,079	146	0	220	0	4	2,149
1992	65	174	769	39	25	224	0	0	1,296
1993	58	118	499	67	175	74	0	0	990

1994	26	229	480	16	6	55	0	0	812
1995	59	223	316	9	20	51	0	0	678
1996	15	136	202	11	4	3	0	0	372
1997	17	49	137	0	1	18	0	0	222
1998	21	56	49	20	2	8	0	0	156
1999	14	27	52	5	7	7	0	0	113
2000	3	123	168	85	9	58	0	0	446
2001	62	5	155	47	126	173	2	0	571
2002	62	42	97	55	0	112	0	0	368
2003	1	0	34	16	0	14	0	0	65
2004	0	3	69	41	0	37	0	0	151
2005	0	6	127	70	1	18	2	0	224
2006	0	48	91	12	0	50	2	0	203
2007	0	52	115	28	0	0	0	0	195
2008	0	13	182	20	0	51	2	0	268
2009	0	111	224	2	0	0	3	0	341
2010	5	15	93	2	0	0	0	0	114
2011	3	116	140	1	0	7	0	0	267
2012	1	29	131	12	0	85	0	0	258
2013	0	59	225	2	0	10	0	0	296
2014	0	25	204	0	0	0	0	0	229
2015	9	20	164	4	0	6	0	0	202
2016	0	9	102	0	0	0	0	0	112
2017	21	28	56	16	0	7	0	0	128
2018	0	138	13	0	0	0	0	0	151
2019	0	61	16	5	0	0	0	0	82
Total	724	4,454	11,733	973	517	1,820	21	14	20,256

Table 4- Key management actions for sea urchin in Oregon, thru 2019.

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 inch) test diameter), minimum harvest depth (3.3 m (10 feet 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 two year to a 1 year 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 Stellar 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 poundage 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 inches) test diameter and reduced the allowable number of undersized urchins to 50 per landing. OFWC adopted a 50.8 mm (2 inch) minimum size limit on purple sea urchins, and a special harvest permit, requiring pre-harvest surveys
1992	Due to stellar sea lion interactions coupled with poor market quality of sea urchins during the summer OFWC established a sea urchin season at Orford Reef (May to 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 # of permits (30) • New annual renewal poundage (2.27 t (5,000 lb.)) • Reinstated 2 year 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

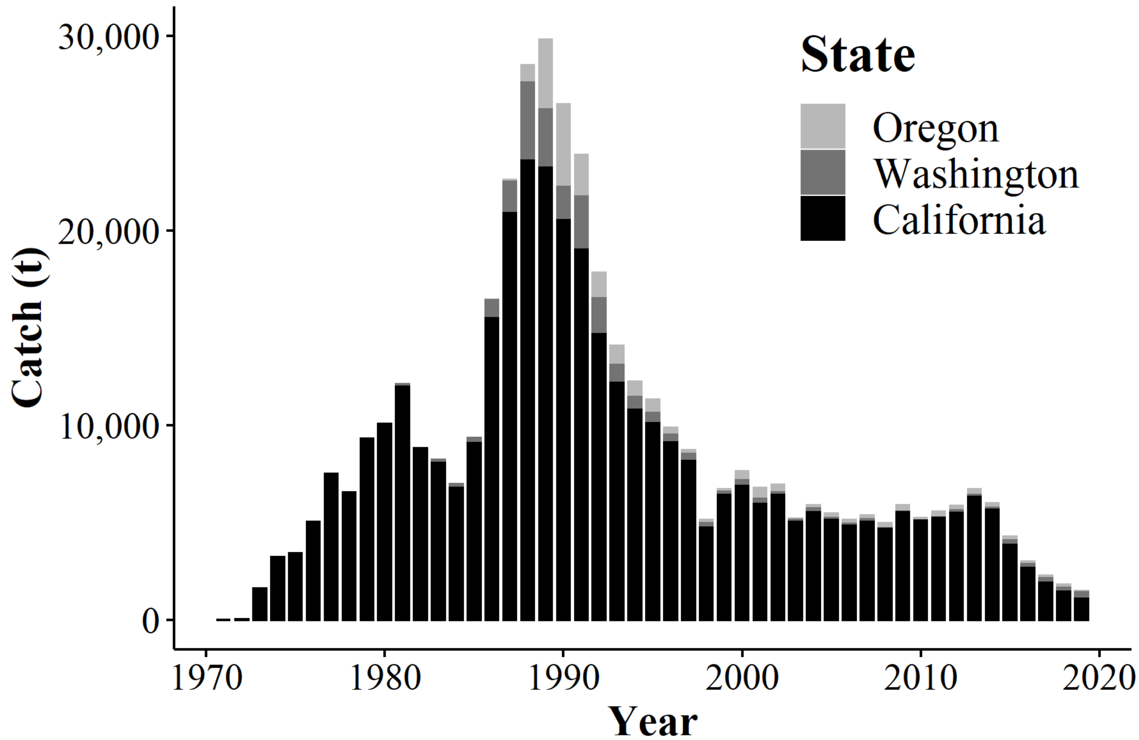

Figure 1: Red sea urchin (Mesocentrotus franciscanus) landings in Oregon, Washington and California by year; from 1972-2020).

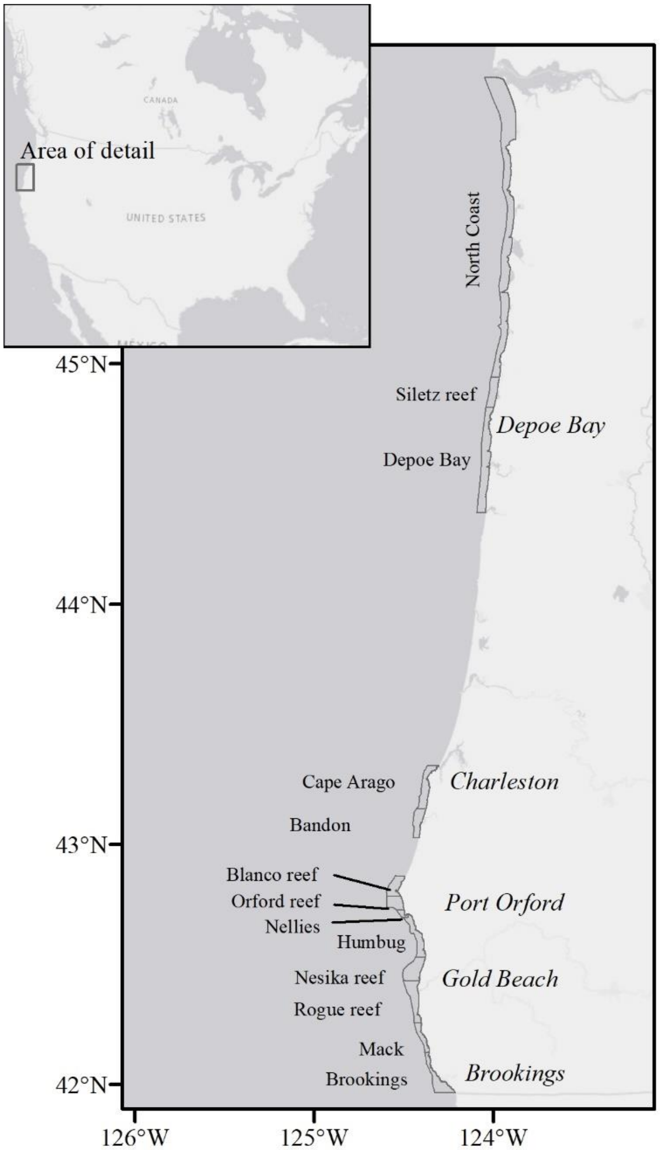

Figure 2: Sea urchin "ODFW areas" (defined by continuous reef) in relation to ports important to sea urchin deliveries along the Oregon coast.

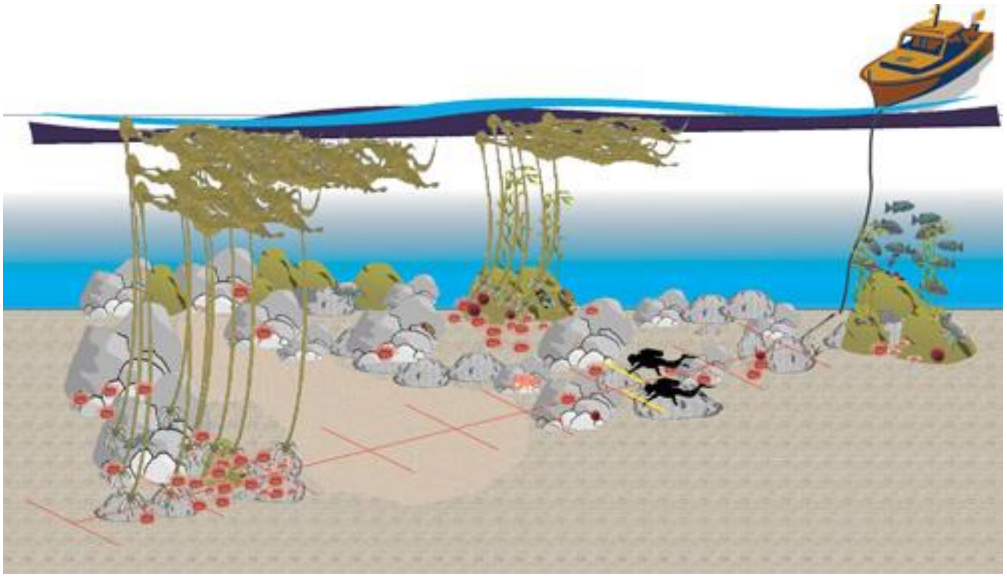

Figure 3: Illustration of methodology for subtidal belt transects used in ODFW sea urchin population surveys.

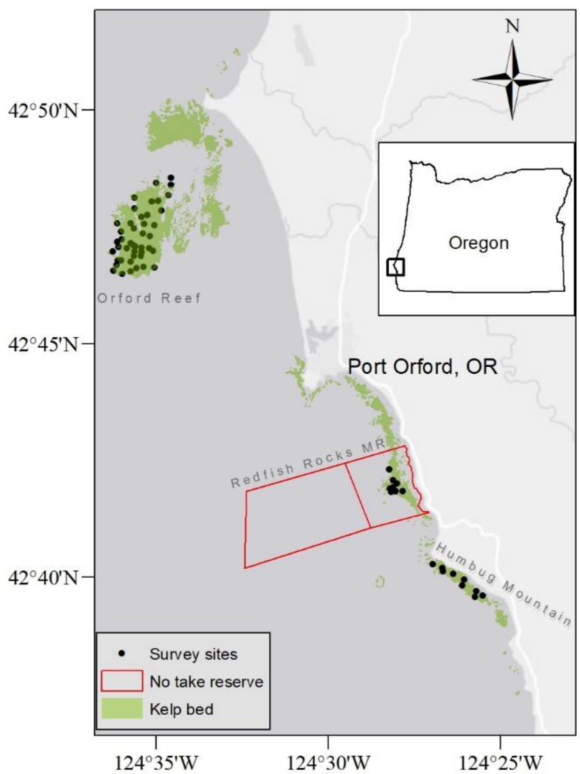

Figure 4: Sea urchin population index survey sites near Port Orford, OR.

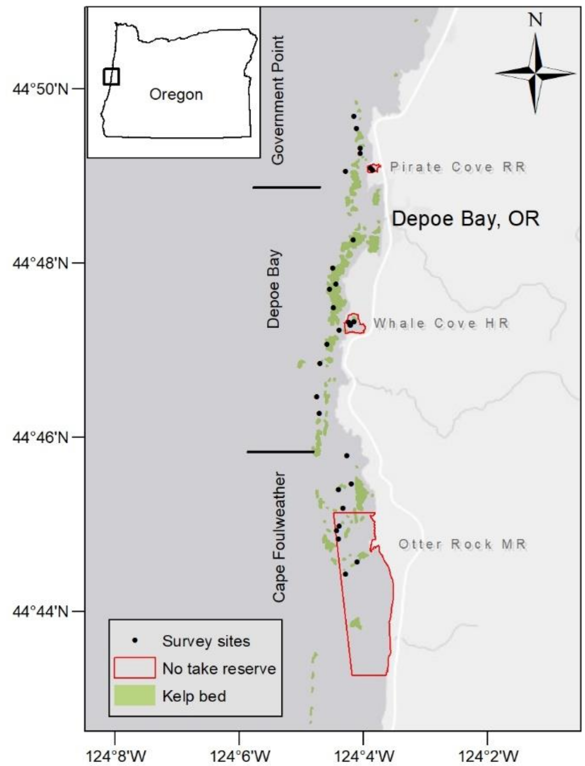

Figure 5: Sea urchin population index survey sites near Depoe Bay, OR.

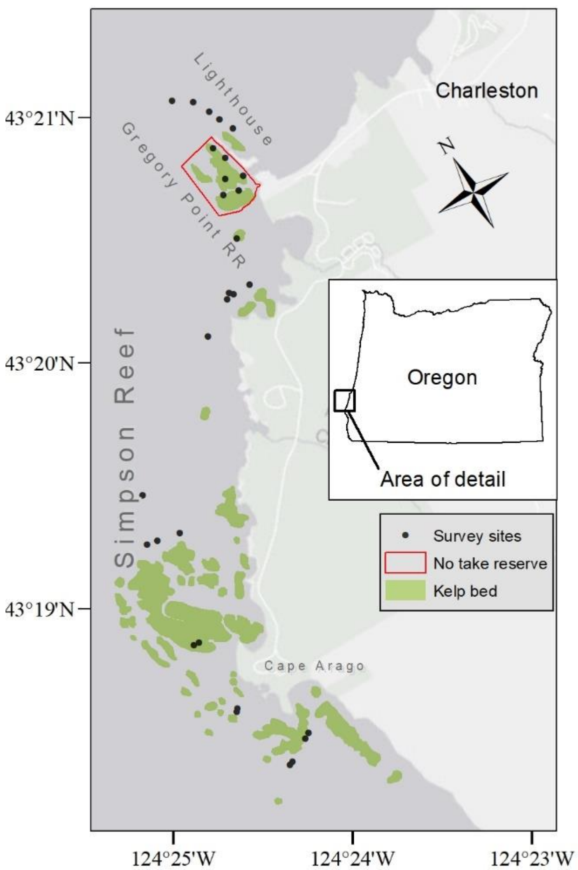

Figure 6: Sea urchin population index survey sites near Charleston, OR.

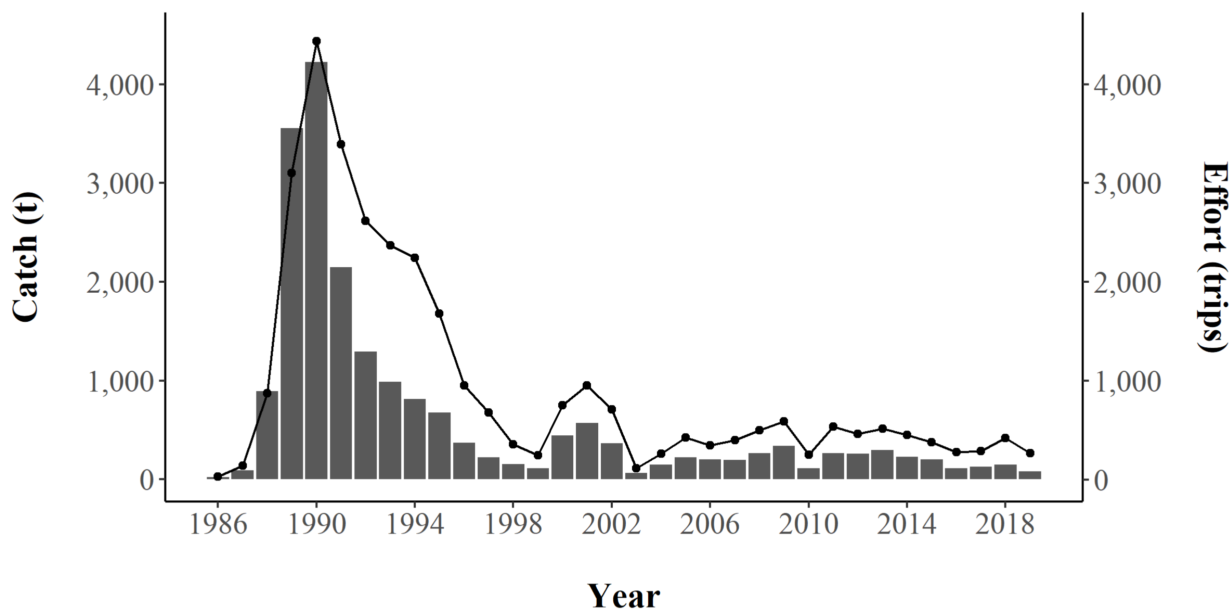

Figure 7: Catch (metric tons) and effort (number of trips) in Oregon's commercial red sea urchin (Mesocentrotus franciscanus) fishery (1986-2019).

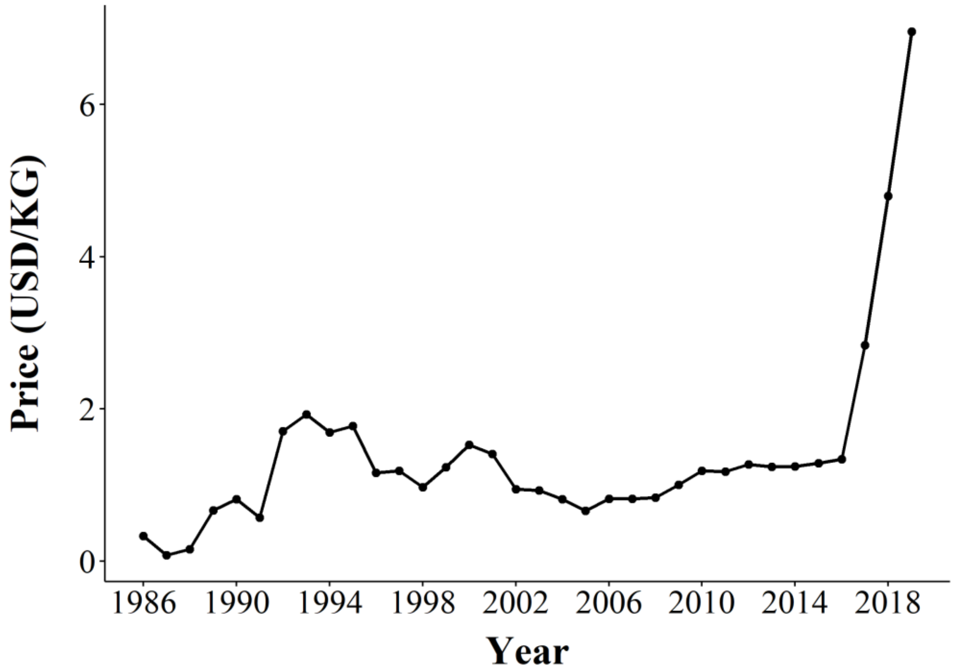

Figure 8: Nominal price (USD) per KG for red sea urchin (Mesocentrotus franciscanus) in Oregon, 1986-2019.

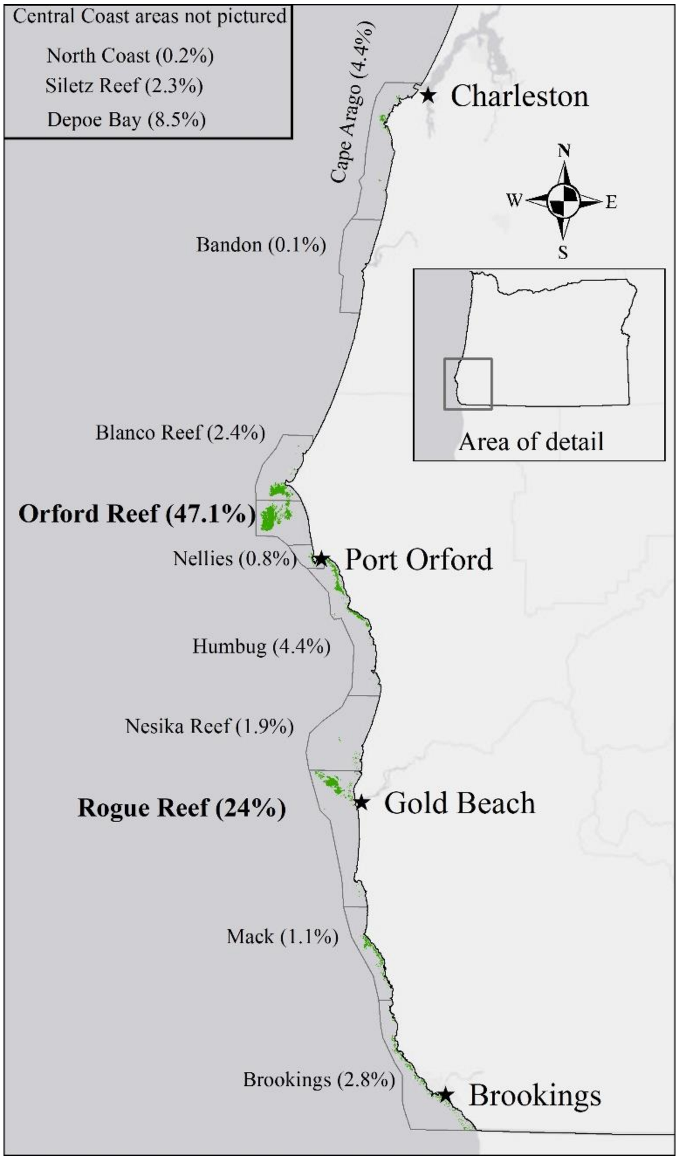

Figure 9. Catch of red sea urchin (Mesocentrotus franciscanus) by ODFW area, in Oregon 1986-2019. Note emphasis on South Coast areas particularly Orford Reef and Rogue Reef.

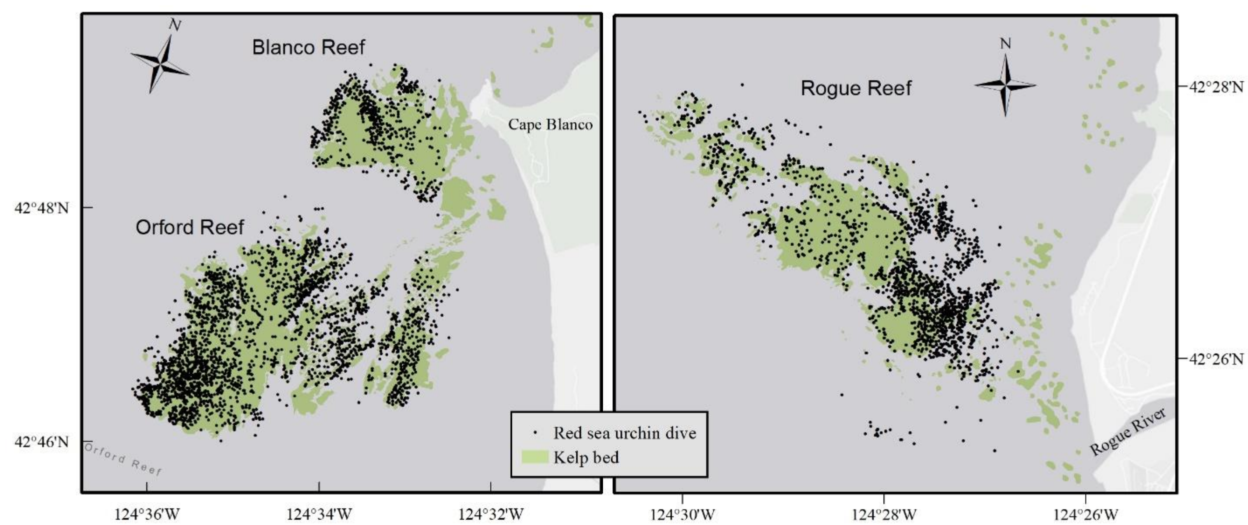

Figure 10: Sites of red sea urchin (Mesocentrotus franciscanus) dives in relation to kelp bed extents at Orford Reef and Rogue Reef, Oregon, 1986-2019.

Figure 11: Average size at Orford Reef

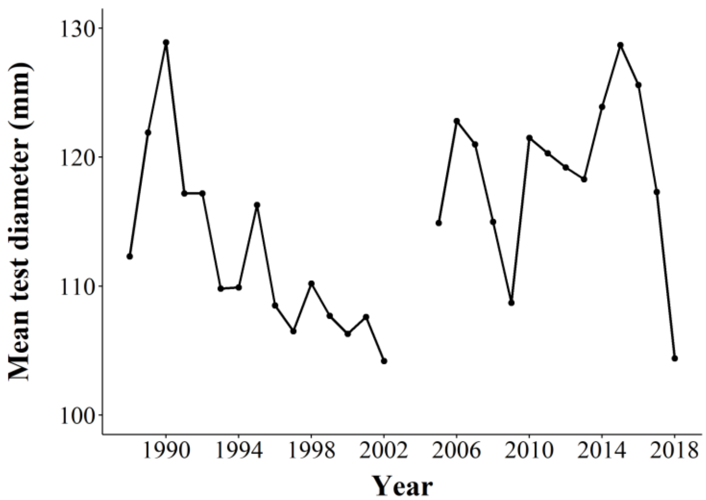

Figure 11: Mean test diameter (mm) of red sea urchin (Mesocentrotus franciscanus) caught in the commercial fishery at Orford Reef, OR 1986-2018.

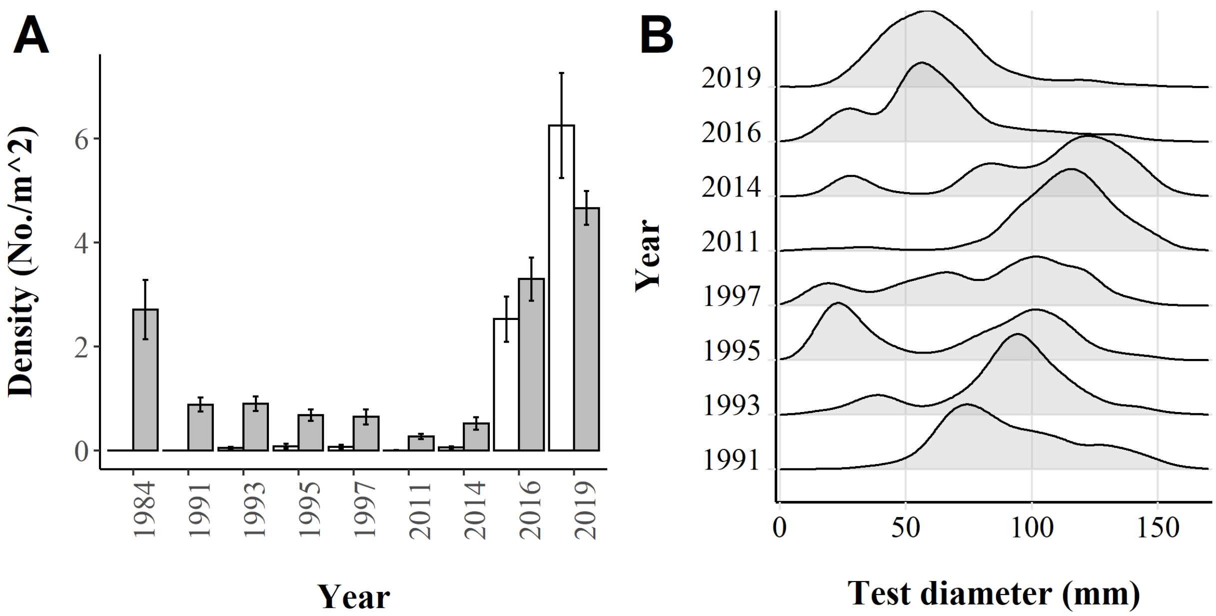

Figure 12: Sea urchin stock dynamics at Orford Reef, OR 1984-2019, a) densities of red sea urchin, Mesocentrotus franciscanus, (shaded bars) and purple sea urchin, Strongylocentrotus purpuratus, (white bars) by year (error bar indicates SE), and b) relative size distribution of red sea urchin by year.

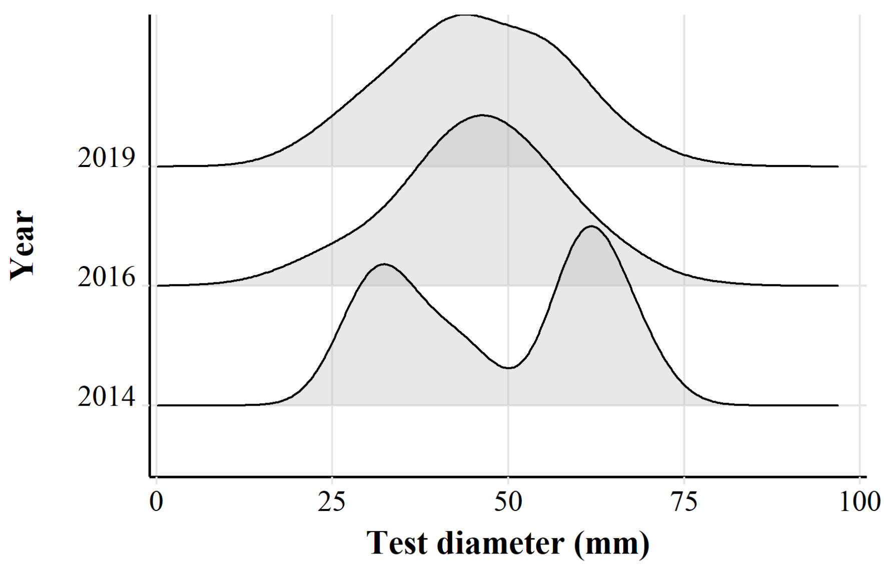

Figure 13: Purple sea urchin (Strongylocentrotus purpuratus) size distribution at Orford Reef, OR 2014-2019.

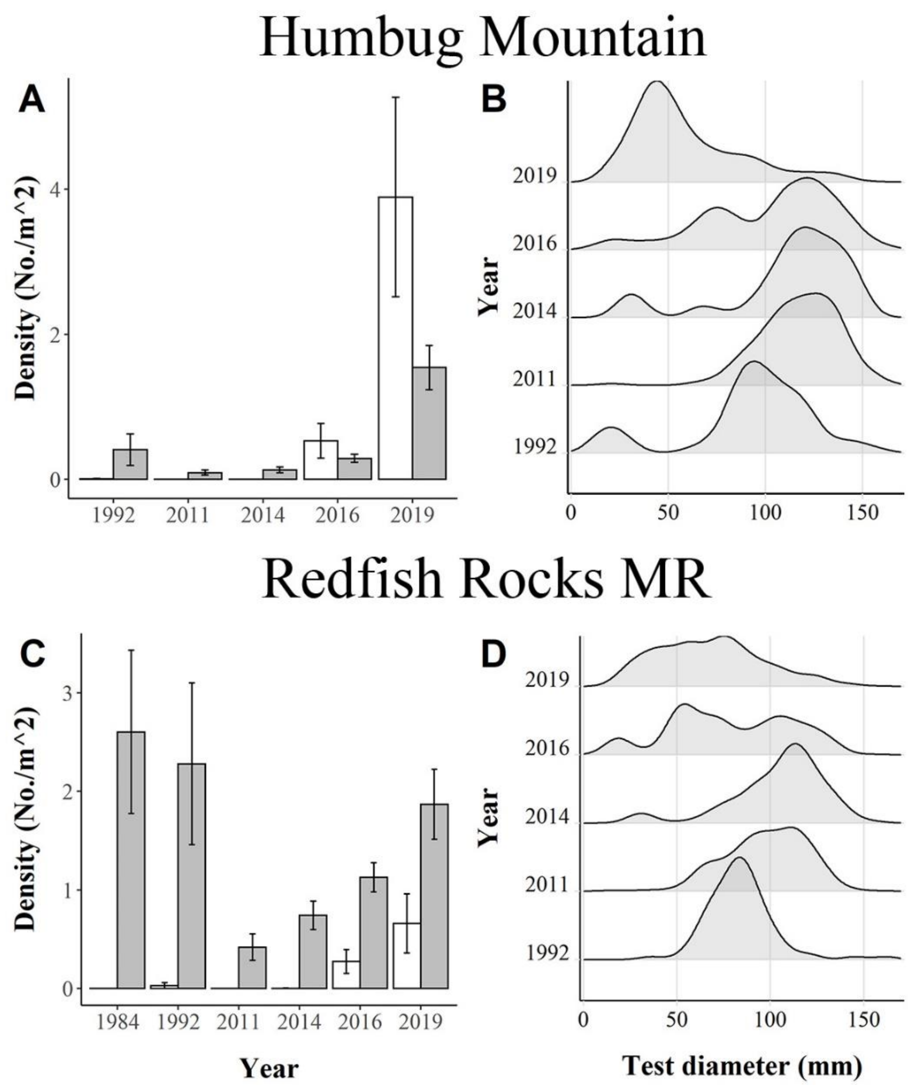

Figure 14: Sea urchin stock dynamics at Humbug Mountain and Redfish Rocks Marine Reserve, OR 1984-2019, a) densities of red sea urchin, Mesocentrotus franciscanus, (shaded bars) and purple sea urchin (white bars) by year (error bar indicates SE), and b) relative size distribution of red sea urchin by year.

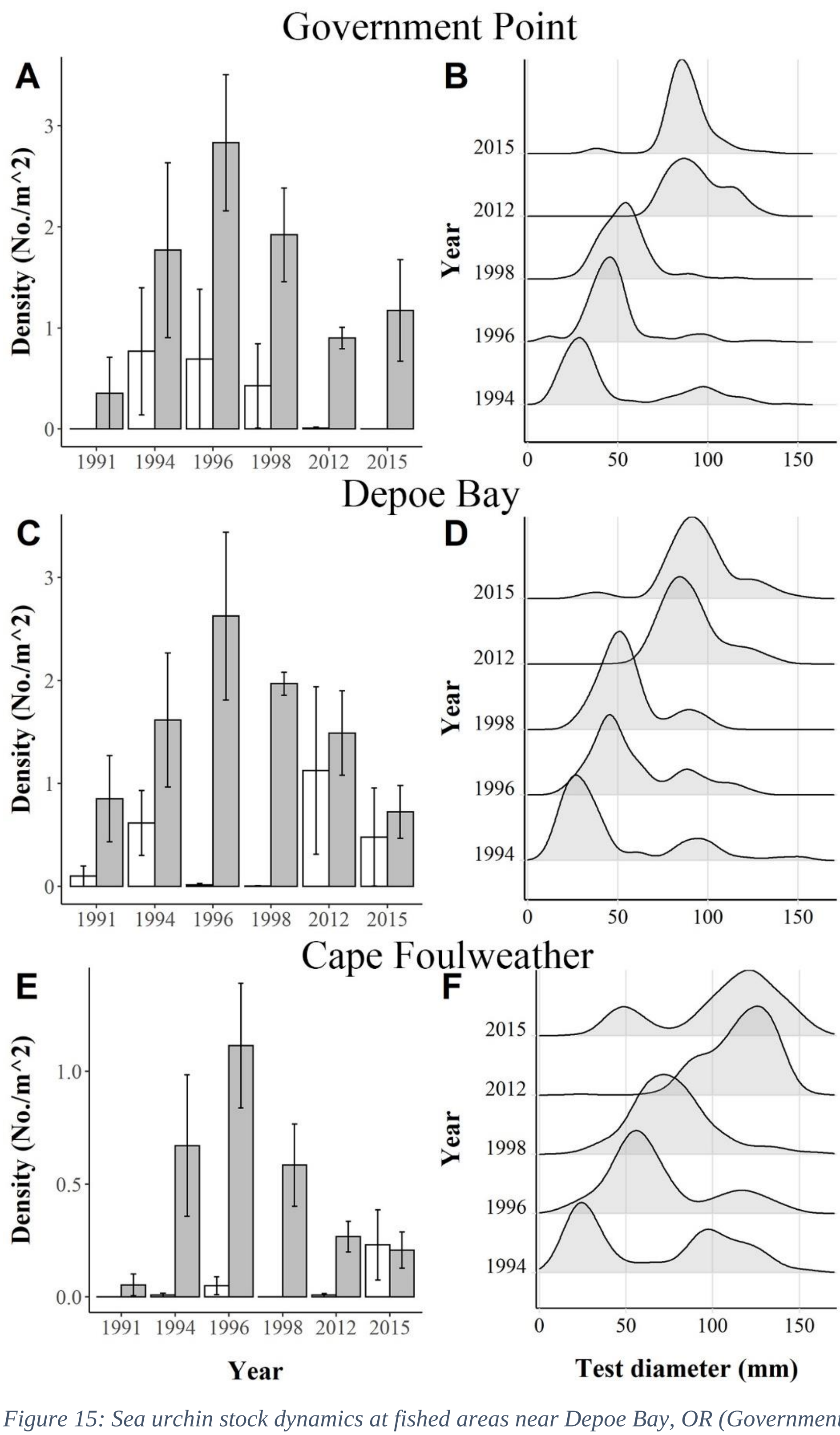

Figure 15: Sea urchin stock dynamics at fished areas near Depoe Bay, OR (Government Point, Depoe Bay and Cape Foulweather) 1991-2015, a) densities of red sea urchin, Mesocentrotus franciscanus, (shaded bars) and purple sea urchin, Strongylocentrotus purpuratus, (white bars) by year (error bar indicates SE), and b) relative size distribution of red sea urchin by year.

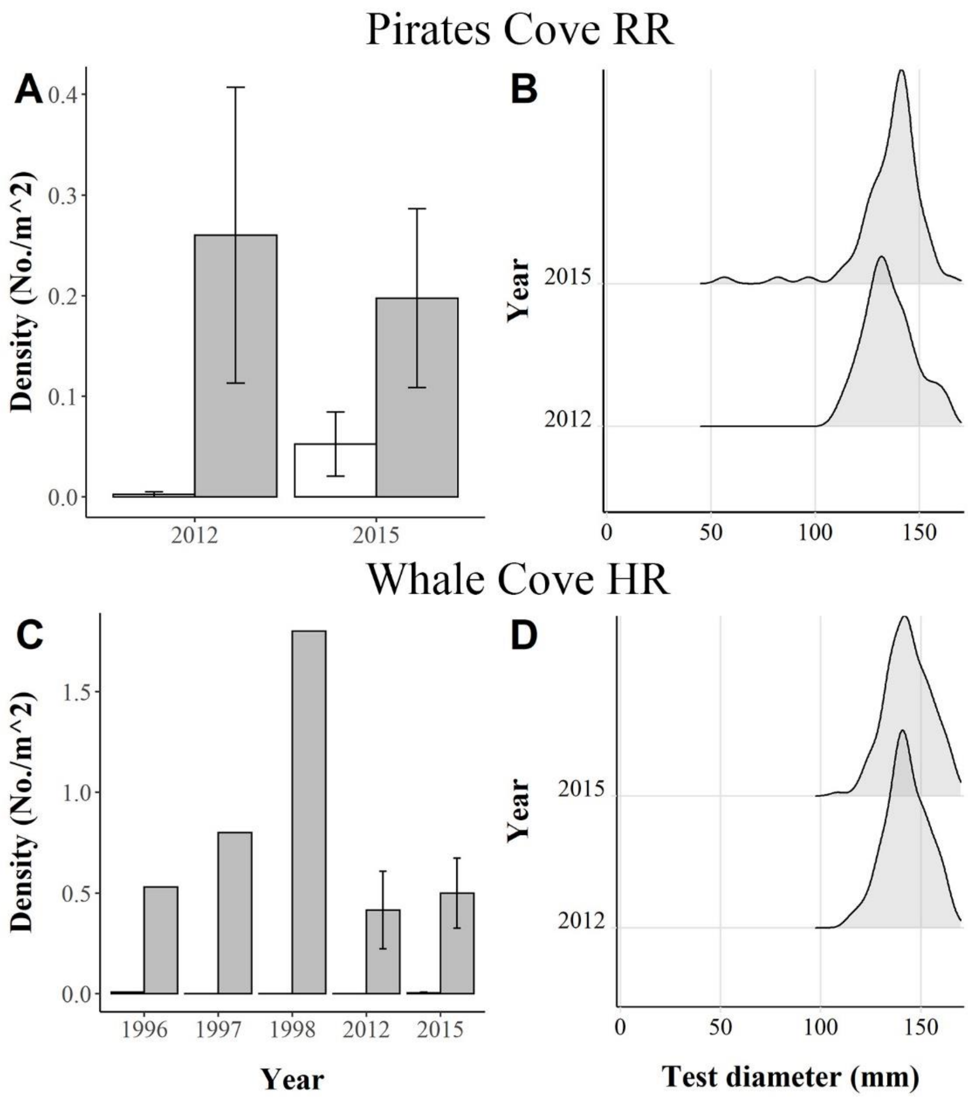

Figure 16: Sea urchin stock dynamics at two subtidal reserve sites near Depoe Bay, OR (Pirates Cove Research Reserve and Whale Cove Habitat Reserve) 1996-2015, a) densities of red sea urchin, Mesocentrotus franciscanus, (shaded bars) and purple sea urchin, Strongylocentrotus purpuratus, (white bars) by year (error bar indicates SE), and b) relative size distribution of red sea urchin by year.

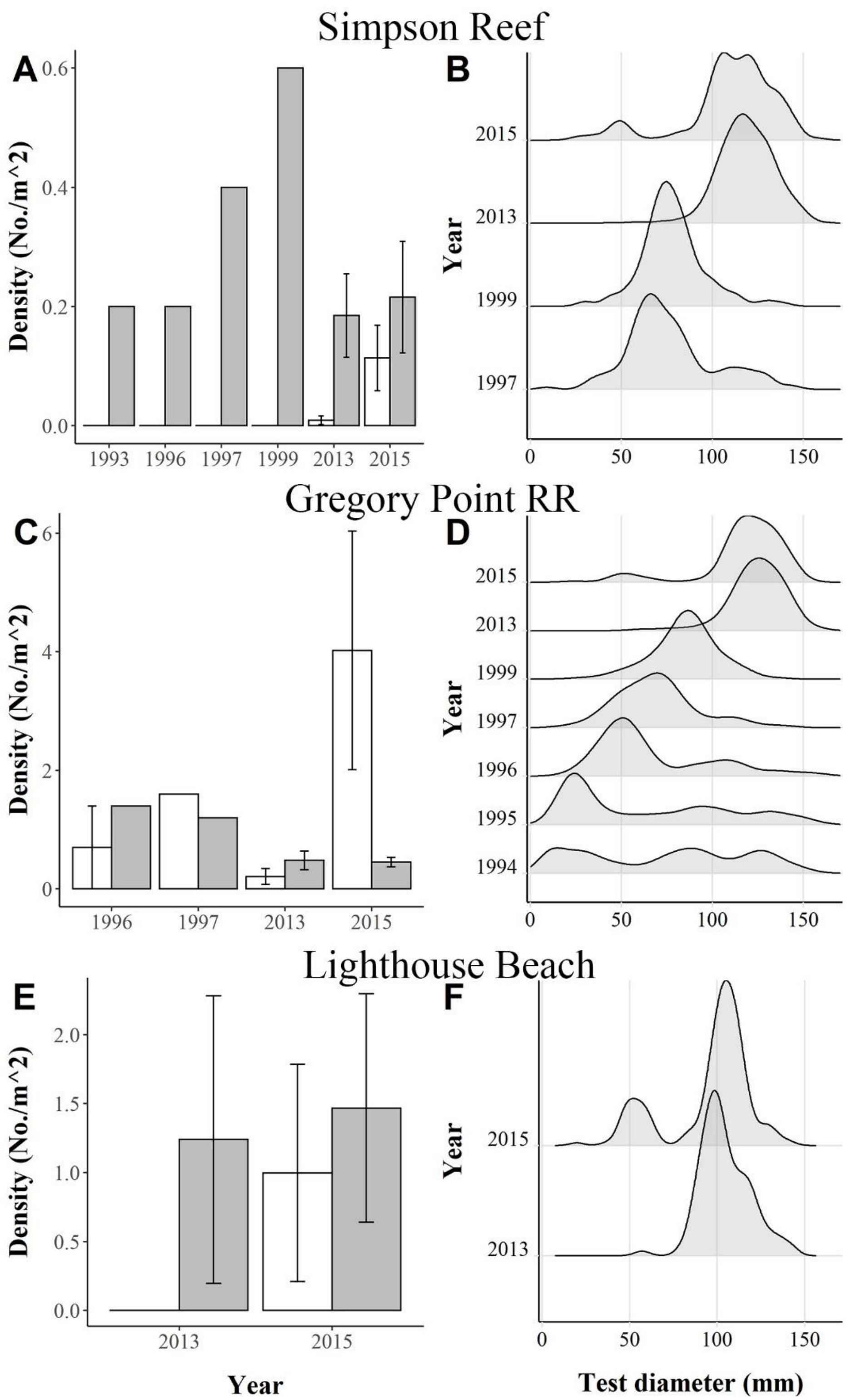

Figure 17: Sea urchin stock dynamics at areas near Charleston, OR (Cape Arago, Gregory Point Research Reserve and Lighthouse Beach) 1993-2015, a) densities of red sea urchin, Mesocentrotus franciscanus, (shaded bars) and purple sea urchin, Strongylocentrotus purpuratus, (white bars) by year (error bar indicates SE), and b) relative size distribution of red sea urchin.

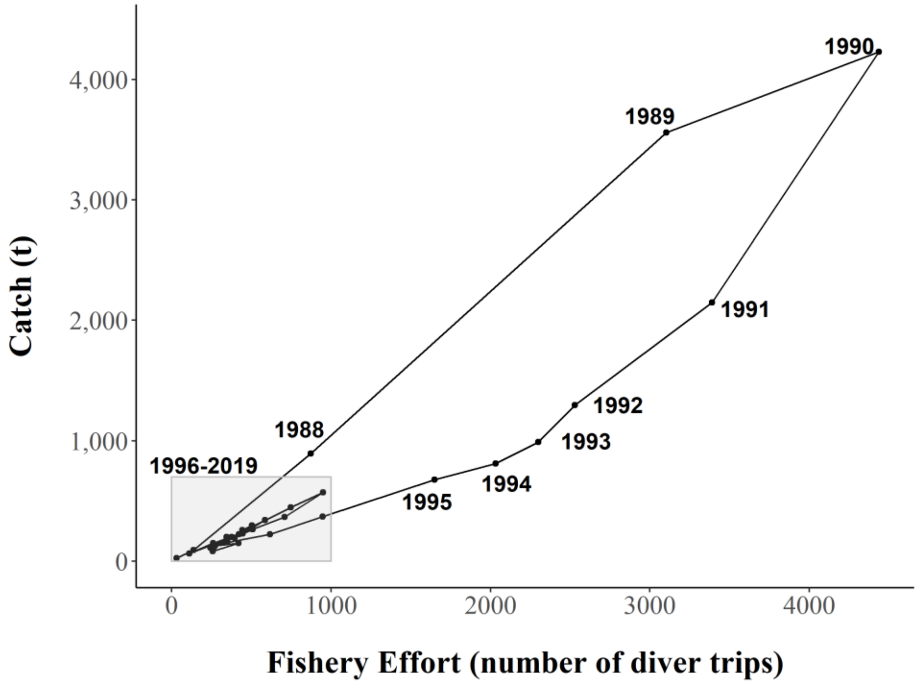

Figure 18: Red sea urchin (Mesocentrotus franciscanus), catch (t) compared effort (vessel trips) in Oregon, 1986-2019, exhibiting Shepherd's (1993) dynamic response pattern.

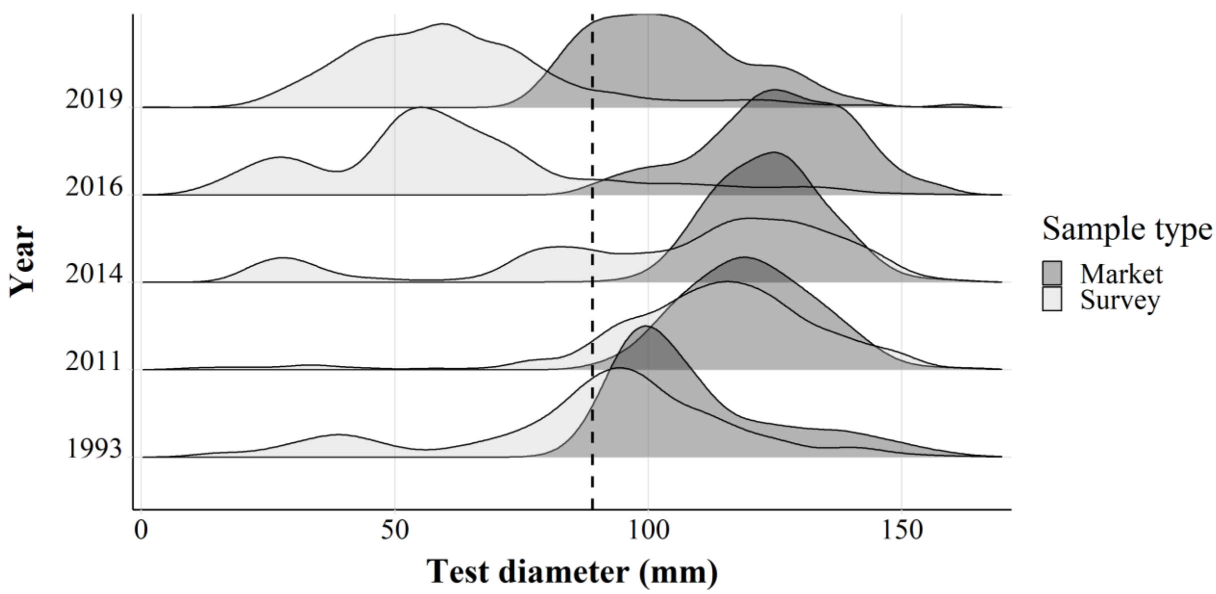

Figure 19: Size distribution of red sea urchin (Mesocentrotus franciscanus), from fishery market samples (dark shaded) and population surveys (light shaded) or Orford Reef, OR.