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*Research Article*

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# Green Sea Urchin Ranching in the Gulf of Alaska: How do Location and Food Influence Market Readiness

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**ABSTRACT**

Sea urchin ranching is advantageous for both coastal health and the human seafood market. In some areas, sea urchins have become hyperabundant and have overgrazed kelp forests,turning these forests into barrens devoid of most seaweeds. A solution to reduce these hyperabundant sea urchins is to harvest them for consumption; however, this is impractical because their gonads (roe, the marketable portion of the urchin) are very small due to a lack of their natural food, seaweeds, in urchin barrens. To be marketable, sea urchins from barrensmust be collected and then ranched, i.e., fed supplemental food so that their gonads can grow to a marketable size and quality. Here, we determined 1) if sea urchin ranching location influences market-readiness, 2) the time needed to grow market-ready gonads, and 3) the success of growing marketable gonads using different foods in the Gulf of Alaska. We collected green sea urchins (Strongylocentrotus droebachiensis) and then ranched them at three locations. Urchins were either starved or fed different foods: bull kelp (Nereocystis leutkeana), wrack (mixed kelp species or rockweed Fucus distichus), kelp fouling on docks/lines/buoys, and manufactured kelp pellets. It was found that ranching location had no effect on gonad marketability. Additionally, any food involving kelp resulted in marketable gonads within 6-8 weeks with equal success. Non-kelp food (F. distichus) performed as poorly as the starved controls and wild-caught sea urchins. This study demonstrates the feasibility of green sea urchin ranching in a high latitude environment.

**Keywords:** Aquaculture, Urchin Ranching, Feed, Market-Ready, Urchin Roe

## Introduction

Sea urchins have been wild-harvested for at least 40,000 years [1]. Harvesting has been done by hand, using scuba, and by trawling [2]. In the last few decades, a rapidly increasing sea urchin harvest has raised concerns in some regions because of the important role that sea urchins have in coastal ecosystems [3]. In other regions, once productive kelp forests have been overgrazed by an overabundance of urchins because of a reduction in local urchin predators [4-6]. These urchin-rich and now kelp- depleted areas are referred to as barrens. They have very little seaweed biomass and are generally thought of as impoverished with low production and diversity [7,8]. To restore barrens to thriving kelp forests, culling is often used for urchinremoval [9-11]. As an alternative to culling, harvesting urchins and ranching them for the seafood industry is gaining popularity.

Sea urchins cannot be directly harvested from barrens for the immediate use for the seafood market because urchin abundance is negatively correlated with gonad size and growth rate [12,13]. Hence, barrens typically have a high abundance of sea urchins with very little gonad development. In some areas, sea urchin populations are being thinned using Quicklime (CaO), which efficiently kills sea urchins with the hopes that the remaining urchins will be able to increase their gonad size to commercial levels within 1-2 years [14]. Kelp restoration is also being attempted by harvesting sea urchins and then ranching them so that they can be sold as a premium seafood [15]. While this is often accomplished at large commercial enterprises, coastal community members, existing aquaculture farmers, or tribal entities could ranch sea urchins on a small scale if local and reliable food sources could be found that would transform starved sea urchins into a marketable product.

It is known that sea urchin feeding rates and gonad indices (GI) are highest on a diet of preferred food, which varies with urchin species but often includes kelp (Laminariales) [16]. Wrack (seaweed that has washed up on beaches) might provide similar results as fresh kelp as dried kelp has resulted in fast sea urchin gonad development [17]. Other marketable gonad

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characteristics such as their taste and smell have been found to be better in sea urchins collected from the wild or fed natural diets than in sea urchins fed animal and vegetable diets [18]. Although prepared feed has been developed for sea urchins and can result in fast gonad growth, their testing on green sea urchins (Strongylocentrotus droebachiensis) is limited; in addition, commercial feeds can also be expensive and may not be economically feasible [19].

In the northern Gulf of Alaska, and across other high latitude regions, green sea urchins are the dominant species and form urchin barrens. Generally, green sea urchin test sizes and GI are smaller in barrens compared to kelp forests [12]. Along the Alaska Aleutian coast, sea urchin densities in barrens can average 120 urchins per square meter but have very low GI [20,12]. In the northern Gulf of Alaska, much less is known about the sea urchin populations other than that barrens exist (authors, pers obs.).

One characteristic that impacts sea urchin grazing rates, and by expansion gonad development, is the relative size of the Aristotle lantern (Lantern Index-LI), which is the mouth part used for feeding. Urchins with larger lanterns can take larger bites out of macroalgae and hence, can consume more [21]. In addition, the size of the lantern can vary (either increase or decrease in size) depending on food source [22-24]. The most important characteristic that determines market-readiness is the relative weight ofgonads to body weight (Gonad Index-GI). A GI over 15% is considered market-ready, with food availability being the key factor regulating the relative size of gonads [25,26]. A morphological characteristic that has had variable results in relation to feeding is the gut index [30]. This index can vary by diet but can also not differ between fed and starved urchins [27-30]. Lastly, gonad color and firmness are important characteristics for market readiness with firm, yellow to orange-colored gonads preferred over soft brown to grey gonads [31-34]. Gonad firmness, in particular, has been found to be influenced by food [35]. While the collection site of sea urchins has been shown to have no impact on sea urchin ranching results ranching location has not been explored [36].

Here, we examine how sea urchin gonad characteristics are influenced by the type of food theyare fed and also if gonad development differs by the specific location where they are being ranched. As ranching locations for small-scale farmers would be most accessible through existing surface structures, such as docks or mariculture structures, we aimed to assess if location would have a strong impact on sea urchin gonad development. We also focused on the effects of naturally available foods (macroalgae) in comparison to a manufactured urchin food. The purpose of this study is to provide a case study for sea urchin ranching in a high-latitude environment.

## Methods

### Study Sites

Sea urchin ranching was conducted in Kachemak Bay, northern Gulf of Alaska (Figure 1). This is a large estuary with existing mariculture interests and oyster and seaweed farm presence in its smaller bays and coves. Along with local subsistence, recreational, and commercial fishing, this region also has the highest density of oyster farms in Alaska. Sea urchins were ranched at two oyster farms in Kachemak Bay (Moss Island Farm in Peterson Bay and Oyster Bay Farm in Bootleggers Cove) in summer 2024 and off the dock at the Kasitsna Bay Laboratory in summer 2024 and 2025. While kelp forests dominate most rocky subtidal substrates in Kachemak Bay, a large and persistent barren exists adjacent to Homer Spit, which was our sea urchin collection site (Figure 1). This barren is largely dominated by the green sea urchin, S. droebachiensis and has little to no kelp or other foliose seaweeds. Sea urchins were hand-collected by divers on scuba and then transported in less than one hour to the Kasitsna Bay Laboratory in large tubs of seawater. Here, they were held in running seawater without food until placement at the farming locations, which was within one week. There was no mortality of urchins during the transportation or holding periods.

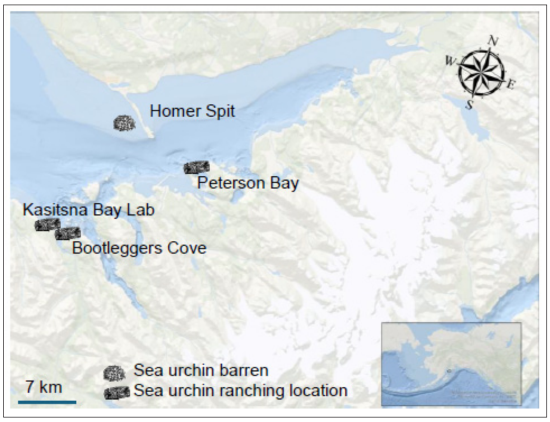


**Figure 1:** Locations where ranching occurred and Homer Spit, the barren where sea urchins were collected. Inset shows the Gulf of Alaska with the location of Kachemak Bay in the black box.

### 8-12 Week Ranching Trial in 2024

In an initial trial, we wanted to determine if ranching location and different types of kelp-basedfood influenced sea urchin gonad development. For this, in May 2024, the largest green sea urchins at the barren were collected. These sea urchins ranged in size from 30-50 mm, averaging 41.8±4.6 mm. From these sea urchins, twelve randomly selected sea urchins were immediately dissected and morphometrics and gonad characteristics were quantified as an initial baseline. All sea urchins were measured for test diameter (mm), total wet weight (g), Aristotle lantern weight (g), gonad weight (g), and gut weight (g). From these measurements, various indices were calculated as a ratio between total weight and the variable of interest, i.e., lantern index, gonad index, and gut index. In addition to these morphological and reproductive measures, we also graded gonad color and firmness to assess market readiness [34]. For this, gonads were separated into two color categories: (1) yellow to orange, and (2) black, brown or grey. Finally, gonads were rated for firmness based on their ability to maintain consistency when placed under different weights: 20, 50, 100, and 200 g [34].

Remaining sea urchins from this initial collection were randomly separated into three groups of 135 for placement at three different ranching sites (Figure 1; Moss Island Farm in Peterson Bay, Oyster Cove Farm in Bootleggers Cove, and the dock at the Kasitsna Bay Laboratory). At each of these sites, the 135 sea urchins were further divided into 15 groups of nine, which were placed into minnow traps (nine sea urchins per trap, 15 traps total). Traps were randomly arranged at each site with three traps attached to one line to be suspended from a dock surface structure. Traps were placed from a depth of about 0.5 to 3.0 m below the surface, and lines were at least 2 m apart from one another. Field experiments using in situ cages for gonad enhancement have been successfully used before [38].

Sea urchins in suspended traps were haphazardly assigned to a feeding treatment where they were either not fed or fed different types of kelp ad libitum. This type of feeding has resulted in high rates of growth and reproduction in green sea urchins [37-39,28]. At each site, three traps (with nine sea urchins each) were fed either 1) fresh kelp wrack that was available from local beaches, which was a mix of different kelp species, 2) manufactured kelp pellets designed and donated to this project by The Nature Conservancy (TNC), 3) fresh bull kelp (Nereocystis leutkeana), or 4) a mix of different kelp species that was found fouling local farm gear and docks. The TNC pellets were developed as a sea urchin feed solution that is consistent and not dependent upon the availability of local kelp products. While this feed has not yet been tested on green sea urchins, it has resulted in premium gonad product for urchin ranchers in California. The other feeding treatments were selected as they were deemed easily accessible to anyone who would want to ranch sea urchins in the study area. In addition to fed sea urchins, three traps with nine sea urchins each were not fed (i.e., starved controls).

To assess ranching success, three sea urchins from each trap were randomly selected at weeks 8, 10, and 12 after the start of the feeding trial, and sea urchin morphometrics and gonad characteristics were determined (as discussed above). This resulted in nine sea urchins from each feeding treatment and site per sampling event. In another study, green sea urchins more than doubled their GI in an eight-week lab experiment when fed ad libitum [40]. At each sampling event, we also collected nine sea urchins from the barren to compare gonads of ranched urchins to those of the wild population.

**Consumption Rates in 2024 Ranching Trial**

To help guide farmers on the amount of food that is needed to feed urchins ad libitum and to determine if consumption rates differed among the feed types in 2024, the amount (wet weight in grams) of bull kelp, kelp wrack, and fouling kelp was determined each time the sea urchins were fed for the first 11 weeks of the trial. At each sampling period, left-over food was removed and weighed and replaced with a pre-weighed amount of new food. At no time, did sea urchins consume all the food in their trap. This included pellets, which were not included in this analysis because once saturated, the pellets dissolve quickly upon touch and weight loss over time simply due to grazing could not be quantitatively assessed. Consumption rate was calculated per sea urchin in weeks 8 and 10 by dividing the total amount consumed by the total number of sea urchins in a trap (typically either 12 or 9, depending on week).

**2-8 Week Ranching Trial in 2025**

Based on the quick gonad development observed in 2024, we examined sea urchin ranching on a shorter time scale in 2025. Sea urchins were again collected from the barren and the ranching trial was conducted at the Kasitsna Bay dock only with the following feeding treatments: starved control-no food, wrack that mostly consisted of Fucus distichus, which is very common in the wrack, TNC pellets (as described above), and kelp found fouling on the dock. Sea urchins were fed similar amounts as during the first trial in 2024 with no feeding treatment ever running out of food between sampling periods. These urchins were assessed for the same morphometric measurements (except for LI) at weeks 2, 4, 6, and 8 to better resolve the early development of the sea urchin gonads. During each assessment, nine sea urchins were collected from the barren as a wild control.

**Analyses**

PERMANOVA was used to determine if morphological measures and gonad characteristics differed significantly among feeding treatments (starved controls and different feeds) and over time (initial and then every two weeks; 2024 examined weeks 8-12 and 2025 examined weeks 2-8) [41]. In 2024, ranching location was included as a random factor in the PERMANOVA (three sites). nMDS and univariate bar graphs were used to visualize differences in gonad structure based on feeding treatments (and location) over time. One-way ANOVAs were used to determine differences across treatments for each univariate measure for each time interval [42]. Post-hoc comparisons using Tukey's HSD test was used to determine which specific treatment difference contributed to the overall significant effect. A one-way ANOVA and Tukey's HSD test were also used to determine if there were differences in consumption rates among various feed types.

**Assimilation of Food**

In 2025, a small portion of the gonad of one randomly chosen sea urchin from each feeding treatment and trap (three sea urchins total per treatment and sampling event) were kept frozen for later stable carbon and nitrogen isotope analysis to assist in the assessment of diet assimilation. Frozen gonad samples were died at 60 °C to dryness, at least for 48 h. Stable isotope composition was determined at the Alaska Stable Isotope Facility (ASIF) at the University of Alaska Fairbanks using continuous-flow isotope ratio mass spectrometry on a Thermo Scientific Flash 2000 elemental analyzer and Thermo Scientific Conflo IV interfaced with a Thermo Scientific DeltaVPlus mass spectrometer. Approximately 0.3−0.5 mg gonad material were used for the analyses. Results are expressed as conventional δ notation in parts per thousand (‰) according to the following equation: $\delta X$ (‰) = ([Rsample/Rstandard] − 1) ×1000, where X is 13C or 15N of the sample and R is the corresponding 13C:12C or 15N:14N ratio. Pee Dee Belemnite and atmospheric $N_2$ served as standards for carbon and nitrogen, respectively. Instrument error at ASIF for either isotope was <0.2 ‰. Here, we mainly used the carbon stable isotope values of gonads during the 2025 trial to assess the assimilation of the provided foods for gonad production.

**Results**

**8-12 Week Ranching Trial in 2024**

No sea urchin mortality occurred during the 8–12-week ranching trial. Sea urchins collected initially and subsequently from the barrens and starved control urchins that were ranched at the various locations had similar morphometric characteristics regardless of ranching location (Figure 2, Table 1). Overall, ranching location and time (8-12 weeks) had no effect on results (Table 1). Sea urchins that were fed kelp wrack, pellets, bull kelp, or fouling kelp during week 8-12 also shared similar morphometric characteristics regardless of food type although the sea urchins fed TNC pellets grouped separately from the other fed sea urchins. Sea urchins fed bull kelp and fouling kelp were most similar in morphometrics (PERMANOVA, t=0.945, p(perm)=0.447), followed by fouling kelp and kelp wrack (PERMANOVA, t=2.014, p(perm)=0.017). Urchin morphometric measures were different between urchins fed bull kelp and kelp wrack (PERMANOVA, t=2.388, p(perm)=0.004). Overall, there was more variability in the sea urchins collected from the barrens or the sea urchins that were not fed (see wider spread of points in Figure 2) compared to any of the fed sea urchins.

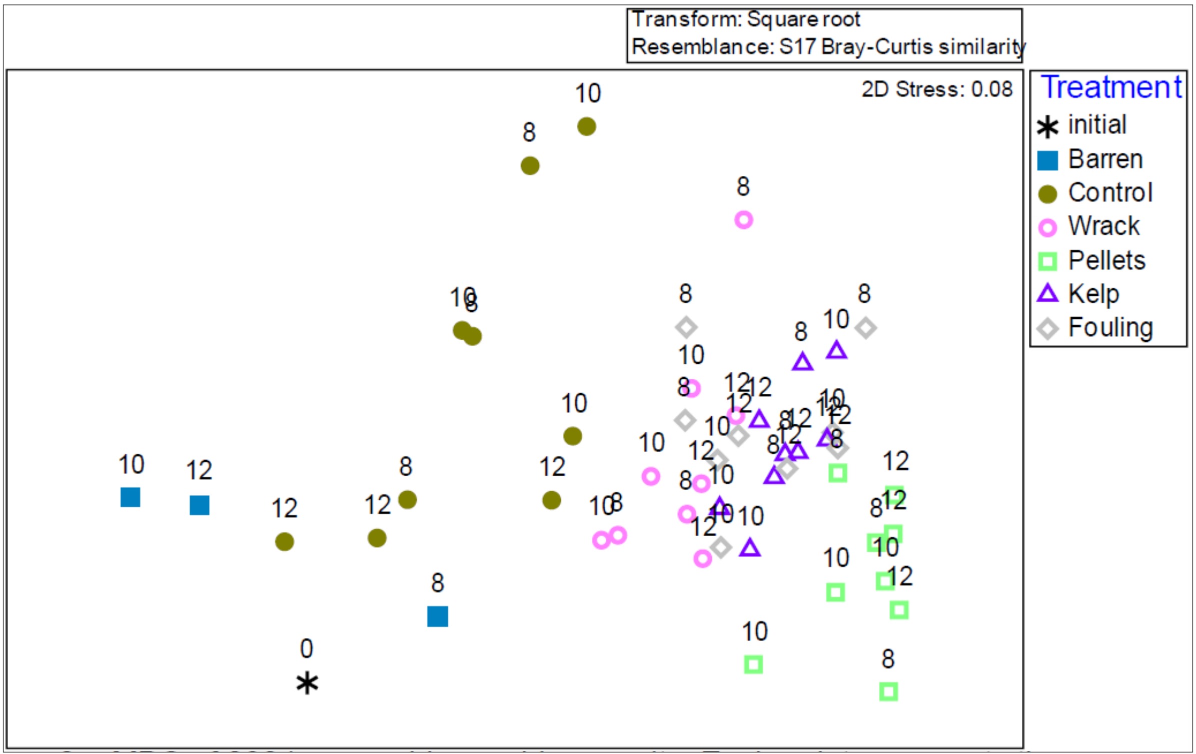


**Figure 2:** nMDS of 2024 sea urchin ranching results. Each point represents the average characteristics of barren and ranched urchins with various feeding treatments for each sampling interval. Characteristics include: Aristotle lantern index, gonad index, gut index, gonad color, and firmness. The numbers above each point correspond to the sampling week.

**Table 1: Permutational Multivariate Analysis of Variance (PERMANOVA) examining the effects of different feeding treatments on sea urchin morphological characteristics from the 2024 trial. The analysis was performed using a Bray-Curtis dissimilarity matrix on square-root transformed data. 9999 permutations were used to calculate the p-values. p-values (P < 0.05) indicate significant differences in characteristics between the specified feeding groups**

| Unique | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **df** | **SS** | **MS** | **Pseudo-F** | **P(perm)** | **perms** |
| Location | 2 | 422.01 | 211 | 0.25 | 0.907 | 998 |
| Week | 2 | 723.46 | 361.73 | 1.468 | 0.209 | 999 |
| Feed(Location) | 12 | 10141 | 845.09 | 17.741 | 0.001 | 998 |
| Location x Week | 6 | 1957.9 | 326.31 | 3.724 | 0.001 | 998 |
| Feed(Location) x Week | 24 | 2104.7 | 87.694 | 1.841 | 0.001 | 997 |
| Res | 397 | 18911 | 47.634 | | | |
| Total | 445 | 41711 | | | | |

Lantern index was similar across time and feeding treatment (Figure 3A) except for an unexplained peak in the sea urchins from the barren at week 8, when the LI was significantly higher (one-way ANOVA, $F(5,138) = 27.673$, $p<0.001$) in sea urchins from the barren than all other sea urchins. The LI in barren urchins was also larger in the starved control sea urchins than the pellet-fed sea urchins ($p<0.05$ for both comparisons). At week 10, significant differences in LI were still apparent (one-way ANOVA, $F(5,138) = 2.455$, $p = 0.036$); however, LI were only significantly larger in the barren sea urchins compared to the pellet-fed sea urchins ($p<0.05$). At 12 weeks, some significant differences remained (one-way ANOVA, $F(5,140) = 8.754$, p =$p<0.001$), with the LI still being larger for the barren sea urchins than any other sea urchins andthe lantern indices of the starved control sea urchins also being larger than in sea urchins fed pellets or bull kelp ($p<0.05$ for both).

Gonad index did differ based on the feeding treatments with the largest GI associated with urchins that were fed the pellets and the smallest associated with wild sea urchins from the barren and the starved control sea urchins (Figure 3B). At the first-time interval at week 8, the differences in GI were significant (one-way ANOVA, $F(5,138) = 65.270$, $p<0.001$) for all treatments, except for urchins fed kelp wrack and both bull kelp and fouling kelp. Significant differences in GI were still found at week 10 (one-way ANOVA, $F(5,138) = 129.857$, $p<0.001$) and 12 (one-way ANOVA, $F(5,140) = 132.143$, $p<0.001$), with smaller GI in barren and starved control sea urchins compared to all others, and larger GI in the pellet-fed sea urchins compared to all others ($p<0.05$). In general, starting at the first sampling interval at 8 weeks, GI resulting from all feeding treatments exceeded the 15% threshold associated with marketable sea urchins.

Gut indices were generally higher in the wild and starved control sea urchins compared to other treatments (Figure 3C). Sea urchins that were fed generally had the least amount of food in their guts. At week 8, there were significant differences in gut indices (one-way ANOVA, $F(5,138) =24.984$, $p = 0$). Barren sea urchins had significantly larger gut indices than urchins in any othertreatment, the starved control sea urchins had similar gut indices to kelp wrack-fed urchins, and the kelp wrack-fed urchins had similar gut indices to the fouling kelp-fed urchins (Figure 3C). The urchins fed pellets and bull kelp had the significantly smallest gut indices at 8 weeks ($p<0.05$).

Significant gut index differences continued through week 10 (ANOVA, $F(5,138) = 36.037$, $p = 0$) and 12 (one-way ANOVA, $F(5,140) = 34.218$, $p<0.001$). In week 10, the barren sea urchins had significantly larger gut indices than any other urchins. In addition, the control and kelp wrack-fed sea urchins had similar gut indices and the bull kelp and fouling kelp-fed urchins were similar ($p<0.05$). Also, at week 10, the pellet-fed sea urchins had significantly smaller gut indices than any other urchins ($p<0.05$). The 12-week measurements were similar to week 10, except that the pellet-fed sea urchins were now similar in their gut index to the bull kelp and fouling kelp fed sea urchins.

Gonad color was similarly yellow-orange (aligned with category 1) in all ranched sea urchins that were fed (Fig. 3D). Barren and starved control sea urchins generally had brown-grey colored gonads (aligned with category 2). Significant differences in gonad color were already observed by week 8 (one-way ANOVA, $F(5,138) = 12.777$, $p<0.001$), with the barren and starved control urchins having darker coloration than any of the fed urchins ($p<0.05$). This trend continued through week 10 (one-way ANOVA, $F(5,138) = 12.758$, $p<0.001$) and week 12 (one- way ANOVA, $F(5,140) = 15.331$, $p<0.001$).

Gonad firmness was variable across treatments and time (Fig. 3E). At 8 weeks, there was no significant difference in gonad firmness among treatments (one-way ANOVA, $F(5,138) = 1.0501$, $p = 0.391$). By week 10, significant differences in firmness arose (one-way ANOVA, $F(5,138) = 3.5554$, $p = 0.005$), with the gonads in starved control sea urchins being significantly firmer than in the barren or pellet-fed sea urchins ($p <0.05$). In week 12, differences were more pronounced (one-way ANOVA, $F(5,138) = 9.1602$, $p<0.001$), where all fed sea urchins had firmer gonads than either the barren or starved sea urchins ($p<0.05$), although there was no difference in gonad firmness between barren and control sea urchins and no differences among the fed urchins.

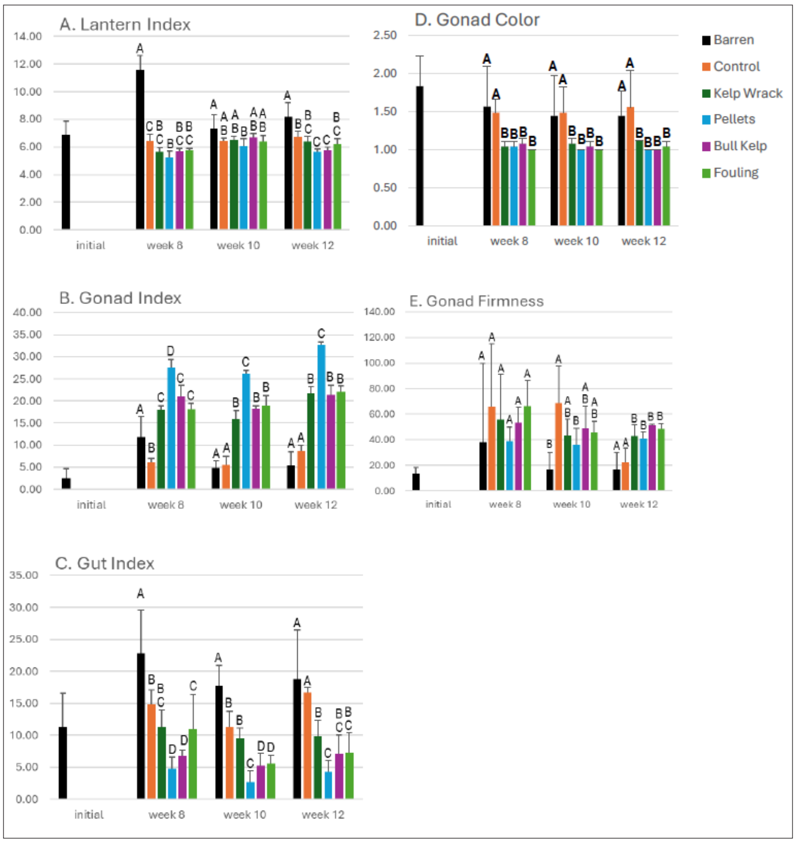


**Figure 3:** Mean (±S.D) of various morphometric characteristics from 2024 sea urchins that were initially sampled and then ranched for 12 weeks (sea urchins were either starved or fed various types of kelp). A) lantern index, B) gonad index, C) gut index, D) gonad color – values close to 1 are yellow/orange and values close to 2 are brown/grey, and E) gonad firmness. Similar letters above bars represent non-significant differences among feeding types within one sampling period.

### Consumption Rates in 2024

During each sampling event, there always was food left in each replicate. Fouling kelp was consumed significantly slower than either bull kelp or kelp wrack in the 12-week trial (one-way ANOVA, $F(2,186) = 41.9589$, $p = 8.882e\text{-}16$). On average, fouling kelp was consumed at a rate of 1.67±0.89 g/day/urchin compared to 3.76±2.1 g/day/urchin for bull kelp and 4.37±1.96 g/day/urchin for kelp wrack.

### 2-8 Week Ranching Trial in 2025

No sea urchin mortality occurred during the 2–8-week ranching trial. This trial was only done at one site (Kasitsna Bay Laboratory dock) because no site differences were seen in the longer 8–12-week trial (Table 1). At this one site, differences in sea urchin characteristics were found among the feeding treatments and across time (Table 2). Based on all morphological measurements combined, the initial collection of wild sea urchins from the barren grouped with all the ranched sea urchins that were sampled after 2 weeks, regardless of feeding treatment (Figure 4). It appears that 2 weeks was not enough time to bring about difference in the sea urchin characteristics among any of the treatments. At 4 weeks, sea urchin characteristics changedenough that they no longer grouped with the initial and 2-week urchins. That said, the 4, 6, and 8-week urchins from the barren and the starved control sea urchins grouped apart from the sea urchins that were fed ad libitum. It should be noted that the wrack-fed sea urchins in this trial were fed Fucus rather than kelp-based wrack used in the 2024 trials. The characteristics of the 4-week Fucus wrack-fed sea urchins were still similar to the barren and starved control sea urchins and did not obtain characteristics similar to the other fed urchins until week 6. Similar to the 8–12-week trial, the sea urchins fed pellets grouped the furthest away from the other feeding treatments (Figure 4).

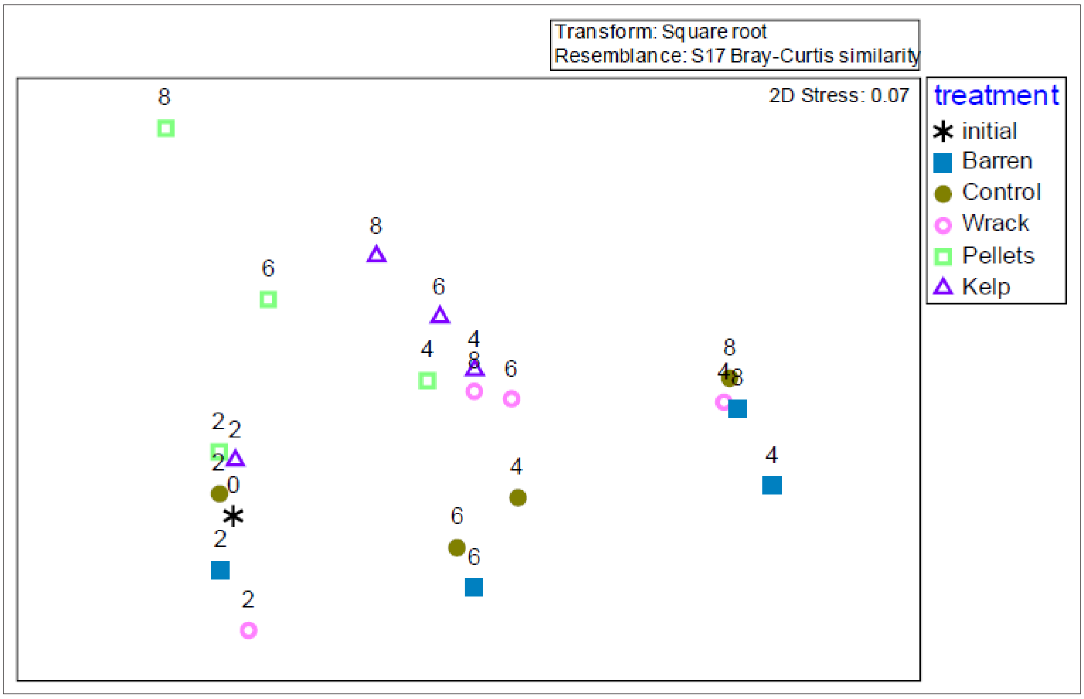


**Figure 4:** nMDS of sea urchin ranching results from 2025. Each point represents the average characteristics of barren and ranched urchins with various feeding treatments for each sampling interval. Characteristics include gonad index, gut index, gonad color, and firmness. The numbers above each point correspond to the sampling week.

**Table 2: Permutational Multivariate Analysis of Variance (PERMANOVA) examining the effects of different feeding treatments on sea urchin morphological characteristics from the 2025 trial. The analysis was performed using a Bray-Curtis dissimilarity matrix on square-root transformed data. 9999 permutations were used to calculate the p-values. p-values ($P < 0.05$) indicate significant differences in characteristics between the specified feeding groups**

| Unique | | | | | | |
|---|---|---|---|---|---|---|
| Source | df | SS | MS | Pseudo-F | P(perm) | perms |
| Feed | 4 | 2038.9 | 509.73 | 24.527 | 0.001 | 999 |
| Week | 3 | 2549.6 | 849.88 | 40.894 | 0.001 | 999 |
| Feed x Week | 12 | 1165.7 | 97.141 | 4.674 | 0.001 | 998 |
| Res | 166 | 3449.9 | 20.782 | | | |
| Total | 186 | 9515.2 | | | | |

Gonad indices were similar among all treatments and urchins from the barren at week 2 (one- way ANOVA, $F(4,40) = 0.757$, $p = 0.559$) but diverged depending on feeding treatment at week 4 (Fig 5A; one-way ANOVA, $F(4,40) = 38.155$, $p = 3.748e\text{-}13$). At 4 weeks, GI were significantly different between either barren sea urchins, starved sea urchins, or Fucus wrack-fed sea urchins and those fed pellets or fouling kelp (p<0.05). Significant GI differences among treatments continued at week 6 (one-way ANOVA, F(4,40) = 41.911, p<0.001) and week 8(one-way ANOVA, F(4,38) = 71.143, p = 0). At week 6, barren and starved control sea urchins had significantly smaller GI than any of the fed sea urchins (p<0.05). Among those, the pellet and fouling kelp fed sea urchins had the largest GI (p<0.05). Fucus wrack fed sea urchins produced intermediate sized gonads at week 6. Trends were similar at week 8, with the barren and starved control sea urchins having significantly smaller GI and pellet-fed sea urchins having significantly larger gonads. Fouling kelp-fed sea urchins did not perform as well as pellet-fed sea urchins but they still had significantly larger gonads than Fucus wrack-fed sea urchins (p<0.05). Similar to the longer, 12-week trial, feeding with pellets produced the largest overall GI (Figures 4 and 5). Additionally, the Fucus wrack treatment in this trial did not perform as well as kelp wrack did in the longer trial.

Gut indices showed no pattern and were highly variable for the first 6 weeks of this trial (Figure 5B). Gut indices were similar among treatments at week 2 (one-way ANOVA, F(4,40) = 2.549, p= 0.054), week 4 (one-way ANOVA, F(4,40) = 0.717, p = 0.585), and week 6 (one-way ANOVA, F(4,40) = 1.992, p = 0.114). This changed in week 8 (one-way ANOVA, F(4,38) = 6.523, p =0.0004), when the pellet-fed sea urchins had significantly smaller gut indices than all other sea urchins except for the starved control sea urchins (p<0.05). Also in week 8, the fouling kelp-fed sea urchins had significantly larger gut indices than pellet-fed sea urchins but smaller gut indices than the Fucus wrack-fed sea urchins (p<0.05). In week 8, the low pellet-fed gut index was similar to what was seen for that treatment in the 8–12-week trial.

Gonad color was variable after the first 2 weeks of this trial with no significant differences among treatments (Fig 5C, one-way ANOVA, F(4,40) = 0.703, p = 0.595) but by week 4, color had similar patterns as in the longer trial (Fig. 5C and 4D). At week 4, there was no significant difference in the color of sea urchin gonads from the barren and the starved control sea urchins (p<0.05). There was also no difference in the gonad color of sea urchins fed any type of food (p<0.05). These fed sea urchins generally had gonads with more marketable coloration (yellow to orange; closer to category 1) than did barren or control sea urchins. By week 6, gonad color differences among some treatments continued (one-way ANOVA, F(4,40) = 0.689, p = 0.0005584), with the control sea urchins having significantly more brown/grey color than sea urchins that were fed any type of food (p<0.05). By week 8, there were no longer significant differences in gonad color among any of the treatments (one-way ANOVA, F(4,40) = 1.578, p = 0.200), with sea urchins from all treatments having more yellow-orange coloration. In general, however, sea urchins that were fed some sort of food typically had a more yellow-orange color than the ones that were starved or collected from the wild, although the differences were not always significant This was consistent with the findings from the 12-week trial (Figures 4 and 5).

Similar to the 12-week trial, gonad firmness was variable across time and feeding treatment (Fig. 5D). At week 2, firmness was similar among treatments (one-way ANOVA, F(4,40) = 1.4884, p = 0.2239). At week 4, significant differences arose (one-way ANOVA, F(4,40) = 6.5559, p = 0.0003727), with the barren sea urchins having significantly firmer gonads than the starved control, the pellet, or fouling kelp-fed sea urchins (p<0.05). Additionally, Fucus wrack- fed sea urchins had significantly firmer gonads than the pellet -fed sea urchins (p<0.05) by week 4. By week 6, significant differences continued (one-way ANOVA, F(4,40) = 3.9931, p = 0.008096) with the Fucus wrack-fed sea urchins having firmer gonads than the control and pellet-fed sea urchins (p<0.05). By week 8, gonad firmness continued to be significantly different (one-way ANOVA, F(4,38) = 3.261, p = 0.022), with the control sea urchins having firmer gonads than the pellet-fed sea urchins (p<0.05). The lack of consistent results with gonad firmness over time was similar to the 12-week trial (Figures 4E and 5D).

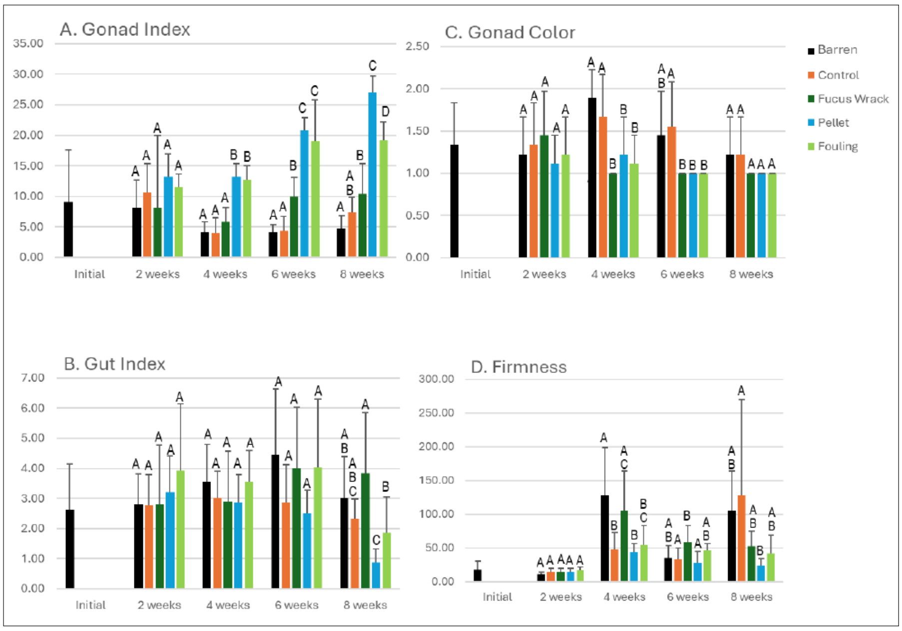


**Figure 5:** Mean (±S.D) of various morphometric characteristics from 2025 sea urchins that were initially sampled and then ranched for 8 weeks (sea urchins were either starved or fed various types of kelp). A) gonad index, B) gut index, C) gonad color – values close to 1 are yellow/orange and values close to 2 are brown/grey, and D) gonad firmness. Similar letters above bars represent non-significant differences among feeding types within one sampling period.

**Assimilation of food**

The three food sources fed to sea urchins (Fucus wrack, pellets, and fouling kelp) had different carbon stable isotope values, with the most 13C-enriched source being fouling kelp with -14.1 ‰, followed by Fucus wrack of -16.0 ‰, and pellets being the most 13C-depleted source with -23.6 ‰ (Figure 6). The gonads of sea urchins from the barren had consistent carbon stable isotope values during the initial and week 2 sampling (about -18.5 ‰), but then dropped by 2-3 ‰ in weeks 4 and 6. In contrast, the δ13C values of starved control sea urchin gonads stayed relatively consistent, and similar to barren urchins in the first 2 weeks, over the duration of the trial. At week 2, the δ13C values of gonads of sea urchins in most feeding treatments were similar to those of barren sea urchins, except those being fed pellets. The gonads of pellet-fed sea urchins were already close to the source carbon isotope value at week 2 and approached this source value even more closely in weeks 4 and 6. The δ13C values of gonads of sea urchins feeding on fouling kelp approached the isotope value of their source more slowly, and the δ13C values of gonads were still about 1.5 ‰ lower than the source by week 6. Gonads of Fucus wrack-fed sea urchins did not change over the first 6 weeks of the trial and did not approach the δ13C values of their source.

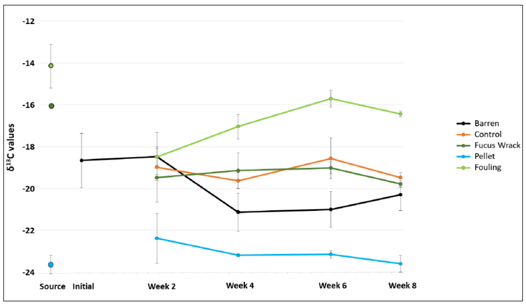


**Figure 6:** Mean carbon isotope values for urchins sampled in 2025 initially and that were starved or fed various types of kelp over the 8-week trial. The carbon isotope values of sources (Fucus wrack, TNC pellets, kelp fouling) are presented as well, indicated by black borders around the symbol.

**Discussion**

This study has shown that high latitude green sea urchins collected from barrens with little to no macroalgal food can obtain marketable gonads when fed, especially kelp-based foods, while being held in suspended traps. These results are similar to other studies that obtained marketable gonads after ranching [26,43]. Based primarily on their gonad index (over 15%) and color (orange-yellow), urchins that were ranched in this study were market-ready at 6 weeks in the shorter-term trial and at 8 weeks (first sampling) during the longer trial. Gonad firmness was found to be variable over among treatments and over time so this was deemed not to be a good measure for marketability in this study. These results are promising for potential green sea urchin ranchers in high-latitude estuarine systems.

All ranched sea urchins were marketable in this study at the end of both trials, but results differed among feeding treatments. In both trials, sea urchins fed pellets were morphologically different from sea urchins that were fed other diets or starved (Figures 2 and 3). These pellet-fed sea urchins had larger gonad indices and smaller gut indices when compared to other sea urchins (Figs. 4 and 5). A similar study found better gonad growth with prepared feed [44]. Although not significant, the pellet-fed urchins in our study had softer gonads but they still held together, so would be appropriate for market. The pellet food was quickly assimilated by the sea urchins and invested into gonad production, based on the carbon stable isotope data, because sea urchin gonads respond quickly to the δ13C values of their algal-based diet [45]. This mirrored the fast development of gonads once sea urchins were fed pellets, as seen in the quick increase of the GI in this feeding treatment. The fast approximation of gonad δ13C values to the diet makes sense because gonads in these sea urchins were newly produced, instead of turned over tissue, which typically takes a longer time [46]. In addition, prepared feeds such as the pellets in this study, are known to enhance gonad growth over natural foods, typically based on water content of the feed, with prepared feeds (pellets) being more nutritionally concentrated [47]. This was consistent with the fast approximation of gonad tissue δ13C values in the pellet-fed sea urchins in our study, compared to fouling kelp-fed sea urchins. Given these results, prepared pellets may be a good option as an urchin feed, particularly in areas where wild kelp are not available. We do caution, however, that we did not conduct any human sensory evaluations on the gonads and this should be considered before large-scale ranching begins as specific food types can influence smell, taste, and aftertaste [35,48].

Kelp in its various forms (wrack, fouling, and wild) produced similar morphological results, but the gonads of the Fucus wrack-fed sea urchins in the shorter trial were more similar to barren collected sea urchins and starvation control sea urchins. When sea urchins were fed Fucus wrack, their gonads were small (not marketable) and their guts were relatively full (Figure 5). This indicates that they were feeding but were not converting the food they had in their guts into gonad production. Sea urchins fed Fucus wrack did not seem to absorb nutrition from the feed for gonad production, as evidenced by the lack of assimilation of the food source (no approximation of gonad δ13C values to the source and low GI over time). Despite that Fucus wrack remains reproductively viable over the summer in the study region, and it is consumed by sea urchins in the trial (see increased gut index), it does not seem to be invested into gonad production [49]. Possibly, this is related to the occasionally low lipid and other nutritional content of Fucus in the study region [50]. This result was unsurprising as sea urchins prefer a kelp to non-kelp diet and tend to grow larger gonads on preferred food [51]. The assimilation of kelp food (fouling kelp) was documented in the steady approximation of the gonad δ13C values to those of the fouling kelp. In one study, green sea urchins were found to prefer fresh bull kelp (Nereocystis leutkeana), which we used successfully in our first 12-week trial. The kelp wrack and fouling kelp used in this study were a mix of N [52]. leutkeana, Cymethaera triplicata, Saccharina latissima, Alaria marginata, and Costaria costata. Unlike another study, when a mix of kelp species was used, no significant differences in sea urchin gonad and morphological characteristics were found compared to urchins fed a single species (N. leutkeana) [51]. One morphological characteristic that did not correlate with food was the LI. Lantern indices have sometimes shown a relationship with food but results have not been consistent [22,53,54]. The lack of a strong relationship between food and LI suggests that most sea urchins, except for barren and, to a lesser degree, starved control sea urchins, were feeding at a similar rate and were ingesting a similar amount of food [21].

Both the pellet and the fouling kelp food sources were quickly assimilated by sea urchins and invested into gonad production, based on the carbon stable isotope data, as sea urchin gonads are a newly produced tissue and respond quickly to the δ13C values of their algal-based diet [45]. This mirrored the fast development of gonads once sea urchins were fed these diets, as seen in the quick increase of the GI in these feeding treatments. The fast approximation of gonad δ13C values to the diet makes sense because gonads in these sea urchins were newly produced, instead of turned over tissue, which typically takes a longer time [46]. In addition, prepared feeds such as the pellets in this study, are known to enhance gonad growth over natural foods, typically based on water content of the feed, with prepared feeds (pellets) being more nutritionally concentrated [47]. This was consistent with the fast approximation of gonad tissue δ13C values in the pellet-fed sea urchins in our study, compared to fouling kelp-fed sea urchins. Sea urchins fed Fucus wrack did not seem to absorb nutrition from the feed for gonad production, as evidenced by the lack of assimilation of the food source (no approximation of gonad δ13C values to the source and low GI over time). Despite that Fucus in wrack remains reproductively viable over the summer in the study region, and it is consumed by sea urchins in the trial (see increased gut index), it does not seem to be invested into gonad production. Possibly, this is related to the occasionally low lipid and other nutritional content of Fucus in the study region [50]. Notably, the δ13C values of sea urchins from the barren changed dramatically between weeks 2 and 4, while the starved control sea urchins did not. Coincidentally, there was an increase in gut index, gonad color, and gonad firmness in week 4 in gonads of the barren sea urchins, even though there was no discernable response in GI. It is possible that sea urchins in the barren were able to start feeding on a seasonally available food source in late May (week 4), such as the development of benthic diatom films (authors, pers. obs.). Benthic microalgae are important in the development of newly metamorphosed sea urchins but it is possible they also serve as a food source for adult sea urchins in the absence of foliose algae [55,56]. The distinct drop in δ13C values could indicate that sea urchins in the barren went from starvation (often characterized by higher δ13C values) to feeding on a seasonal food source, which was not observed in the experimentally starved urchins [57]. This study found that ranching location had no impact on gonad development in ranched sea urchins. This is similar to another study that found that sea urchin collection location had no impact on ranching results [36]. Our sites consisted of two oyster farms in two different bays and a dock in a third bay. This lack of location differences is unsurprising as some environmental characteristics that are expected to vary with sites, such as light, have been found to have little influence on gonad growth, especially when compared to food quality and quantity [58]. Environmental site characteristics were not quantified in this study, but all sites are located in larger Kachemak Bay, which is known for having oceanic conditions and many successful oyster farms [59]. While no site effects on gonad development were found, further study of environmental conditions may be worthwhile. One environmental characteristic that might be worth further examination is temperature [60]. It has been shown that capturing sea urchins in cooler water and ranching them at a site with relatively warmer water increases gonad production [61]. Additionally, increased gonad growth has been achieved at higher temperatures in summer compared to winter [62]. In contrast to gonad growth, gonad color, texture, and firmness were found to not be significantly affected by temperature, diet, or the interaction of these two factors [44].

We recommend that future green sea urchin ranching start with a sensory evaluation to examine smell, taste, and aftertaste. Different foods can produce different sea urchin flavors and smells, and preferred taste can depend on the market [48,63]. We also recommend that the ranching site be one where other invertebrate thrive as an indicator of generally amenable conditions. For this study, we used oyster farms and a dock with little boat traffic. We found farms and docks to be desirable because traps could easily be brought to the surface for feeding and harvesting. A kelp product (wild, fouling, wrack, or pelletized) should be used with sea urchins being fed approximately 6 g of kelp per day per green sea urchin. Initial sampling of the sea urchins for market-readiness could start at 6 weeks in a location as described (productive region, locations with diverse other marine communities). We used sea urchins with 30-50 mm test size in this study because that was the available size in the barren. If larger sea urchins are used, more food and a longer time may be needed. It should also be noted that overall results may vary if differently sized green sea urchins or different species of sea urchins are used [64-66].

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**References**

1. Kaharudin HA, O'Connor S, Kroh A, Kealy S. Sea urchin exploitation over 40,000 years. J Isl Coast Archaeol. 2024. 1-28.
2. Reynolds JA, Wilen JE. Sea urchin fishery economics. Mar Resour Econ. 2000. 15: 115-126.
3. Brundu G, Farina S, Domenici P. Behavioural effects of raising sea urchins in captivity. Conserv Physiol. 2020. 8: 015.
4. Estes JA, Duggins DO. Sea otters and kelp forests in Alaska. Ecol Monogr. 1995. 65: 75-100.
5. Filbee-Dexter K, Scheibling RE. Sea urchin barrens as stable states. Mar Ecol Prog Ser. 2014. 495: 1-25.
6. Flukes EB, Johnson CR, Ling SD. Formation of sea urchin barrens. Mar Ecol Prog Ser. 2012. 464: 179-94.
7. Metzger JR, Konar B, Edwards MS. Macroalgal community variation. Mar Biol. 2019. 166: 156.
8. Edwards M, Konar B, Kim JH, Gabara S, Sullaway G, McHugh T, et al. Marine deforestation impacts ecosystem function. PLoS One. 2020. 15: e0226173.
9. Guarnieri G, Bevilacqua S, Figueras N, Tamburello L, Fraschetti S. Sea urchin culling reduces barrens. Front Mar Sci. 2020. 7: 519.

10. Miller KI, Shears NT. Sea urchin removal methods. Restor Ecol. 2023. 31: e13754.
11. Miller KI, Blain CO, Shears NT. Sea urchin removal review. Front Mar Sci. 2022. 9: 831001.
12. Konar B. Seasonal changes in sea urchin populations. Polar Biol. 2001. 24: 754-763.
13. Claisse JT, Williams JP, Ford T, Pondella DJ, Meux B, Protopapadakis L. Kelp restoration increases sea urchin gonad biomass. Ecosphere. 2013. 4: 1-19.
14. Strand HK, Christie H, Fagerli CW, Mengede M, Moy F. Quicklime use in management. Ecol Eng. 2020. 143: 100018.
15. Piazzi L, Ceccherelli G. Harvest effects on algae restoration. Estuar Coast Shelf Sci. 2019. 219: 273-277.
16. Keats DW, Steele DH, South GR. Depth-dependent reproduction in S. droebachiensis. J Exp Mar Biol Ecol. 1984. 80: 77-91.
17. Carrier TJ, Eddy SD, Redmond S. Solar-dried kelp as feed in sea urchin aquaculture. Aquac Int. 2017. 25: 355-366.
18. Senaratna M, Evans LH, Southam L, Tsvetnenko E. Feed formulation effects. Aquac Nutr. 2005. 11: 199-207.
19. Pearce CM, Daggett TL, Robinson SMC. Protein effects on gonads. Aquaculture. 2002. 214: 307-332.
20. Weitzman BP, Konar B, Edwards MS, Rasher DB, Kenner MC, Tinker MT, et al. Abiotic drivers of sea urchins. J Mar Sci. 2023. 2023: 1198953.
21. Black R, Codd C, Hebbert D, Vink S, Burt J. Functional significance of Aristotle's lantern in Echinometra mathaei. J Exp Mar Biol Ecol. 1984. 77: 81–97.
22. Heflin LE, Gibbs VK, Powell ML, Makowsky R, Lawrence AL, Lawrence JM. Diet quality effects on sea urchin morphology. J Shellfish Res. 2012. 31: 867.
23. Levitan DR. Skeletal changes in Diadema antillarum. Mar Biol. 1991. 111: 431-455.
24. Ebert TA. Relative growth of sea urchin jaws. Bull Mar Sci. 1980. 30: 467-474.
25. Angwin RE, Hentschel BT, Anderson TW. Gonad enhancement of the purple sea urchin, Strongylocentrotus purpuratus, collected from barren grounds and fed prepared diets and kelp. Aquac Int. 2022. 30:1353-1367.
26. Garrido CL, Barber BJ. Temperature and food effects on gonad growth. Mar Biol. 2001. 138: 447-456.
27. Barker MF, Keough JA, Lawrence JM, Lawrence AL. Feeding rate, absorption efficiencies, growth, and enhancement of gonad production in Evechinus chloroticus. J Shellfish Res. 1998. 17: 1583-1590.
28. Meidel SK, Scheibling RE. Reproductive cycle of S. droebachiensis. Mar Biol. 1998. 131: 461-78.
29. Meidel SK, Scheibling RE. Food effects on reproduction. Mar Biol. 1999. 134: 155-166.
30. Guillou M, Lumingas C, Michel C. Feeding effects on reproduction of Sphaerechinus granularis. J Exp Mar Biol Ecol. 2000. 245: 183-196.
31. Shpigel M, Schlosser SC, Ben-Amotz A, Lawrence AL, Lawrence JM. Dietary carotenoids effects. Aquaculture. 2006. 261: 1269-1280.
32. Ciriminna L, Signa G, Vaccaro AM, Visconti G, Mazzola A, Vizzini S. Sustainable feed promotes gonad development in Paracentrotus lividus. Aquac Rep. 2021. 21: 100881.
33. Jangoux M. Closed-cycle echiniculture of Paracentrotus lividus. J Shellfish Res. 1998. 17:152-153.
34. Pert CG, Swearer SE, Dworjanyn S, Kriegisch N, Turchini GM, Francis DS, et al. Gonad conditioning. Aquac Environ Interact. 2018. 10: 345-361.
35. Siikavuopio SI, Dale T, Carlehög M. Gonad sensory quality. J Shellfish Res. 2007. 26: 637-643.
36. James P, Evensen T, Johansson G. Temperature effects on S. droebachiensis. Aquac Res. 2023. 2023: 6360865.
37. Minor MA, Scheibling RE. Feeding regime effects. Mar Biol. 1997. 129: 159-67.
38. Juinio-Meñez MA, Bangi HGP, Malay MCD. Feed and density effects on sea urchin growth. Philipp Agric Sci. 2008. 91:439-149.
39. Walker CW, Lesser MP. Photoperiod and gametogenesis. Mar Biol. 1998. 132: 663-676.
40. Christiansen JS, Siikavuopio SI. Feed intake and gonad growth of Strongylocentrotus droebachiensis. Aquaculture. 2007. 262: 163-167.
41. Anderson MJ, Gorley RN, Clarke KR. PERMANOVA+ for PRIMER: Guide to software and statistical methods. Plymouth: PRIMER-E Ltd; 2008.
42. R Core Team. R: A language and environment for statistical computing. Vienna: R Foundation; 2024.
43. Gardner L, Lindsey H, Neylan K, Chang W, Herrmann K, Rintoul M, et al. Roe enhancement feasibility. Bull Jpn Fish Res Educ Agency. 2021. 50: 47-53.
44. Azad AK, Pearce CM, McKinley RS. Effects of diet and temperature on ingestion, absorption, assimilation, gonad yield, and gonad quality of the purple sea urchin (Strongylocentrotus purpuratus). Aquaculture. 2011. 317: 187-196.
45. Cyrus MD, Bolton JJ, Macey BM. Stable isotope tracking in sea urchin gonads. Aquac Nutr. 2020. 26: 174-85.
46. McBride SC, Lawrence JM, Lawrence AL, Mulligan TJ. Diet ration effects on gonads. J World Aquac Soc. 1999. 30: 364-370.
47. Zhao C, Feng W, Wei J, Zhang L, Sun P, Chang Y. Temperature and feeding effects. J Mar Biol Assoc UK. 2016. 96: 185-195.
48. Phillips K, Bremer P, Silcock P, Hamid N, Delahunty C, Barker M, et al. Gonad quality factors. Aquaculture. 2009;288: 205-215.
49. Ulaski BP, Konar B, Otis EO. Seaweed reproduction. Estuaries Coasts. 2020. 43: 2046-2062.
50. Kim MA, Iken K. Glacial discharge effects on rockweed. J Exp Mar Biol Ecol. 2024. 576: 152019.
51. Larson BR, Vadas RL, Keser M. Feeding ecology of S. droebachiensis. Mar Biol. 1980. 59: 49-62.
52. Vadas RL. Preferential feeding in sea urchins. Ecol Monogr. 1977. 47: 337-371.
53. Russell MP. Resource allocation plasticity. J Exp Mar Biol Ecol. 1998. 220: 1-14.
54. Lau DCC, Lau SCK, Qian PY, Qiu JW. Morphological plasticity in sea urchins. J Shellfish Res. 2009. 28: 383-388.
55. Xing RL, Wang CH, Cao XB, Chang YQ. Diatoms as food source. Aquaculture. 2007. 263: 142-9.
56. Zupo V, Glaviano F, Caramiello D, Mutalipassi M. Diatoms and post-larvae survival. Aquaculture. 2018. 495: 13-20.
57. Hertz E, Trudel M, Cox MK, Mazumder A. Effects of fasting on isotopic ratios. Ecol Evol. 2015. 5: 4829-4839.
58. Matheson K, Gagnon P. Growth resilience of sea urchins. Mar Biol. 2021. 168: 179.

59. Spurkland T, Iken K. Kelp bed dynamics. J Coast Res. 2011. 27: 133-643.
60. McBride SC, Pinnix WD, Lawrence JM, Lawrence AL, Mulligan TM. Temperature effects on gonad production. J World Aquac Soc. 1997. 28: 357-365.
61. James PJ, Heath P, Unwin MJ. Seasonal effects on roe enhancement. Aquaculture. 2007. 270: 115-131.
62. Siikavuopio SI, Christiansen JS, Dale T. Temperature and season effects. Aquaculture. 2006. 255: 389-394.
63. Takagi S, Sato Y, Murata Y, Kokubun A, Touhata K, Ishida N, et al. Taste of sea urchin gonads. Sensors. 2020. 20: 7008.
64. Pearce CM, Daggett TL, Robinson SMC. Urchin size and diet effects. Aquaculture. 2004. 233: 337-367.
65. Krumhansl KA, Okamoto DK, Rassweiler A, Novak M, Bolton JJ, Cavanaugh KC, et al. Global kelp forest changes. Proc Natl Acad Sci USA. 2016. 113:13785-13790.
66. Miller KI, Balemi CA, Blain CO, Spyksma AJ, Shears NT. Roe quality improvement. Ecosphere. 2024. 15: e4911.