Over the Brink — A History of the Maine Sea Urchin Fishery and DMR Sea Urchin Research and Management

Margaret Hunter, DMR, December 2022

Abstract

The Maine green sea urchin fishery has been described as a classic "boom-bust" fishery. Significant harvesting of this "pest" species began in 1987, and by the time the first management controls were in place in 1994 there were 2,725 licensed harvesters and annual landings were 17,200 mt. Management, minimally influenced by state-sponsored research programs, suffered from early reliance on fishery-dependent data, including non-informative catch rate data. Sea urchins are now commercially extinct on large stretches of the coastline. In many regions, urchin barrens have been replaced by algal-dominated habitat, which has become an alternate stable state despite the cessation of fishing. A limited urchin fishery is still conducted in remaining areas, with about 100 active fishers and annual landings of about 383 mt in the 2021–22 season. Recognizing that each urchin ledge is still effectively in an open access condition vulnerable to depletion, despite strict controls on fishing, the State is still searching for appropriate management strategies.

Early History of the Fishery

The green sea urchin, *Strongylocentrotus droebachiensis* (Müller), was harvested along the Maine coast for human consumption of the "roe" (male and female gonads) long before European colonization (Spiess *et al.* 1990; Spiess and Lewis, 2001). Urchin tests (shells) are fairly common in Native American shell middens, but have not always been documented (Arthur Spiess, pers. com.). More recent records back to 1929 describe a small seasonal commercial fishery for this spiny echinoderm, using dip nets, hand rakes, or scallop drags. Reported annual Maine landings between 1929 and 1985 ranged from 3,000 pounds (1.4 mt) in 1929 to 180,000 pounds (82 mt) in 1948. Urchins were trucked live to ethnic European and Asian markets in New York and Boston (Anon. 1929; Scattergood 1947; Scattergood 1961). In the 1970s and early 1980s, a few SCUBA divers supplied a small live market in Europe (Dean 1983; Rioux 1988; Amory 1994).

An "invasion" of *S. droebachiensis* in the western North Atlantic from the late 1960s through the 1980s, also described as an "explosion" and a "plague" (Lannin 1986), was documented at the Isles of Shoals off New Hampshire in the southwest Gulf of Maine (GOM) (Witman *et al.* 1982; Witman 1985), at Pemaquid Point in midcoast Maine (Steneck *et al.* 1995; Steneck 1997), and at several sites along the southern coast of Nova Scotia. (Breen and Mann, 1976; Wharton 1980; Wharton and Mann, 1981; Bernstein and Mann, 1982). Scientists hypothesized that the outbreak

of sea urchins in eastern Canada may have been the result of heavy fishing on a keystone predator, the American lobster (*Homarus americanus*) (Mann and Breen, 1972). Later work suggested that release from the predation of a suite of crustacean and fish predators may have caused the urchin explosion in eastern Canada (reviewed by Scheibling and Hatcher, 2013). In the Gulf of Maine, a similar outbreak was likely due to release from predation by large fish (reviewed by Tegner and Dayton, 2000).

Sea urchins are important algal grazers and at high density can be ecologically destructive, mowing down kelp forests and directly or indirectly reducing primary productivity and species diversity (reviewed by Steneck (2013) and Scheibling and Hatcher (2013)). Researchers wondered whether the western North Atlantic urchin invasion posed a threat to valuable lobster stocks (Pringle *et al.* 1980). Wharton and Mann (1981) concluded that it did. There was discussion of the need and opportunity to develop fisheries for sea urchins, as well as other methods of urchin eradication (Neish 1973; MacKay 1976; Pringle *et al*. (eds.) 1980; Wharton and Mann, 1981; Bernstein and Welsford, 1982; Miller 1985).

Lobster harvesters in Maine were complaining of a proliferation of the prickly sea urchin by 1971 (*e.g.* letter to Maine's Department of Sea and Shore Fisheries — later renamed Department of Marine Resources (DMR) — from Russell Woodman, Owls Head, Maine, July 11, 1971). In 1981, biologists attempted to learn more about this possible threat to the State's lobster fishery through a poll of lobster harvesters. Of 109 responses received, 72% reported seeing an increase in sea urchin abundance, about equally distributed along the entire Maine coast (76% of western, 64% of midcoast, and 70% of eastern Maine respondents), and 70% reported a decrease in legal-sized lobsters (Stickney 1981). Sea urchins were certainly worse than a nuisance, filling lobster traps and clinging on like balls of Velcro®, eating the bait, damaging traps, destroying lobster habitat, and stabbing lobstermen's fingers (Stickney 1981; Lannin 1986; Rioux 1988; Riddle 1989). They were despised and routinely destroyed, and nicknamed "whore's eggs" and other less printable epithets (Kleiman 1990; Canfield 1991).

Stickney (1981) was one of the first to propose the development of a market in Japan for Maine sea urchin roe. The Maine green sea urchin is similar to Japan's highly-prized Hokkaido green sea urchins, *S. intermedius* and *S. nudas* (Kleiman 1990; Sonu 1995). In the mid-to-late 1980s, when the Japanese yen strengthened relative to the US dollar, it became economical to ship (air freight) whole sea urchins from the US east coast to existing markets in Japan (Muraoka 1990; Amory 1994; Reynolds and Wilen, 2000).

The Gold Rush Years

The first full year (1987–88 season) of the newly developing Maine fishery was fraught with problems. The fishery was conducted by both divers (using SCUBA) and draggers (mostly using modified scallop drags). It was estimated that there were about 50–75 dealers in the state buying

whole sea urchins (Rioux 1988). A few processors set up shop in Maine (Rioux 1988; Amory 1994), but most of the market was in live whole urchins air-freighted to Japan (Lignell 1990; Jones 1992; Amory 1994). Buyers and processors there were very particular about the quality of the product, the sea urchin roe. Unlike most fisheries, the price paid depended not only on the volume or weight of the catch, but more importantly on the yield and quality of the roe. Grades of acceptable roe depend on freshness, color (pale yellow to bright orange), size, texture, firmness, uniformity, wholeness, optimum ripeness, and taste, and the nature of the buyer's market — low-end supermarkets and dried, salted, steamed, or cured products, to high-end restaurants and sushi bars (Wilen and Wessels, 1997; Reynolds and Wilen, 2000). The roe characteristics cannot be determined without breaking open, thus killing, the sea urchin, and many urchins were discarded, on the boats, by the buyers at the dock, by local processors, and by the rejection of both processed roe and whole urchins once they arrived in Japan (Plante 1990; Canfield 1991; Ryan 1992; Amory 1994). It was estimated that only one in ten sea urchins harvested during the winter of 1987–88 was actually paid for (Baxter and Chamberlain, 1988).

The arrival and involvement of Japanese trainers and technicians to teach Maine buyers and harvesters about the requirements of the Japanese market were vital to the growth of the industry (Rioux 1988; Jones 1992; Chenoweth 1992a). The DMR's first direct involvement with the fishery was in industry development, by members of the Department's Fisheries Technology Service. Area meetings were held in 1988 to discuss markets, harvest technology, and processing techniques (Baxter and Chamberlain, 1988).

A *Wall Street Journal* article about the urchin fishery in eastern Maine in 1988 was one of the first to mention the possibility of over-harvesting, as had happened in the California red sea urchin fishery (Chipello 1988). But some industry leaders claimed the sea urchins were so abundant in Maine they would be impossible to wipe out (Plante 1990; Canfield 1991; Austin 1993; Amory 1994).

Sea urchins in the GOM spawn (release gametes) about once per year in the spring, usually during March–April (Vadas *et al.* 1995); gonads begin recovery during summer and fall feeding, and have the highest commercial roe yields in winter, usually peaking in February before spawning again (Hunter 2015). Further development of local processing capability and the development of a low-priced product for Japanese supermarkets in 1989 fueled industry growth and made urchin buying less risky. It also created a market for poorer quality urchins (roe less than 10% of whole body weight), and effectively lengthened the season when urchins could be profitable, from winter months (November–March) to year round (Canfield 1992; Quimby 1993; Amory 1994). Reported landings jumped from 4 million lbs (1,800 mt) in the 1987–88 season to 19.7 million lbs (8,900 mt) in 1991–92 (Table 1, based on voluntary information collected by National Marine Fisheries Service port agents).

In 1991 an article in the *Maine Sunday Telegram* (Canfield 1991) was one of the first to suggest that the resource in southwestern Maine, particularly Casco Bay in Cumberland County, was becoming depleted and divers were moving further east to find product. The author pointed out that although there were estimates of 800–1000 active divers, no one really knew the number of participants or the amount of fishing effort. There were almost no legal restrictions on who could fish, where, when, the fishing gear, or how much could be taken. The entire fishery was conducted within State waters, and the State had a laissez-faire approach to emerging fisheries.

DMR biologists looked on with great interest, reviewed the scientific literature and lessons from other urchin fisheries around the world, talked with participants, attended meetings, and planned monitoring programs, but lacked funding to undertake any formal research, monitoring, or stock assessment (Chenoweth 1992a, 1992b; Creaser 1993a, 1993b; Austin 1993). The most detailed sources of information about the rapid development of the Maine fishery were in the news media, which often described the amount of money divers could make in a week and likened the fishery to a gold rush. By the end of 1992 the urchin fishery had become the State's second most valuable wild fishery ($15 million US unadjusted ex-vessel value in 1992), after lobsters. A March 1993 front page article in *The Maine Times* blasted the State for missing an opportunity to coordinate the urchin fishery's economic and environmental issues to develop a sustainable fishery. The article also raised the question: was the resource being overfished? (Austin 1993).

DMR proposed fishery restrictions in 1990 and again in 1992 — a five-month closed season, drag size limit, prohibition on nighttime harvesting, and the requirement that discarded urchins be culled at sea (Jones 1993) — that were not implemented due to a lack of industry support, and lack of scientific justification. Said DMR commissioner William Brennan: "*There is no clear consensus from industry on what should be done; and there is no stock assessment information to lead the department*" (Jones 1992). "*It's not clear what [regulations] to put into effect. It forces us to go to the higher level of developing industry consensus about what to do, if anything*" (Austin 1993). The DMR was undergoing staff and budget cuts (Austin 1993; Amory 1994), and was ill-prepared to take on another major fishery or even maintain existing programs; the commissioner was making the point that his hands were tied without adequate funding for management, monitoring, research, and enforcement.

One observer later described these attempts to manage "like trying to stop a freight train" (S. Hoyt, pers. comm.). The fishery was later dubbed "a Rodney Dangerfield fishery — It don't get no respect" by DMR staff (Hunter, personal obs.). The characterization of the sea urchin as a pest, a plague (Lannin 1986), and the lobsterman's bane — "…*the best way to get rid of a pest is to eat it*…" (Rioux 1988), — not to mention discussions of eradication, may have made it difficult to take sea urchins seriously as a valuable resource. Their lack of "cuteness appeal" might also explain the non-involvement of local environmental groups in their protection (Austin 1993). The fishery was prosecuted by divers mostly working from lobster boats, and draggers, some of which were lobster boats rigged for dragging during their winter off-season. The lobster

industry had no love for the pesky sea urchin, and lobstermen were described as "*thrilled with the prospect of reducing the urchin population*" (Riddle 1989). Participants also believed that the favorable yen/dollar exchange rate was temporary and the Japanese market would never last (B. Chamberlain, pers. comm.).

State harvesting licenses (one for diving and one for dragging) specific to sea urchins were required beginning in 1992, with an $89 annual fee. Before then, harvesters only had to have a general commercial fishing license ($20 annually for divers and single draggers, or $53 for draggers and crew, in 1987); there was no way to know how many harvesters were participating, since that license type was also sold to groundfish, herring, and a few other fishery harvesters. There were no harvester logbooks, and dealer landings reports were voluntary. By the end of 1992, there were 1,075 urchin harvester licenses issued — 829 divers and 246 draggers — but no way to tell how many of them were actually active.

In the spring of 1993, working with recommendations from an informal 18-member industry task force organized by the DMR commissioner (Austin 1993), the Maine legislature passed laws establishing a 2-inch (50.8 mm) minimum size and a three-month closed season during the summer when urchin roe yields are low, and authorizing the commissioner to implement (in regulation) the minimum size, a prohibition on nighttime dragging, and a maximum drag width (5.5 ft., 1.67 m) (Jones 1993). These are authorities the commissioner already held (Maine Statute, Title 12 §6171), but had not acted upon. Although there was some evidence at the time that the 2-inch minimum size would protect some spawners (Munk 1992; Chenoweth 1994), the size was also chosen as a common sense conservation measure, since harvesters and processors already discarded smaller urchins (Canfield 1991). The news media continued to produce headlines like "*Too many divers, not enough urchins*" (A.P. 1993) and "*Urchins: 'Pest' in Peril*" (Canfield 1993a).

It may have been the drowning deaths of four urchin divers within four months later in 1993 following two other deaths in 1992 (CDC 1994) that finally caught the serious attention of Maine law makers, and in 1994 laws were passed to require safety training for divers, establish a DMR research fund from a license surcharge collected from harvesters, buyers, and processors, create a moratorium on new harvester licenses (Maine's first closed access in a State-managed fishery), require a special permit for buyers and processors, divide the coastline into two exclusive fishing zones (Figure 1), lengthen the closed season, and grant authority to the commissioner to require monthly landings reporting for buyers (another first for a Maine non-federal fishery). Landings peaked at 39 million lbs (17,800 mt) in the 1992–93 season (Table 1, Figure 2). There were 1,725 licensed urchin divers and 1,000 licensed urchin draggers by the end of 1994, after which no further entrants were allowed until 1999–2004, when there were very limited annual lotteries for new licenses. See Appendix A for a chronology of the extensive Maine sea-urchin-fishery-related legislation and rule-making, and Table 2 for annual license sales.

Diver safety also caught the attention of the federal Occupational Safety and Health Administration (OSHA) who ruled that boat captains were employers, and therefore responsible for the safety of the divers; at least two boat operators were cited but the ruling was later relaxed (CDC 1994; Canfield 1993b; O'Quinn 1993).

In the same year, concerns about safety, the condition of the resource, and quality of the roe led to the formation of two industry groups, the Maine Urchin Association (MUA) and the Maine Urchin Harvesters Association (MUHA) (Wormwood 1994). Several of their members were on the commissioner's informal task force, and later, the Maine Sea Urchin Zone Council (SUZC), which was created in statute in 1996 to formally advise the DMR.

Prices paid to the harvesters doubled (Table 1), and prices for exported urchin roe shipped to Japan from New York and Boston increased four- to five-fold between 1991 and 1995, as the industry matured and knowledge accumulated (Wilen and Wessells, 1997), and the dollar/yen exchange rate continued to rise, peaking in 1995 (Lynham 2016).

Fishery Monitoring and DMR-Sponsored Research Begin

With the establishment of a significant and long-term funding source, State-sponsored monitoring and research began. DMR co-hosted a science workshop in 1994 (Harris and Carr (eds.), 1995) to review work already done or underway in Maine, New Hampshire, Massachusetts, and New Brunswick. The department issued requests for proposals for research projects in 1995, and those contracted projects began in 1996, including studies of growth, age, and roe characteristics spatially and seasonally (Vadas and Beal, 1999; Seward *et al*. 2000, Seward 2002), a study of settlement and juvenile survival (McNaught and Steneck, 1998; McNaught 1999, Steneck *et al*. 2013), a study of green urchin reproduction (Wahle and Peckham, 1998; Wahle and Peckham, 1999), and an economic analysis of the market (Wilen and Wessells, 1997). See Taylor (2004) for descriptions of those and subsequent Maine DMR and contracted research projects, funded by license surcharges, and the DMR website for more recent project information.

DMR began a port sampling and harvester interview program. During its first season (1994–95), it was limited to harvester telephone interviews, and was expanded the following season to in-person harvester interviews and catch sampling at the docks when funds for travel became available from the new license surcharges. See Hunter *et al*. (2010) for details of the project protocols and sampling intensity.

The CPUE Trap

One of the main purposes of DMR's port sampling project was to collect trip-level catch and effort information, to develop catch rate — also called catch per unit effort (CPUE) — indices

for the fishery for each of the two gear types and new management zones. The assumption was that catch rates would rise and fall in proportion to abundance, making CPUE indices a useful tool for assessing the health of the stock, and data collection was relatively inexpensive. CPUE data were used in other sea urchin fisheries as indices of stock abundance to inform fishery management (*e.g.* Pfister and Bradbury, 1996; DFO 1996; Perry *et al.* 2002), although Pfister and Bradbury cautioned that changes in harvester behavior (fishing deeper or fishing further from home) could indicate increasing effort that is not characterized by bottom hours alone. Median pounds per bottom hour for divers was chosen as a robust estimator of CPUE (Perry *et al.* 2002; Zhang and Perry, 2005).

Landings per unit effort (LPUE) was utilized as a proxy for catch per unit effort (CPUE); DMR lacked data on total catches because there was much discarding of catch at sea, the extent of which was unknown but anecdotally considerable. See Meredith (2012) and Hunter (2015) for further discussion about LPUE and CPUE.

A comparison of the median pounds landed per bottom hour, summarized from diver interviews conducted during 1994–95 through 2021–22 harvesting seasons by zone (Figure 3), shows that Zone 2 diver LPUE dropped steadily over the first eight years of the series, to what was probably an economic threshold, about 125 to 150 lbs/hr. Zone 1 LPUE had probably declined nearly to that level before the project began, and continued to decline during the next four seasons.

When Zone 1 LPUE jumped back up to about 150 lbs/hr during the next three seasons (1998–99, 1999–2000, and 2000–01), DMR scientists were both relieved and confused, since harvesters and buyers were still leaving the fishery at a higher rate in Zone 1 than in Zone 2 where LPUE continued to decline. By 2001, 54% of Zone 1 dive licenses issued in 1995 had been retired, compared with 34% retired in Zone 2 (Table 2).

Rising or stable LPUE does not necessarily indicate increasing or stable stock abundance, according to our survey results (see next section) and analytical model (Chen and Hunter 2003). LPUE has proven to be a poor index of stock abundance for this fishery. There is extensive literature on the problems resulting from assuming that catch rates rise and fall in proportion to abundance, even with standardization methods (*e.g.* Hilborn and Walters, 1992; Keesing and Baker, 1998; Prince and Hilborn, 1998; Schroeter *et al.* 2001; Maunder *et al.* 2006; Miller and Nolan, 2008)). We now believe that the elevated catch rates in Zone 1 during this period were likely due to several of the following factors that can cause hyperstability in LPUE:

1. **Attrition of the least successful harvesters:**
   LPUE could be maintained at higher-than-expected levels (hyperstability) if the least successful harvesters in a closed fishery dropped out of the fishery each year. Using dealer logbook data, we compared the landings data for the 81 Zone 1 divers who fished in 1997–98 but didn't fish in 1998–99 — the "dropouts" — with the landings data for the 234 Zone 1 divers who fished in both years. The mean daily landings in 1997–98 for the dropouts was

377 lbs, which was significantly lower than the landings of 436 lbs in 1997–98 for those who stayed in (two-sample, one-tailed t-test, p=0.0060). Comparing the mean daily value paid to the harvester instead of pounds landed gave similar results. This confirms that those who dropped out were, on average, less successful than those who stayed in for the next season, and because it was a closed fishery, they were not replaced by new inexperienced divers. Similarly, researchers have identified interactions between angler skill level and catch rates in recreational fisheries ("effort sorting" — van Poorten *et al.* 2016); others found that the culling of inefficient vessels in commercial trawl fisheries makes interpretation of CPUE/LPUE difficult (Meredith, 2012). There may be additional reasons for a lack of success, such as illness or injury, inability or unwillingness to travel further to better fishing grounds, or other personal reasons. Losing some of the less successful fishers from the fishery each season because of an economic threshold could elevate or cause overall catch rates to remain stable, despite declines in stock abundance.

2. **Serial depletion:**
   Worldwide, many sea urchin fisheries have shown a pattern of serial depletion followed by stock declines and sometimes collapse (reviewed by Andrew *et al.* 2002). LPUE could be maintained if harvesters were able to move away from depleted areas to fish less exploited areas. There is considerable information from harvester interviews that describes how that happened in Maine (*e.g.* Canfield 1991; Johnson *et al.* 2013). Lacking specific catch locations and harvester logbook information for the early years of the fishery, it is difficult to prove analytically that Maine's sea urchin stock was depleted spatially in a serial manner, but it is strongly suggested by Figure 4, which shows the distribution of landings by county and zone, illustrating that over time, landings shifted away from the west toward the east in each zone. Note that the location of the landing might not be close to the harvest location if the urchins were trucked some distance to the buyer, and there were a lot of buyers in the Casco Bay/Portland area (Cumberland County in western Zone 1). In 1996 the last buyer in Portland (not including the processors) closed his doors. By 2003–04 about 66% of Zone 1 harvesting was being landed in Knox County, the easternmost county in Zone 1 (Figure 4). That is, most fishing effort in the zone had shifted away from the western counties and was now piling up against the eastern boundary of the zone with nowhere else to go; zone switching rules made it almost impossible for Zone 1 harvesters to switch to Zone 2. Likewise, in 2003–04 in Zone 2, landings were highest in Washington County (Figure 4), the most remote Maine coastal county, being the farthest from the remaining processors who were mostly in the greater Portland area.
3. **Aggregating behavior of the stock:**
   Green sea urchins aggregate, primarily to feed, and perhaps defensively (reviewed by Scheibling and Hatcher 2013) and perhaps to spawn (Brian Soper's "Casco Bay Crawl", and Larry Harris, pers. comms.). As long as harvesters can find an aggregation, catch rates can remain high even if the number of aggregations dwindles (Erisman *et al.* 2011; Dassow *et al.* 2020).

4. **Changes in fishing strategy:**
   Fishing on poorer-quality urchins (Canfield 1993a) can bolster catch rates. The higher rates in Zone 1 during 2009–2013 (Figure 3) were accompanied by a decline in roe content, suggesting that Zone 1 harvesters changed their fishing strategy, away from targeting high-quality urchins to targeting higher volume, poorer-quality urchins as well (Hunter 2015). This change in fishing strategy was confirmed by Zone 1 divers at SUZC meetings (Hunter, personal obs.).
5. **Management actions:**
   Shifts in management approaches can also influence CPUE (Maunder *et al.* 2006; Meredith 2012). Maunder *et al*. provide examples of closing the less productive part of a fishing season, or a less productive area; both situations could result in higher CPUE indices. This may have been the case in Maine, when the State repeatedly shortened the sea urchin fishing seasons, with advice from the SUZC — it was usually the least productive days that were cut from the calendar, such as days during months that tended to have the worst weather or price (*e.g.* February) or days when the urchins were starting to spawn and it was harder to find good quality (March–April).

More recent management actions (Appendix A), such as implementing daily landings limits, and allowing harvesters to choose their fishing days (thus reducing fishing in bad weather) could also boost LPUE indices.

Other Research

Other DMR research projects have investigated dragging impacts, and ways to reduce catches of under-sized sea urchins by divers and drags. A large-mesh catch bag rule for Zone 2 divers (in 2003), a culling-on-bottom rule for divers in Zone 1 (in 2003, and later (in 2012) for Zone 2), and an escape panel rule for drags (in 2003 for Zone 2) have been implemented (Appendix A).

A population dynamics model was also developed for Maine's sea urchin stock (Chen and Hunter 2003; Kanaiwa *et al*. 2005), and was used to inform management during 2002–2013, but was abandoned when it became apparent that its results were too optimistic, especially for Zone 1. See Hunter (2015) for further details. Because of steady declines in sea urchin license sales, DMR lacked the funds to invest in an updated model.

Fishery-Independent Data Collection

Recognizing the limits of fishery-dependent data, DMR began an annual spring dive survey in 2001, dividing the Maine coastline into nine regions. Each year since then a mix of fixed and random sites in depths of 0–15 meters with hard substrate have been chosen for evaluation. Survey protocols and results are described in Hunter (2015).

Figure 5 illustrates that, according to the survey, sea urchin abundance in each zone has declined since 2001, and that urchins have been consistently much more abundant in Zone 2 than in Zone 1. Neither of these two observations would have been apparent from LPUE data.

The figure also shows that the stock has not shown any sign of recovery in either zone, and may still be declining.

Management Issues

A Broken Conveyor Belt?

Harvesters described the replenishment of sea urchins as a conveyor belt, with urchins from deeper water crawling up to replace those that were harvested in shallow water (Canfield 1993a). The ecological role and distribution of deep-living (40–85 m) green sea urchins in Nova Scotia were reviewed by Filbee-Dexter and Scheibling (2017); Miller and Nolan (2008) also suggested that the onshore movement of deep-living adult urchins could be a source for shallow areas. During the 1994–95 to 1999–2000 Maine seasons, diver depths averaged about 15 ft (6.9 m) with maximum depths about 75 ft (34 m), while draggers fished somewhat deeper, averaging about 35 ft (16 m) with maximum depths about 175 ft (79 m) (from port interviews, DMR unpublished data). Harvesters tended to fish deepest in the spring, when shallower urchins were spawning (Hunter 2015). The presence and then loss of deep-living urchins might explain why some shallow areas could be harvested intensely, year after year, and then, suddenly, could not.

The Alternate Stable State

Sea urchins feed on kelps and other macroalgae, and play an important ecological role in determining algal distribution and abundance (reviewed by Steneck 2013 and Scheibling and Hatcher, 2013). Their grazing can reduce kelp beds to "urchin barrens", dominated by urchins and encrusting coralline algae. When urchins are removed, fleshy algae will recolonize. This algal habitat, in turn, may create a hospitable environment for crabs and other predators which feed on newly settling urchins, making it difficult for urchins to become reestablished once they have been removed. These alternate states (urchin-dominated or algal-dominated) can be locally stable at decadal time scales or longer. The threshold sea urchin density or biomass required to "flip" an algal-dominated state back to urchin-dominated is higher than that required to maintain the urchin-dominated state (Steneck *et al.* 2013).

Johnson *et al.* (2012, 2013) make the case that the statewide depletion of Maine sea urchins is the result of sequential depletion of localized populations that flip — ledge by ledge — to the algal-dominated state when overharvested. Each patch of urchins is effectively in an open access state and is vulnerable to depletion and stable-state flip regardless of restrictions on the total fishing effort in the management zone.

Researchers from other parts of the world (reviewed by Ovitz and Johnson, 2019) have also noted a mismatch between sea urchin management spatial scale and population dynamics spatial scale (like Maine's management zone vs patch), and have recommended more spatially explicit management regimes, such as territorial based rights, local management, rotational closures, reserves, and local enhancement projects. They have also noted that it is likely that traditional analytical models, reference points, and definitions of overfishing are not appropriate for a small-scale fishery on a relatively sedentary stock with strong spatial structure (*e.g.* Orensanz *et al.* 2005).

DMR recognizes that an important goal of sea urchin management should be the avoidance of further flips from urchin habitat to the stable algal state. However, a return to the extensive and less productive urchin barrens (a lot of urchins and encrusting algae and little else) of the 1980s is certainly not desirable. A mosaic of kelp beds and urchin patches is a reasonable objective for productive Maine fisheries (Larry Harris at SUZC meetings, pers. obs.).

Current management rules (for the 2019–20 to 2022–23 seasons) have been designed to encourage harvesters to leave more urchins on the bottom, and to fish for quality instead of quantity. They include:

- Minimum ($2^{1}/_{16}$ inch) and maximum (3 inches) size limits with 5% tolerance by count.
- Divers must cull over- and under-sized urchins on bottom, to no more than 20% by count, and the rest must be culled at sea for both divers and draggers. Zone 2 drags must have an escape panel.
- Zone 1 harvesters may fish 15 days out of a 40+ day season, with a 9 tray (about 810 lbs) daily limit per diver or per drag boat.
- Zone 2 harvesters may fish 30 days out of a 40 day season, with a 6 tray (about 550 lbs) daily limit per diver or per drag boat.
- There is one limited access area in Zone 2 in the Whiting River–Dennys Bay region, open only 15 days.
- Harvesters have a choice of early or late seasons, with different seasons for the two gears and the two exclusive management zones, in order to supply product to the processors during 6½ months per year.
- The fishery is closed to new entrants (except tenders, and except for tribal licenses, which are limited to 24 total licenses per tribe).
- Mandatory monthly logbook reporting for harvesters.
- Harvesters must present swipe cards to buyers at point-of-sale, for data collection that replaced mandatory dealer reporting.
- There is a surcharge on annual license fees for research, management, and enforcement.

Attrition and Aging Out

Although the market appears to be strong, as evidenced by prices paid to harvesters even during the COVID19 pandemic years (Table 1), several major processors have gone out of business recently, probably due to the lack of product and difficulty keeping workers. DMR realizes that the fishery is also being managed by attrition, as illustrated by license sales (Table 2). About 24% of harvester licenses have been retired since 2016. In 2021–22, the average age of active Zone 1 divers was 55 yrs, in Zone 2 it was 53, and the average age of draggers was 57 (preliminary data from swipe card transactions and license applications).

Does Local Management Lie in Maine's Sea Urchin Future?

Maine has had experience with local management in the soft-shelled clam fishery, with a conservation area in Taunton Bay (Moore and Sowles, 2010; Sowles 2011) and, more recently and on a broader spatial scale, with limited and rotational areas in the scallop fishery. There are also seven management zones for lobsters, not to mention the informal territories of individual lobster harbors and harvesters. New and effective local management initiatives for sea urchins would require extensive DMR involvement, at least at startup (Miller and Nolan 2008), with collaborative, active engagement of the industry and community stakeholders (Sowles 2011).

There is currently no management plan for the Maine sea urchin fishery. A recently concluded five-year DMR research project in Maine's Blue Hill Bay area, which involved requiring vessel trackers on all sea urchin fishing vessels, with voluntary harvester interviews, may inform future research and management.

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References

Andrew, N.L., Y. Agatsuma, E. Ballesteros, A.G. Bazhin, E.P. Creaser, D.K.A. Barnes, L.W. Botsford, A. Bradbury, A. Campbell, J.D. Dixon, S. Einarsson, P. Gerring, K. Hebert, M. Hunter, S.B. Hur, C.R. Johnson, M.A. Juinio-Meñez, P. Kalvass, R.J. Miller, C.A. Moreno, J.S. Palleiro, D. Rivas, S.M.L. Robinson, S.C. Schroeter, R.S. Steneck, R.I. Vadas, D.A. Woodby and Z. Xiaoqi. 2002. Status and management of world sea urchin fisheries. *Oceanogr. Mar. Biol. Annu. Rev*. 40:343–425. https://doi.org/10.1201/9780203180594

Anonymous. 1929. Sea urchins from Maine a delicacy to aliens here. *New York Times*, New York, NY. June 2, 1929.

Associated Press. 1993. Too many divers, not enough urchins. *Portland Press Herald*, Portland, ME, July 29, 1993: p. 5B.

Amory, J. 1994. Urchins! *Salt Magazine.* Salt Center for Documentary Feld Studies, Portland, ME. **45**: 4–35. https://www.saltstoryarchive.com/articleview.php?id=20740

Austin, P. 1993. A major sustainable industry waits to be born — the urchin fiasco illustrates a failure of state policy. *Maine Times*, Brunswick, ME. March 5, 1993, pp 1–5.

Baxter, B. and B. Chamberlain. 1988. The green sea urchin industry in Maine – guidelines and ideas for harvesting. Maine Cooperative Extension Service, University of Maine, Orono, ME, and Maine Department of Marine Resources, West Boothbay Harbor, ME. 13 pp. Also summarized in *Commercial Fisheries News*, Stonington, ME. December 1988: p. 60.

Bernstein, B.B. and K.H. Mann. 1982. Changes in the near-shore ecosystem of the Atlantic coast of Nova Scotia, 1968–1981. NAFO Sci. Coun. Studies, 5:101–105. https://archive.nafo.int/open/studies/s5/bernstein.pdf (1 MB)

Bernstein, B.B. and R.W. Welsford. 1982. An assessment of feasibility of using high-calcium quicklime as an experimental tool for research into kelp bed/sea urchin ecosystems in Nova Scotia. CanadianTechnical Report of Fisheries and Aquatic Sciences 968: i–ix, 1–51. https://publications.gc.ca/site/eng/452239/publication.html

Breen, P.A. and K.H. Mann. 1976. Destructive grazing of kelp by sea urchins in eastern Canada. *J Fish Res Board Can* 33: 1278–1283. https://doi.org/10.1139/F76-164

Canfield, C. 1991. Urchin boom may lead to crash. *Maine Sunday Telegram*, Portland ME. December 22, 1991: pp 1B, 14B.

Canfield, C. 1992. Cracking the market. *Maine Sunday Telegram*, Portland ME. October 25, 1992: pp 1F, 5F.

Canfield, C. 1993a. Urchins: 'pest in peril'. *Maine Sunday Telegram*, Portland ME. November 7, **106**(16): pp 1, 14A.

Canfield, C. 1993b. OSHA ruling holds boat captains liable for urchin divers. *Portland Press Herald*, Portland ME. November 24, 1993, pp 1, 5A.

Centers for Disease Control and Prevention (CDC). 1994. Fatalities associated with harvesting of sea urchins — Maine, 1993. Morbidity and Mortality Weekly Report, April 8, 1994, 43(13); 235, 241–242. http://www.cdc.gov/mmwr/preview/mmwrhtml/00026070.htm

Chen, Y. and M. Hunter. 2003. Assessing the green sea urchin (*Strongylocentrotus droebachiensis*) stock in Maine, USA. *Fis. Res.* **60**:527–537. https://doi.org/10.1016/S0165-7836(02)00082-6

Chenoweth, S. 1992a. Maine's growing sea urchin fishery, Part 1. *Commercial Fisheries News*, Stonington, ME. June 1992, p 4B.

Chenoweth, S. 1992b. Maine's growing sea urchin fishery, Part 2. *Commercial Fisheries News*, Stonington, ME. July 1992, p 4B.

Chenoweth, S. 1994. The green sea urchin in Maine — fishery and biology. Maine Department of Marine Resources, W. Boothbay Harbor, Maine. 10pp. https://www.maine.gov/dmr/science/species-information/green-sea-urchins/the-green-sea-urchin-in-maine-fishery-and-biology

Chipello, C.J. 1988. A miracle in Maine: sea urchin is turned into the golden uni. *The Wall Street Journal*, New York, NY. No. 54, March 18.

Creaser, T. 1993a. DMR describes sea urchin research needs. *Commercial Fisheries News*, Stonington, ME. July 1993, p 4B.

Creaser, T. 1993b. What Maine should study about sea urchins. *Commercial Fisheries News*, Stonington, ME. August 1993, p 4B.

Dassow, C.J., A.J. Ross, O.P.Jensen, G.G. Sass, B.T. van Poorten, C.T. Soloman, and S.E. Jones. 2020. Experimental demonstration of catch hyperstability from habitat aggregation, not effort sorting, in a recreational fishery. *Can. J. Fish. Aquat. Sci.* **77**(4): 762–769. https://doi.org/10.1139/cjfas-2019-0245

Dean, N. 1983. Gathering sea urchins by the sea shore. *Down East Magazine*. Rockport, ME. February, pp 38–39.

Department of Fisheries and Oceans, Canada (DFO). 1996. Southwestern New Brunswick green sea urchins. *DFO Atlantic Fisheries Stock Status Report 96/131E*. 5 pp.

Erisman, B.E, L.G.Allen, J.T. Claisse, D.J. Pondella II, E.F. Miller, and J.H.Murray. 2011. The illusion of plenty: hyperstability masks collapses in two recreational fisheries that target fish spawning aggregations. *Can. J. Fish. Aquat. Sci.* **68**: 1705–1716. https://doi.org/10.1139/F2011-090

Filbee-Dexter, K. and R.E. Scheibling. 2017. The present is the key to the past: linking regime shifts in kelp beds to the distribution of deep-living sea urchins. *Ecology* **98**(1) 253–264. https://doi.org/10.1002/ecy.1638

Harris, J. and H.A. Carr (eds.). 1995. 1994 Workshop on the Management and Biology of the Green Sea Urchin (*Strongylocentrotus droebachiensis*). Massachusetts Division of Marine Resources and Maine Department of Marine Resources, 124 pp. https://www.maine.gov/dmr/sites/maine.gov.dmr/files/docs/1994workshop.pdf (5 MB)

Hilborn, R. and Walters, C.J. 1992. Quantitative fisheries stock assessment, choice, dynamics and uncertainty. Chapman and Hall, London. https://doi.org/10.1007/BF00042883

Hunter, M., K. Lyons, and R. Russell. 2010. Monitoring and assessment of Maine's sea urchin resource. In: report to NOAA National Marine Fisheries Service for Interjurisdictional Fisheries Resource Monitoring and Assessment, Grant#NA10NMF4070015, by Maine Department of Marine Resources, Augusta, ME. https://www.maine.gov/dmr/sites/maine.gov.dmr/files/docs/2009ij.pdf (1.2 MB)

Hunter, M. 2015. Monitoring Maine's sea urchin resource. Maine Department of Marine Resources, W. Boothbay Harbor, Maine. 95 pp. https://www.maine.gov/dmr/sites/maine.gov.dmr/files/docs/datareport2015.pdf (2.4 MB)

Johnson, T.R., J.A. Wilson, C. Cleaver, and R.L. Vadas. 2012. Social-ecological scale mismatches and the collapse of the sea urchin fishery in Maine, USA. Ecology and Society 17(2): 15. http://dx.doi.org/10.5751/ES-04767-170215

Johnson, T.R., J.A. Wilson, C. Cleaver, G. Morehead, and R. Vadas. 2013. Modeling fine scale urchin and kelp dynamics: Implication for management of the Maine sea urchin fishery. *Fish. Res*. **141**:107–117. https://doi.org/10.1016/j.fishres.2012.05.008

Jones, S. 1992. Urchin industry cracks processing. *Commercial Fisheries News*, Stonington, ME. December 1992, pp 1A, 22A.

Jones, S. 1993. Maine urchin task force sets stage for regulations. *Commercial Fisheries News*, Stonington, ME. March 1993, pp 1A, 18A.

Kanaiwa, M., Y. Chen, and M. Hunter. 2005. Assessing a stock assessment framework for the green sea urchin *Strongylocentrotus droebachiensis* fishery in Maine, USA. *Fish. Res*.**74**:96–115. https://doi.org/10.1016/j.fishres.2005.03.006

Keesing, J.K. and J.L. Baker. 1998. The benefits of catch and effort data at a fine spatial scale in the South Australian abalone (*Haliotis laevigata* and *H. ruba*) fishery. In: Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. *Can. Spec. Publ. Fish. Aquat. Sci.* **125**:179–186. https://publications.gc.ca/site/eng/9.816499/publication.html

Kleiman, D. 1990. Scorned at home, Maine sea urchin is a star in Japan. *The New York Times*, New York, NY. October 3, 1990, p. C6.

Lannin, J. 1986. Invasion of sea urchins "a plague". *Maine Sunday Telegram.* Portland ME. July 20, 1986. p. 1A.

Lignell, K. 1990. Harvesting sea urchins – a prickly business. *Nor'Easter*, Maine Sea Grant, Fall 1990, pp 22–25.

Lynham, J. 2016. Identifying peer effects using gold rushers. University of Hawai`i at Mānoa, Department of Economics Working Paper Series, No. 16-9. 46 pp.

MacKay, A.A. 1976. The sea urchin roe industry on New Brunswick's Bay of Fundy coast. Final Report NB75-1 to the New Brunswick Department of Fisheries, Fredericton NB. 100 pp.

Mann, K.H. and P.A. Breen. 1972. The relation between lobster abundance, sea urchins and kelp beds. *J. Fish. Res. Bd. Canada* 29: 603–609. https://doi.org/10.1139/F72-104

Maunder, M.N., J.R. Sibert, A. Fonteneau, J. Hampton, P. Kleiber, and S.J. Harley. 2006. Interpreting catch per unit effort data to assess the status of individual stocks and communities. ICES *J. Mar. Sci*. **63**:1373–1385. https://doi.org/10.1016/j.icesjms.2006.05.008

McNaught, D.C. and R.S. Steneck. 1998. Settlement and survival of the green sea urchin in Maine: effects of algal habitat. Report to the Maine Department of Marine Resources, W. Boothbay Harbor, ME. 59 pp.

McNaught, D.C. 1999. The indirect effects of macroalgae and micropredation on the post-settlement success of the green sea urchin in Maine. PhD. thesis, University of Maine, Orono, ME. 161 pp.

Meredith, E. 2012. Utility of catch and landings per unit of fishing effort (CPUE and LPUE) in Gulf of Maine and Georges Banks cod stock assessments. Northeast Fisheries Science Center. Proceedings of Cod CPUE Workshop, Gloucester MA August 12, 2012. 14 pp.

Miller, R.J. 1985. Sea urchin pathogen: a possible tool for biological control. *Mar. Ecol. Prog. Ser.* **21**:169–174. https://doi.org/10.3354/MEPS021169

Miller, R.J. and S.C. Nolan. 2008. Management methods for a sea urchin dive fishery with individual fishing zones," *J. Shellfish Res*. **27**(4): 929–938. https://doi.org/10.2983/0730-8000(2008)27[929:MMFASU]2.0.CO;2

Moore, S. and J. Sowles. 2010. Local-scale ecosystem-based fisheries in a Gulf of Maine estuary: managing for complexity, adapting to uncertainty. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* 2:146–158. https://doi.org/10.1577/C08-040.1

Munk, J.E. 1992. Reproduction and growth of green urchins *Strongylocentrotus droebachiensis* (Müller) near Kodiak, Alaska. *J. Shellfish Res.* **11**(2):245–254. https://www.biodiversitylibrary.org/item/52251#page/258/mode/1up

Muraoka, D.D. 1990. Managing the sea urchin fishery: an economic perspective. *Natural Resources Journal* **30**:139–151. https://digitalrepository.unm.edu/nrj/vol30/iss1/9

Neish, I.C. 1973. The distribution of sea urchins in Charlotte County, New Brunswick. Report AMR 73-3B by Applied Marine Research Ltd. to the New Brunswick Department of Fisheries and Environment. Fredericton, NB. 26pp.

O'Quinn, K. 1993. Boatman faces fine in death of diver. *Portland Press Herald*, Portland ME. November 7, 1993, pp 1–2B.

Orensanz, J.M., A.M. Parma, C. Jerez, N. Barahona, M. Montecinos, and I. Elias. 2005. What are the key elements for the sustainability of "S-fisheries"? Insights from South America. *Bul. Mar. Sci*. **76**(2): 527–556. https://www.ingentaconnect.com/contentone/umrsmas/bullmar/2005/00000076/00000002/art00017

Ovitz, K.L. and T.R. Johnson. 2019. Seeking sustainability: Employing Ostrom's SESF to explore spatial fit in Maine's sea urchin fishery. *International Journal of the Commons*, **13**(1), 276–302. DOI: http://doi.org/10.18352/ijc.866

Perry, R.I., Z. Zhang, R. Harbo. 2002. Development of the green sea urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, Canada — back from the brink using a precautionary framework. *Fish. Res*. **55**:253–266. https://doi.org/10.1016/S0165-7836(01)00283-1

Pfister, C. A. and A. Bradbury. 1996. Harvesting red sea urchins: recent effects and future predictions. *Ecological Applications* **6**(1):298–310. https://doi.org/10.2307/2269573

Plante, J.M. 1990. DMR proposes harvesting regs. *Commercial Fisheries News*, Stonington, ME. April 1990, p. 11B.

Prince, J. and R. Hilborn. 1998. Concentration profiles and invertebrate fisheries management. IN: Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. G.S Jamieson and A. Campbell, eds. Canadian Special Publication of Fisheries and Aquatic Sciences **125**:187–196. https://publications.gc.ca/site/eng/9.816499/publication.html

Pringle J.D., G.J. Sharp, and J.F. Caddy. 1980. An update on the relationship between commercial lobstering and urchin and macroalgal densities. In: J.D. Pringle, G.J. Sharp and J.F. Caddy (eds.), Proceedings of the Workshop on the Relationship Between Sea Urchin Grazing and Commercial Plant/Animal Harvesting. July, 1980. *Canadian Technical Report of Fisheries and Aquatic Sciences* 954: 237–251. https://publications.gc.ca/site/eng/452170/publication.html

Pringle, J.D., G.J. Sharp and J.F. Caddy (editors). 1980. Comments on urchin eradication by workshop delegates. In: Proceedings of the Workshop on the Relationship Between Sea Urchin Grazing and Commercial Plant/Animal Harvesting. July, 1980. *Canadian Technical Report of Fisheries and Aquatic Sciences* 954:270–271. https://publications.gc.ca/site/eng/452170/publication.html

Quimby, B. 1993. Mmmmm good? Urchins: fishing is limited. *Sunday Eagle-Tribune*, North Andover, MA. September 12, 1993, pp A1, A13.

Reynolds, J.A. and J.E. Wilen. 2000. The sea urchin fishery: harvesting, processing and the market. *Marine Resource Economics* 15(2): 115–126. https://doi.org/10.1086/mre.15.2.42629295

Riddle, L. 1989. Fishermen's foe, the sea urchin, is a winter friend. *New York Times*, April 16, 1989. New York, NY.

Rioux, J.F. 1988. Processing expands sea urchin fishery. *Commercial Fisheries News*, Stonington, ME. January 1988, pp 46–47 and 51.

Ryan, G. 1992. Urchins on the rise. *Maine Boats & Harbors*. Rockland, Maine. December/January 1992, pp 26–29.

Scattergood, L.W. 1947. The sea urchin fishery. US Dept. of the Interior. Fishery Leaflet 231. 2 pp. https://spo.nmfs.noaa.gov/Fishery%20Leaflets/231.pdf (1.4 MB)

Scattergood, L.W. 1961. The sea urchin fishery. US Dept. of the Interior. Fishery Leaflet 511. 6 pp. https://spo.nmfs.noaa.gov/Fishery%20Leaflets/511.pdf (1.5 MB)

Scheibling, R.E. and B.G. Hatcher. 2013. *Strongylocentrotus droebachiensis*. In: J. M. Lawrence (ed.), *Sea Urchins: Biology and Ecology*. 3rd Edition. *Developments in Aquaculture and Fisheries Science* 38:381–412. Elsevier Academic Press, Amsterdam. https://doi.org/10.1016/B978-0-12-396491-5.00026-5

Schroeter, S.C., D.C. Reed, D.J. Kushner, J.A. Estes, and D.S. Ono. 2001. The use of marine reserves in evaluating the dive fishery for the warty sea cucumber (*Parastichopus parvimensis*) in California, U.S.A. *Can. J. Fish. Aquat. Sci*. 58: 1773–1781. https://doi.org/10.1139/f01-127

Seward, L.C.N., R.L. Vadas, B. Beal., and D.W. Townsend. 2000. Environmental factors influencing spawning in the green sea urchin, *Strongylocentrotus droebachiensis*, in Maine, USA. In: Proceedings of the Workshop on the coordination of research on the green sea urchin in Atlantic Canada, Univ. of Moncton, New Brunswick, Canada. 6 pp.

Seward, L.C.N. 2002. The relationship between green sea urchin spawning, spring phytoplankton blooms, and the winter-spring hydrography at selected sites in Maine. University of Maine. Electronic Theses and Dissertations. Paper 354, 184 pp. https://digitalcommons.library.umaine.edu/etd/354/

Sonu, S. 1995. The Japanese sea urchin market. NOAA Technical Memorandum NMFS: NOAA-TM-NMFS-SWR-030. iv + 33 pp. https://repository.library.noaa.gov/view/noaa/3020

Sowles, J. 2011. Evaluation of a community ecosystem-based natural resource management plan for Taunton Bay, Maine. Maine Dept. of Marine Resources, W. Boothbay Harbor, Maine. 32 pp.

Spiess, A.E., E. Trautman, and T. Kupferschmid. 1990. Prehistoric occupation at Reversing Falls. File report. Maine Historic Preservation Commission, Augusta, Maine. 30 pp.

Spiess, A.E. and R. Lewis. 2001. The Turner Farm fauna: 5000 years of hunting and fishing in Penobscot Bay, Maine. *Occ. Publ. in Maine Archeol*. 11:1–120. https://doi.org/10.1002/oa.644

Stickney, A.P. 1981. Sea urchins — a resource or a nuisance? Maine Department of Marine Resources, West Boothbay Harbor, ME. 3 pp.

Steneck, R. S., D. McNaught and S. Zimsen. 1995. Spatial and temporal patterns in sea urchin populations, herbivory and algal community structure in the Gulf of Maine. In: J .Harris and H.A. Carr (eds.), 1994 Workshop on the Management and Biology of the Green Sea Urchin (*Strongylocentrotus droebachiensis*). Massachusetts Division of Marine Resources and Maine Department of Marine Resources, pp 34–73.

Steneck, R.S. 1997. Fisheries-induced biological changes to the structure and function of the Gulf of Maine ecosystem In: Wallace G.T., Braasch E.F., editors. Proceedings of the Gulf of Maine Ecosystem Dynamics Scientific Symposium and Workshop Hanover (NH): Regional Association for Research on the Gulf of Maine. pp 151–65.

Steneck, R.S. 2013. Sea urchins as drivers of shallow benthic marine community structure. In: J. M. Lawrence (ed.), *Sea Urchins: Biology and Ecology*. 3rd Edition. *Developments in Aquaculture and Fisheries Science* 38:195–212. Elsevier Academic Press, Amsterdam. https://doi.org/10.1016/B978-0-12-396491-5.00014-9

Steneck, R.S., A. Leland, D.C. McNaught, and J. Vavrinec. 2013. Ecosystem flips, locks, and feedbacks: the lasting effects of fisheries on Maine's kelp forest ecosystem. Bul. Mar. Sci. **89**(1): 31–55**.** http://dx.doi.org/10.5343/bms.2011.1148.

Taylor, P.H. 2004. *Green Gold: Scientific Findings for Management of Maine's Sea Urchin Fishery*, Maine Dept. of Marine Resources, W. Boothbay Harbor, Maine. 36 pp. https://www.maine.gov/dmr/sites/maine.gov.dmr/files/docs/greengold.pdf (2 MB)

Tegner, M. J. and P.K. Dayton. 2000. Ecosystem effects of fishing in kelp forest communities. ICES *Journal of Marine Science*, 57: 579–589. https://doi.org/10.1006/jmsc.2000.0715

Vadas, R.L., B. Beal, S. Dudgeon, and W. Wright. 1995. Spatial and temporal variability in reproduction and spawning in green sea urchins in Maine. In: J .Harris and H.A. Carr (eds.), 1994 Workshop on the Management and Biology of the Green Sea Urchin (*Strongylocentrotus droebachiensis*). Massachusetts Division of Marine Resources and Maine Department of Marine Resources, W. Boothbay Harbor, Maine, 74 pp.

Vadas, R.L. and B.F. Beal. 1999. Temporal and spatial variability in the relationships between adult size, maturity and fecundity in green sea urchins: the potential use of a roe-yield standard as a conservation tool. Report to the Maine Department of Marine Resources for the project entitled: Research necessary to develop a management plan for the green sea urchin, *Strongylocentrotus droebachiensis*, in the territorial waters of Maine. Maine DMR, W. Boothbay Harbor, Maine. 47 pp.

https://www.maine.gov/dmr/sites/maine.gov.dmr/files/docs/vadas&%20beal.pdf (3.6 MB)

van Poorten, B.T., C.J. Walters, and H.G.M. Ward. 2016. Predicting changes in the catchability coefficient through effort sorting as less skilled fishers exit the fishery during stock declines. Fish. Res. 183:379–384. http://dx.doi.org/10.1016/j.fishres.2016.06.023

Wahle, R.A. and S.H. Peckham. 1998. Density-related reproductive trade-offs in the green sea urchin, *Strongylocentrotus droebachiensis* & implications to the Gulf of Maine fishery. Report to Maine Department of Marine Resources, W. Boothbay Harbor, ME. 37pp.

Wahle, R.A. and S.H. Peckham. 1999. Density-related reproductive trade-offs in the green sea urchin, *Strongylocentrotus droebachiensis. Mar. Biol.* 134:127–137. http://dx.doi.org/10.1007/s002270050531

Wharton, W.G. 1980. The distribution of sea urchin-dominated barren grounds along the south shore of Nova Scotia. In: J.D. Pringle, G.J. Sharp and J.F. Caddy (eds.), Proceedings of the Workshop on the Relationship Between Sea Urchin Grazing and Commercial Plant/Animal Harvesting. July, 1980. *Canadian Technical Report of Fisheries and Aquatic Sciences* 954:33–47.

Wharton, W.G. and K.H. Mann. 1981. Relationship between destructive grazing by the sea urchin, *Strongylocentrotus droebachiensis*, and the abundance of American lobster, *Homarus americanus*, on the Atlantic coast of Nova Scotia. *Can J Fish Aquat Sci* 38: 1339–1349. https://doi.org/10.1139/f81-180

Wilen, J.E. and C.R. Wessells. 1997. An economic analysis of the market for Maine sea urchins. Report submitted to Maine DMR, Augusta Maine. 88 pp.

Witman, J. D., A. H. Hulbert, and L. G. Harris. 1982. Morphology of a sea urchin front (*Strongylocoentrotus droebachiensis*) at the Isles of Shoals, N.H. Page 205 in Lawrence, J.M. (Ed.) (1982) Echinoderms: Proceedings of the International Conference, Tampa Bay, 14–17 September 1981. A. A. Balkema, Rotterdam.

Witman, J.D. 1985. Refuges, biological disturbance, and rocky subtidal community structure in New England. *Ecol Monogr* 55: 421–445. https://doi.org/10.2307/2937130

Wormwood, L. 1994. Two urchin groups form with distinct priorities. *Boothbay Register*, January 6, 1994. Boothbay Harbor, Maine.

Zhang, Z. and R.I. Perry. 2005. Use of state-space modeling with a Bayesian approach to estimate target reference points for green sea urchin (*Strongylocentrotus droebachiensis*) stocks in the Queen Charlotte Strait region, British Columbia, Canada. *Fish. Res*. 74: 253–264. https://doi.org/10.1016/j.fishres.2005.01.019

Tables

Table 1. Maine sea urchin landings, by season and management zone.

	Pounds			Metric Tons			Value	Price
Season	Zone 1	Zone 2	Total	Zone 1	Zone 2	Total	$	$/lb
1987-88			4,074,614			1,848.2	840,104	0.21
1988-89			7,479,854			3,392.8	2,512,549	0.34
1989-90			10,507,781			4,766.3	4,238,658	0.40
1990-91			17,500,228			7,938.1	8,291,892	0.47
1991-92			19,705,059			8,938.2	11,063,187	0.56
1992-93			39,288,946			17,821.3	23,478,555	0.60
1993-94			37,829,393			17,159.3	26,968,165	0.71
1994-95	17,430,440	19,706,850	37,137,290	7,906.4	8,939.0	16,845.4	35,536,073	0.96
1995-96	15,479,639	14,782,860	30,262,499	7,021.5	6,705.5	13,727.0	33,183,441	1.10
1996-97	10,389,420	13,465,189	23,854,609	4,712.6	6,107.8	10,820.4	26,580,434	1.11
1997-98	6,609,750	10,338,950	16,948,700	2,998.2	4,689.7	7,687.9	18,339,532	1.08
1998-99	5,772,995	10,929,943	16,702,938	2,618.6	4,957.8	7,576.4	20,102,119	1.20
1999-00	5,072,148	8,982,967	14,055,115	2,300.7	4,074.6	6,375.4	18,858,460	1.34
2000-01	4,426,427	7,391,533	11,817,960	2,007.8	3,352.8	5,360.6	16,119,624	1.36
2001-02	3,202,928	4,647,644	7,850,572	1,452.8	2,108.2	3,561.0	9,717,479	1.24
2002-03	1,952,361	4,748,271	6,700,632	885.6	2,153.8	3,039.4	8,758,199	1.31
2003-04	1,293,602	5,040,920	6,334,522	586.8	2,286.5	2,873.3	8,860,609	1.40
2004-05	156,803	3,630,293	3,787,096	71.1	1,646.7	1,717.8	5,802,979	1.53
2005-06	112,192	3,740,713	3,852,905	50.9	1,696.8	1,747.7	5,371,416	1.39
2006-07	154,991	2,874,500	3,029,491	70.3	1,303.9	1,374.2	4,581,572	1.51
2007-08	178,550	2,975,853	3,154,403	81.0	1,349.8	1,430.8	5,043,356	1.60
2008-09	138,683	2,960,823	3,099,506	62.9	1,343.0	1,405.9	5,089,928	1.64
2009-10	121,710	2,991,471	3,113,181	55.2	1,356.9	1,412.1	5,902,851	1.90
2010-11	148,767	2,152,991	2,301,758	67.5	976.6	1,044.1	5,143,746	2.23
2011-12	181,226	2,149,873	2,331,099	82.2	975.2	1,057.4	5,081,370	2.18
2012-13	273,371	1,564,810	1,838,181	124.0	709.8	833.8	5,721,560	3.11
2013-14	384,143	1,539,565	1,923,708	174.2	698.3	872.6	5,067,105	2.63
2014-15	377,862	1,635,359	2,013,221	171.4	741.8	913.2	5,553,463	2.76
2015-16	373,174	1,613,029	1,986,203	169.3	731.7	900.9	5,751,001	2.90
2016-17	300,091	1,795,103	2,095,194	136.1	814.3	950.4	6,864,168	3.28
2017-18	272,286	1,869,939	2,142,225	123.5	848.2	971.7	6,397,042	2.99
2018-19	214,701	1,753,823	1,968,524	97.4	795.5	892.9	5,898,382	3.00
2019-20	209,709	1,277,469	1,487,178	95.1	579.5	674.6	5,285,997	3.55
***2020-21**	177,115	853,782	1,030,897	80.3	387.3	467.6	3,105,500	3.01
***2021-22**	150,391	693,805	844,196	68.2	314.7	382.9	2,975,796	3.53

**preliminary* *Not adjusted for inflation.*

Table 2. Annual counts of Maine sea urchin commercial fishing licenses, by calendar year and management zone.

Year	Zone 1					Zone 2					Statewide							
	Dive	Drag	Rake	Trb**	Total	Dive	Drag	Rake	Trb**	Total	Dive	Drag	Rake	Trb**	Harv. Totals	Tender	Buyer	Proc.
1992											829	246			**1,075**			
1993											1,437	567			**2,004**			
1994											1,725	1,000			**2,725**	843		
1995	611	237	3		851	580	404	5		989	1,191	641	8		**1,840**	736	96	18
1996	501	167	2		670	562	327	4		893	1,063	494	6		**1,563**	730	70	19
1997	405	133	1		539	514	287	2		803	919	420	3		**1,342**	648	65	20
1998	348	95	1		444	460	260	1		721	808	355	2		**1,165**	544	51	18
1999	332	87	2		421	437	252	2		691	769	339	4		**1,112**	538	42	15
2000	313	74	2		389	407	242	2		651	720	316	4		**1,040**	530	31	18
2001	281	65	2		348	383	240	2		625	664	305	4		**973**	453	30	11
2002	246	53	2		301	343	242	1		586	589	295	3		**887**	355	23	12
2003	182	44	2		228	289	224	1		514	471	268	3		**742**	276	18	13
2004	134	30	2		166	261	206	1		468	395	236	3		**634**	212	12	12
2005	106	27	1		134	234	187	1		422	340	214	2		**556**	155	13	13
2006	83	24	0		107	213	178	1		392	296	202	1		**499**	150	13	12
2007	75	24	0		99	195	164	1		360	270	188	1		**459**	142	12	12
2008	61	21	0		82	188	163	1		352	249	184	1		**434**	138	13	12
2009	60	18	0		78	181	152	1		334	241	170	1		**412**	192	12	13
2010*	54	18	0		72	167	157	2		326	221	175	2		**398**	97	11	11
2011*	49	15	0		64	156	159	1		316	205	174	1		**380**	78	7	10
2012*	47	16	0		63	143	143	5		291	190	159	5		**354**	67	11	10
2013*	49	15	0		64	125	134	3	3	265	174	149	3	3	**329**	62	9	7
2014*	47	14	1		62	109	125	9	12	255	156	139	10	12	**317**	46	11	5
2015*	46	14	0	1	61	108	134	1	1	244	154	148	1	2	**305**	40	11	5
2016*	43	14	0	0	57	108	134	1	1	244	151	148	1	1	**301**	35	9	5
2017*	41	13	0	1	55	105	133	1	8	247	146	146	1	9	**302**	40	7	6
2018*	40	13	0	2	55	101	121	1	3	226	141	134	1	5	**281**	38	12	5
2019*	36	14	0	3	53	91	113	1	1	206	127	127	1	4	**259**	29	7	5
2020*	34	14	0	0	48	86	112	1	0	199	120	126	1	0	**247**	30	7	4
2021*	33	12	0	1	46	81	100	1	0	182	114	112	1	1	**228**	27	8	4

Notes:

* 2010–2021 include about 10–20 tribal licenses, mostly draggers.

**DMR does not always have information on whether tribal licenses are dive, drag, or rake.

No tender license until 1994. No zones until 1995. No buyer/processor permit until 1995. No raker/trapper license until 1995.

Entry closed with no new harvester entrants 1995–1998 and 2005–2021. Limited entry with a harvester license lottery 1999–2004.

Note that the identical numbers of Zone 2 licenses in 2015 and 2016 are correct.

Also see a table and graph of Maine sea urchin landings and value by calendar year online.

Figures

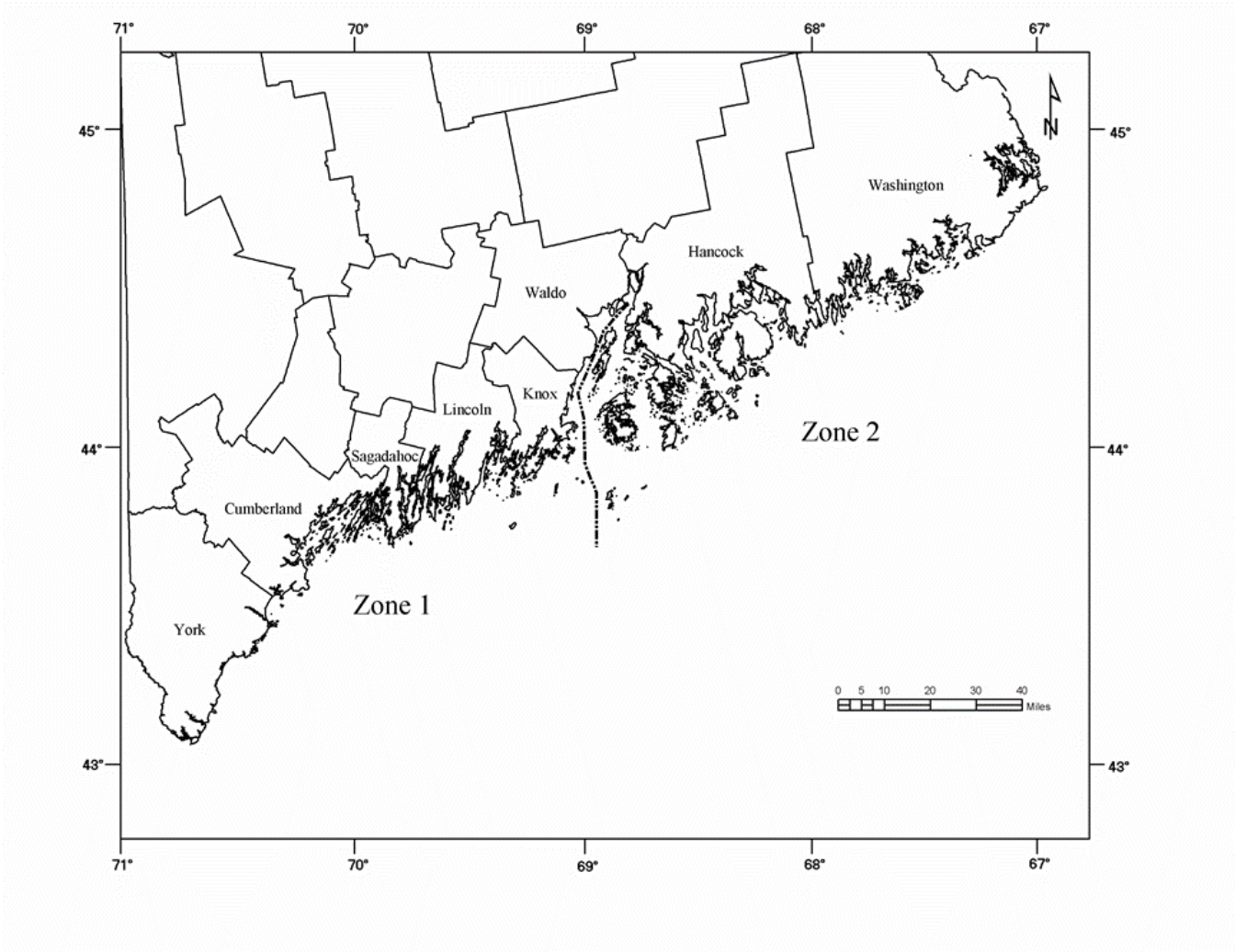

Figure 1. Maine coastal counties and the two sea urchin management zones.

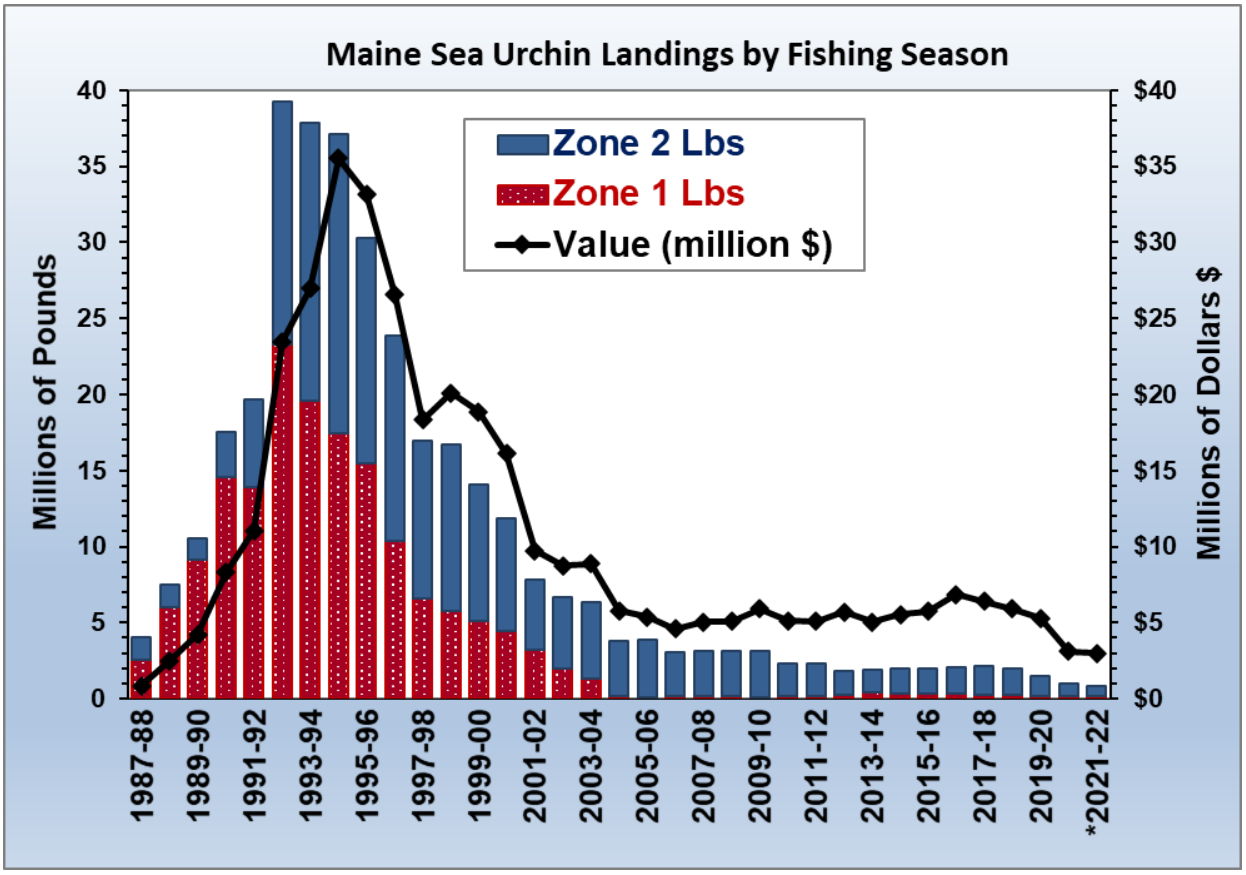

Figure 2. Maine sea urchin landings, by season and management zone.

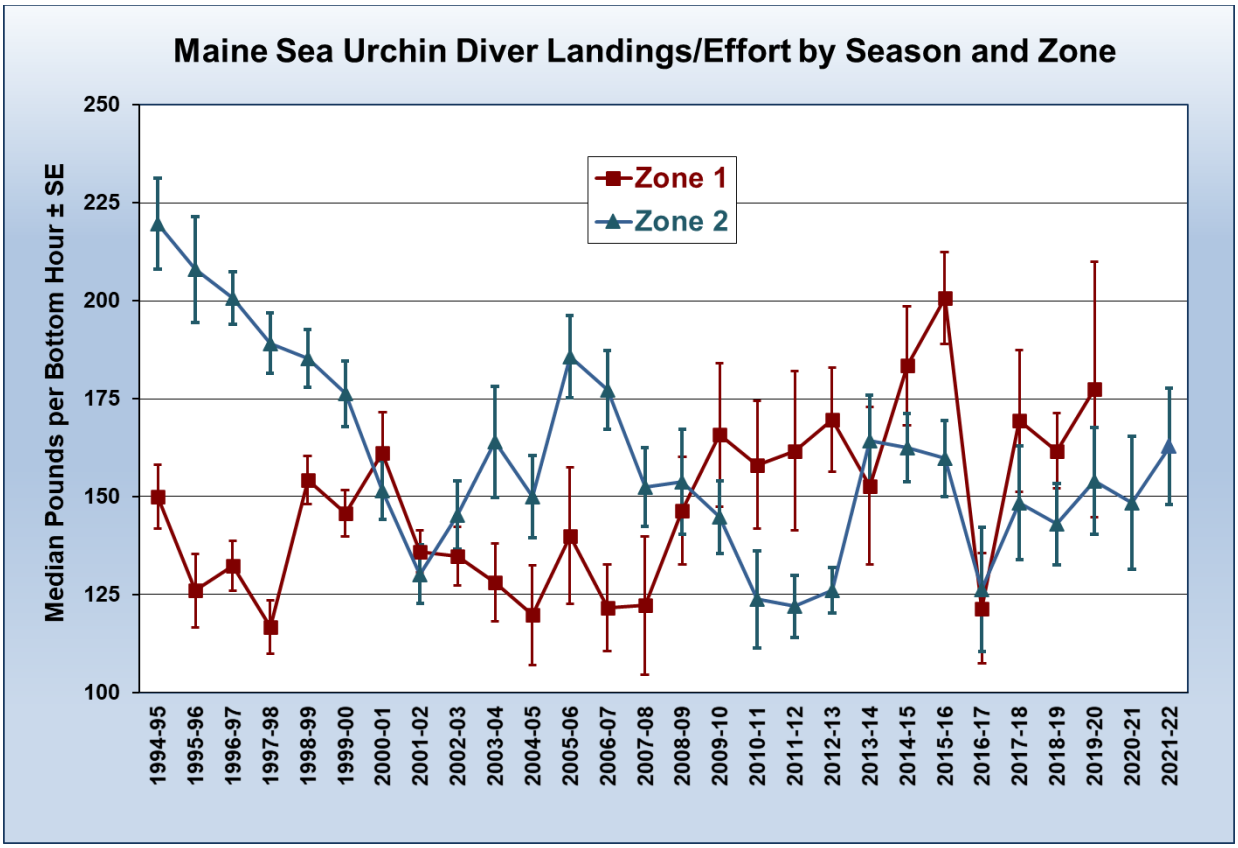

Figure 3. Landings per bottom hour for Maine commercial sea urchin divers, by season and management zone, from port interviews. Zone 1 data for 2020–21 and 2021–22 are not presented because fewer than 5 interviews were conducted during each of those seasons.

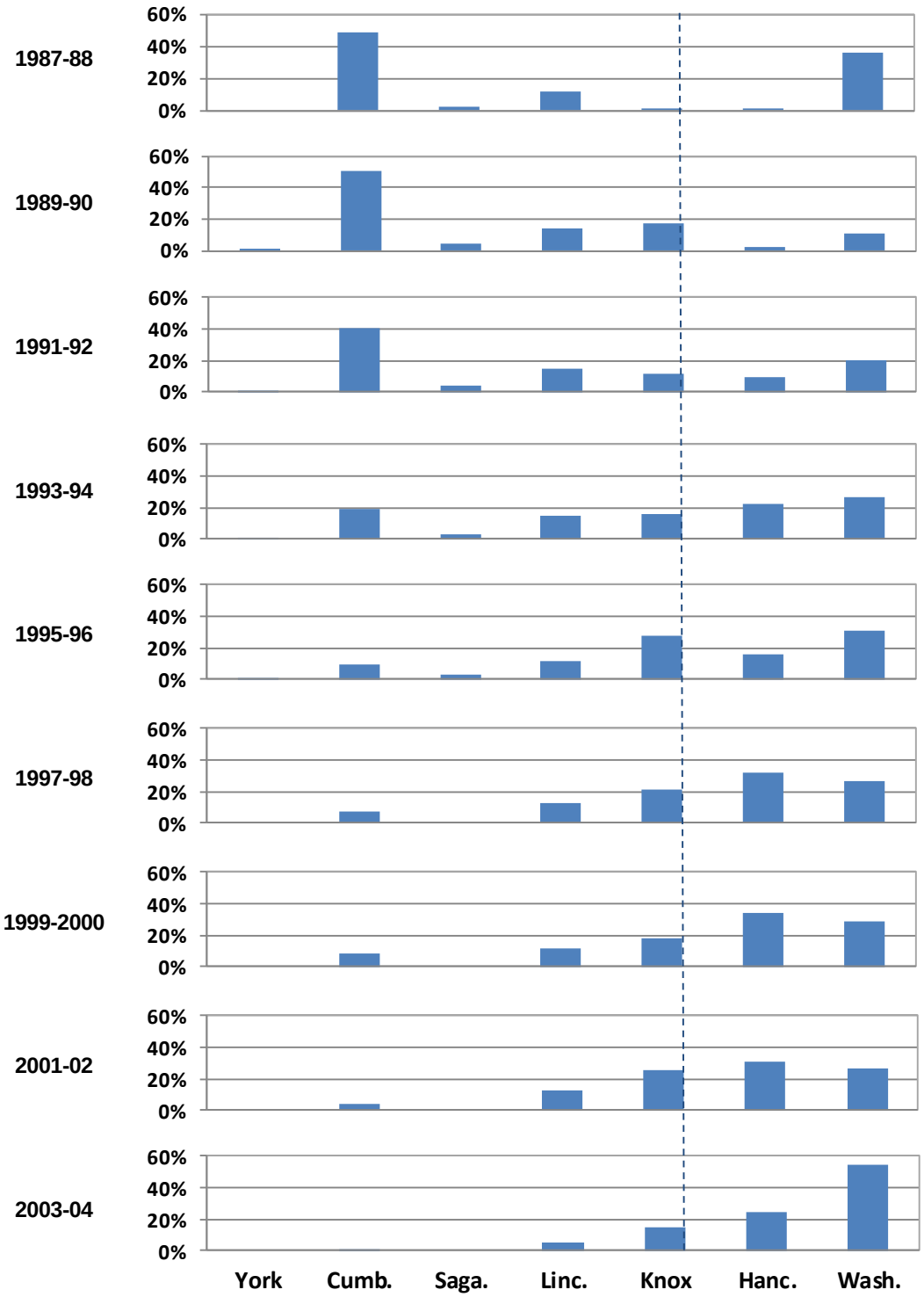

Figure 4. Maine sea urchin landings as percentages by county, west to east, for every other season from 1987–88 to 2003–04. Dotted line indicates boundary between Zone 1 and Zone 2. Note that some landings at Rockland in Knox County could have come from nearby areas in Zone 2 (*e.g.* Isleboro and Vinalhaven), but those areas were highly depleted by 2003 (DMR unpublished data from port interviews).

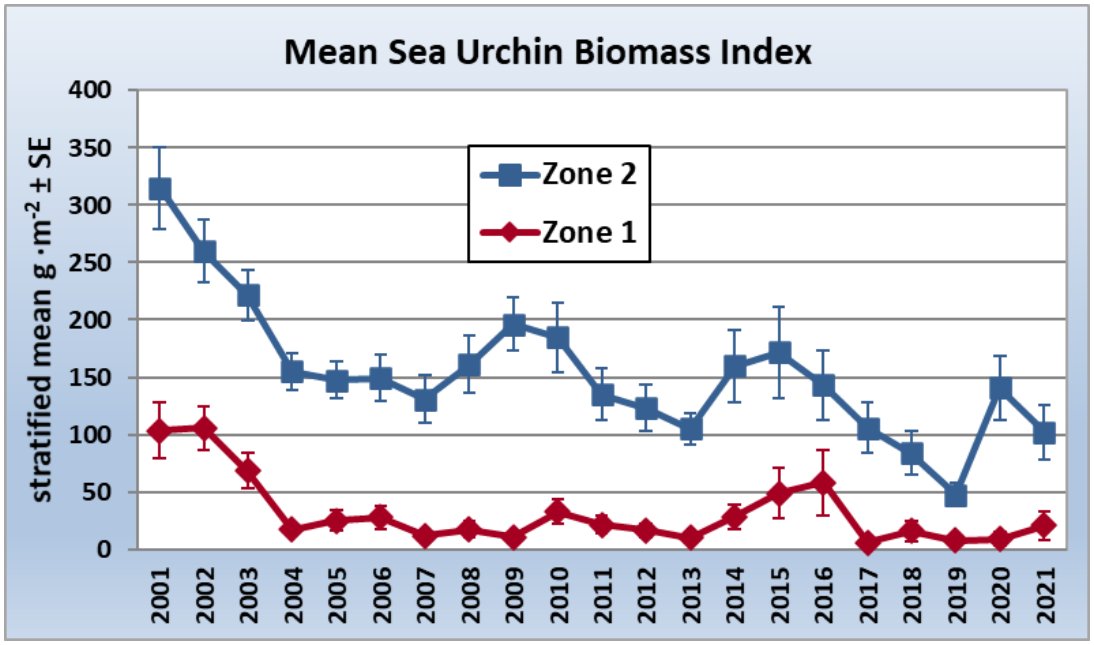

Figure 5. Stratified mean sea urchin biomass index (grams per square meter) from the spring dive survey by zone and year.

Appendix A

History of Maine Sea Urchin Management Laws (law) and Regulations (reg)

Laws and regulations usually go into effect during the late summer.

Before 1992

- Commercial fishing license ($20 for divers and single draggers, $53 for draggers with crew) required annually (law)

1992

- $89 sea urchin licenses required for hand harvesting and dragging annually (law)

1993

- Minimum size limit of 2 inches (law) (Implemented in reg. Jan. 1, 1994)
- Authority to adopt rules on drag size, nighttime dragging, and tolerance on under-sized urchins granted to DMR commissioner (law, see below for implementation in reg)
- Sea urchin boat tender license required for tenders (law)
- Season closed May 15 to August 7 for 1993, to August 15 for 1994 (law)
- Nighttime harvesting of urchins prohibited (reg, effective May 25, 1994)
- 10% tolerance by count on sea urchins less than 2 in. (reg, effective Jan. 1, 1994)
- Urchin drag width restricted to 5½ ft. (reg, effective Aug. 14, 1994)

1994

- Research surcharge on licenses: $160/harvester, $500/buyer, $2500/processor annually (law, effective Jan. 1, 1995)
- Sea urchin research fund established (law)
- Moratorium on new licenses (law, effective July 1994)
- Two fishing zones established with seasons (effective Jan. 1, 1995) (law):

  Zone 1: Closed Apr. 1 – Aug. 15, Zone 2: Closed May 15 – Oct. 1

- Authority to adopt rules for processor/buyer logbooks granted to DMR commissioner (law)
- Permits for buyers and processors required (law)
- Safety training required for divers, effective 1995 (law)

1995

- Modified season closures (law):

  Zone 1: Apr. 1 – Aug. 31 (not enacted in time for Zone 1 opening on Aug. 16, 1995)
  Zone 2: May 1 – Oct.

- Hand-raking and trapping license added ($89 plus $160 surcharge annually) (law)
- Exception to license moratorium due to medical conditions, and deceased license transfer to family members (law)
- Authority to extend closing dates for entire zones or portions thereof, to conserve spawning urchins, granted to DMR commissioner (has never been exercised) (law)
- License ($89) and surcharge ($35) annually and safety training required for tenders (law)

1996

- Sea Urchin Zone Council established (to advise on selection of fishing days), consisting of appointed members: three draggers, three divers, one buyer, and one processor from each zone plus two scientists (law)
- Fishing days limited to 150 per year in Zone 1 and 170 in Zone 2 (law)
- Limitations on switching zones — cap at the zone's previous year's total (law)
- Logbooks required from buyers/processors (reg)
- Modified zone season closure: May 1 – July 31, for both zones (law)
- Draggers not allowed to fish during August or September (law)
- Violations of sea urchin laws result in mandatory $500 fine (law)

1997

- Fishing days limited to 120 per year in each Zone (reg)
- Role of Sea Urchin Zone Council expanded: recommend fishing days, advise on the spending of the research fund, and other matters of interest to the urchin industry (law)
- Harvesters cannot switch zones during the open season (law)

1998

- Role of Sea Urchin Zone Council expanded: recommend limited entry ratio (law)
- Lottery for issuing a limited number of new licenses with a 1:5 exit ratio (law and reg)
- Up to 30% of license surcharge may be used for enforcement overtime (law)
- Two seasons in Zone 2 (harvester chooses one) (law)

  Early: Oct.–Mar. or Late: Nov.–Apr.
- Tender added to Zone Council (law)

1999

- Surcharge may be used for Council support, 30% for law enforcement (law)
- Failure to submit logbook reports may prevent license renewal (law)
- No possession of urchins on boat during no-fishing day (law)
- Mandatory suspension of license for violation of season or zone restrictions (law)
- Condition for switching zones: 1 in for 1 out (law)
- Sea Urchin Zone Council membership changed to 2 buyer/processors per zone (law)
- Six small areas closed for research (reg)

2000

- No exceptions to the license moratorium for medical conditions; no transfer of deceased harvester's license to family members (law)
- Minimum size tolerance reduced from 10% to 5% by count (reg)
- Season reduced to 110 days per year (reg)
- Maximum size of 3½" established, with a 5% tolerance by count, to be reduce to 3 3/8" in 2001 and reduced again to 3¼" in 2002 (reg) (but see 2001)
- Casco Bay research area closed for reseeding (reg)

2001

- Season reduced to 94 days per year (reg)
- Minimum size increased to 2 $^{1}/_{16}$", 5% tolerance by count (reg)

- Maximum size reduced to 3.0", 5% tolerance by count (reg)
- DMR given authority to implement limited entry system (law, see 2002 for reg)
- Drag license holder must be on boat, exceptions for multiple license holders, one-time transfer of license allowed (law)
- Surcharge may be used for Council travel expenses (law)
- Mandatory suspension of license for violation of closed areas (law)
- Diving from a vessel with urchins aboard illegal without license etc. (law)
- Processor's surcharge reduced from $2500 to $1000 (law)

2002

- One-time expansion of drag license eligibility (law)
- Limited entry license lottery system as defined in law in 1998 repealed (law) and repromulgated in regulation with minor changes (reg)

2003

- License lottery exit ratio changed from 1 in for 5 out to 1 in for 10 out (reg)
- DMR commissioner given authority to prohibit new entry to protect fishery from imminent depletion (law)
- Surcharge may be used for safety training and other management programs (law)
- Mandatory $1000 fine for 2nd violation of minimum size rule and mandatory 1 to 3 -year license suspension for 3rd violation of minimum size rule within 5 years (law)
- Zone 1 divers must "cull on bottom", 20% tolerance by count (law and reg)
- Zone 1 dragger season shortened from 94 days to 84 days (reg)
- Western Zone 2 closed for an additional 10 days (reg)
- Zone 2 divers must use large-mesh catch bags (reg)
- Zone 2 draggers must use large-mesh "escape panel" in back of drag (reg)
- License fees increased from $89 to $111 for harvesters and tenders (effective 1/1/04), and from $217 to $385 for buyers and processors (effective 4/1/04), research surcharges unchanged (law)

2004

- Re-opened six of the seven areas closed for research in 1999–2000 (reg)

- License lottery (new entry) suspended indefinitely (reg)
- Zone 1 season reduced from 94/84 days to 10 days (reg)
- Zone 2 season reduced from 94 days to 45 days (reg)

2005

- Choice of early or late seasons for Zone 1 divers (reg)

2007

- Sea Urchin Zone Council restructured, fewer members, some elected (law and reg, not implemented until 2008)

2008

- Tender research surcharge to be divided 50:50 between the urchin research fund and the new scallop research fund (law)

2009

- Whiting River and Denny's Bay area in Zone 2 closed to the taking of scallops and sea urchins until May 1, 2011 (reg). Later changed to May 1, 2012 (reg)
- Choice of early or late seasons for Zone 1 draggers (reg)
- New license for hand harvesting with tender, fee $161, research surcharge $160 (law)
- No more temporary tender license (law)
- Changes to safety training requirements for divers and tenders (law and reg), effective 12/21/09 for new licenses and 1/1/11 for licenses renewed before 8/1/10
- Zone 1 hand harvester and hand harvester with tender license fees reduced to $25 and $50 respectively (law)

2010

- License fees increased from $111 to $152 for harvesters and $133 for tenders (effective 4/27/10), from $161 to $202 for hand harvesting with tender (effective 7/5/10 but not implemented until 2011 licenses were issued), and from $385 to $443 for buyers and processors (effective 4/27/10); research surcharges unchanged. Exceptions: fees for Zone 1 harvesters and hand harvesters with tenders remain $25 and $50 respectively; and tender research surcharge increased to $50 (effective 7/12/10 but not implemented until 2011 licenses were issued) (law)
- Mandatory logbook reporting for Zone 1 harvesters (reg)

2012

- Zone 1 season increased to 15 days (reg)
- Zone 2 season reduced to 36 days (reg)
- Whiting River and Dennys Bay closed area in Zone 2 reopened for 4 days to divers and 4 days to draggers; 10-tote daily possession limits after the first day (reg)
- Zone 2 divers must "cull on bottom", 20% tolerance by count (reg)

2013

- Zone 2 season increased to 38 days (reg)
- Zone 2 harvester 7-tote daily possession limit (about 600 lbs) (reg)
- Mandatory logbook reporting for Zone 2 harvesters (reg)
- Whiting River and Dennys Bay limited-access area in Zone 2 opened for 9 days

2014

- Zone 1 harvester 12-tote daily possession limit (about 1,020 lbs) (reg)

2015

- Zone 2 divers no longer required to use large-mesh catch bags (reg)
- Cat Ledges area in Zone 1 closed to harvest until May 1, 2018, for experimental transplant project (reg)

2016

- Harvesters must present swipe cards to buyers at point-of-sale, for data collection to replace mandatory dealer reporting (reg)

2017

- Zone 1 harvesters may fish up to 15 of 20 opportunity days, and Zone 2 may fish up to 38 of 45 opportunity days (reg)
- Whiting River and Dennys Bay limited-access area in Zone 2 opened for 15 days (reg)
- Zone 2 harvesters fishing in the Blue Hill Bay area must have a tracker (supplied by DMR) operating on their vessel during their urchin season until April 2022, for a 5-year research project (reg).

2019

- Zone 1 early season divers may fish up to 15 of 43 opportunity days (5 days/wk, Sept–Oct), and draggers and late season divers may fish up to 15 of 63 opportunity days (5 days/wk, Dec–Feb) (reg).
- Zone 2 harvesters may fish up to 30 of 40 opportunity days (reg)
- Zone 1 harvester 9-tote daily possession limit (reg)
- Zone 2 harvester 6-tote daily possession limit (reg)