Final Report Executive Summary for: Informing restoration and recovery of central coast kelp forests: understanding the dynamics of urchin recruitment, reproduction and density

Project Summary
Foundation species create complex habitats that support diverse ecosystems and functions. Projects that inform and prioritize restoration and recovery projects of foundational species are necessary to restore potential lost functions. Kelp ecosystems have undergone major shifts historically, but more recently they have faced unprecedented declines across northern and central California precipitated by marine heat waves and increases in sea urchin abundances. Effective efforts to restore economically and ecologically important kelp requires a better understanding about the relative effects of biological and physical factors, especially important herbivores like sea urchins.

For this study, we identify three objectives that will help inform management decisions about kelp recovery and restoration:

- **Objective 1: Assess reproductive capacity of intertidal sea urchins as a reproductive refuge for urchin barrens.**
- **Objective 2: Identify spatial and temporal patterns in recruitment of sea urchins**

This project provided important authentic research experiences for undergraduate and graduate students at CSUMB - is a minority serving institution with a majority first generation college student body (Figure 1). Authentic research experiences are a high impact teaching practice shown to increase retention in STEM fields and narrow the gap in performance of students from underrepresented groups in science.

Introduction and background
Foundational species create complex habitats and support marine ecosystems, which make them an important target for restoration and recovery. However, effective restoration and recovery is challenging and requires an understanding of the direct and indirect effect of environmental changes on foundation species. Kelp ecosystems have undergone historic shifts and changes globally (Krumhansl et al. 2016; Steneck et al 2014). Currently kelp ecosystems face unprecedented loss in the face of increasing temperatures and rising urchin populations (Rogers-Bennett and Catton 2019). Changes in sea urchin behavior plays an important role in shifting kelp forests to urchin barrens through alternation of stable states (Steneck et al. 2002; Hart and Scheibling 1998).

For restoration efforts to be effective and to prioritize spatial areas most likely to be successful, managers and policy makers need complete information especially about herbivores like urchins that can precipitate large scale changes in kelp abundance. Sea urchins in urchin barrens devoid of food for them often have highly reduced gonadosomatic index (GSI) and virtually no gonads (Eurich et al. 2014). How urchin populations reproductively sustain themselves when there is so little biological effort put towards reproduction is not well understood. Increases in urchins have been well documented in the subtidal, and we have also seen corresponding increases in intertidal urchins adjacent to barren subtidal areas (Haupt unpublished data). Though reproductive capacity of urchins within urchin barrens is fairly well understood, reproductive capacity of intertidal areas adjacent to urchin barrens has not been well studied and intertidal areas may serve as reproductive refugia for subtidal urchin barrens.

Summary of methods and key findings

Objective 1: Assess reproductive capacity of intertidal sea urchins as a reproductive refuge for urchin barrens.

Methods: Survey of intertidal populations at nine sites across the Monterey Peninsula. Sampling included swaths for large mobile invertebrates and quadrats to measure urchin sizes, habitat, and percent cover of sessile invertebrates and algae. 25 urchins were collected seasonally from each site to measure GSI. To look for changes in urchin densities over time we used past data collected through PI Haupt's CSUMB capstone class and ran an ANOVA. We used a structural equation model approach to look at drivers of intertidal sea urchin densities. To look at drivers of urchin reproduction, we ran a series of ANOVAs and Linear Regressions. We used a multivariate approach to look at impacts of increases in urchin herbivory on intertidal communities.

Key Findings:

- Urchin population patterns: Urchin populations have increased dramatically since 2002 with the increase beginning around 2019 or 2020 - much later than the increase in subtidal systems (Figure 2 & 3). Intertidal urchin densities are high yet variable across sites. Neither intertidal algae had a significant relationship with intertidal urchin abundance, where habitat complexity seems to be a strong driver of intertidal urchin density in this model. Overall characteristics other than the main food source may be driving intertidal urchins densities across the sites.
- Urchin reproduction patterns: We compared our data to GSI data collected by Josh Smith at UCSC and found that drivers of urchin reproduction in the intertidal were found to be different than drivers in the subtidal (Table 1). We found that intertidal urchin reproductive capacity is not only driven by the algae growing in the intertidal, but likely also drift algae that is washing onto the intertidal from subtidal kelp forests and other areas (Figure 4). Even in areas of high urchin density, low fleshy algae growth, and high coralline algae cover, intertidal urchins show relatively high reproductive capacities, indicating that they must be getting food from an outside source: likely drift algae (Figure 5). This indicates that intertidal urchin populations represent a high reproductive output for purple urchin populations, and they must be monitored as a potential source population for urchin barren urchins.
- Intertidal communities: We found that intertidal communities were largely resilient to large increases in urchin populations (and likely urchin herbivory). This is in contrast to subtidal systems that see extreme shifts in algal communities.

Objective 2: Identify spatial and temporal patterns in recruitment of sea urchins

Methods: We have monitored weekly or bi-weekly urchin recruitment levels using the scrub brush technique with mooring lines hung off of piers in the Monterey Harbor and Stillwater Cove. PI Haupt has set up a training system where upper-division students mentor lower-division students; this peer-mentorship program provides important entry-level field and lab experiences for undergraduate students. These recruitment collectors were swapped in the field weekly or every other week and processed using flow-through sea water and sieved through a 250 micron sieve to collect potential urchin recruits. Samples were stored in 70% EtOH and sorted under a dissection scope and urchin recruits.

Key Findings: This objective of the study was most impacted by covid delays on field work and research. The Haupt lab is continuing to monitor urchin recruitment at Stillwater Cove and the

Monterey Harbor. Because of these delays due to covid, we will continue to work on this objective beyond the timeline of this grant. Haupt lab has a graduate student starting in Fall 2024 with funding from another source who will be able to take the lead on expanding this study to complete this full objective. This objective provided the basis for countless entry-level undergraduate research experiences at CSUMB.

Main Conclusions

- Urchin populations have dramatically increased in the intertidal
- Sites with higher rugosity are correlated with higher urchin abundances
- Intertidal communities appear to be more resilient to increases in urchin populations than subtidal communities
- There is high spatial variability in urchin reproduction across sites and within a site
- Patterns and drivers of intertidal urchin reproduction are different than subtidal urchins
- Intertidal urchins have high quality gonads even at high densities and food availability
- Kelp restoration efforts, especially those that focus on urchin culling, cannot ignore intertidal urchin populations
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References

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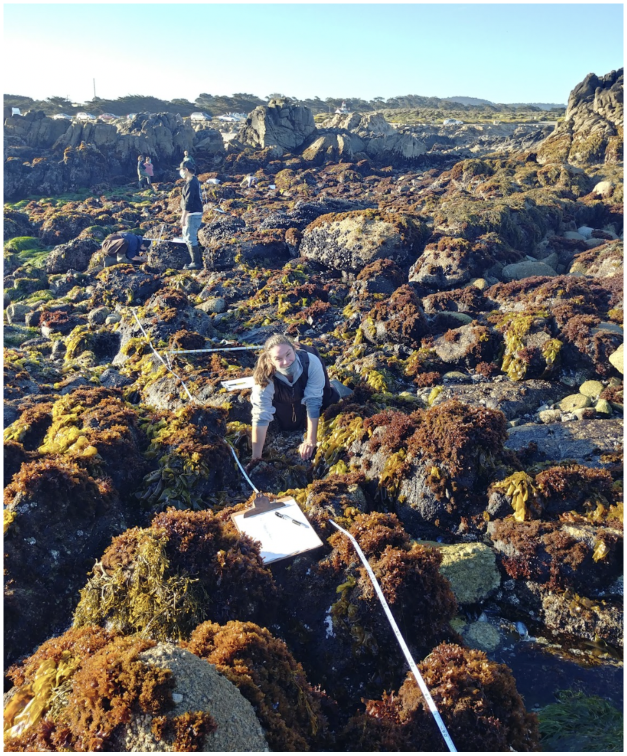

Figure 1. Students collecting data at China Rocks in Pebble Beach, CA.

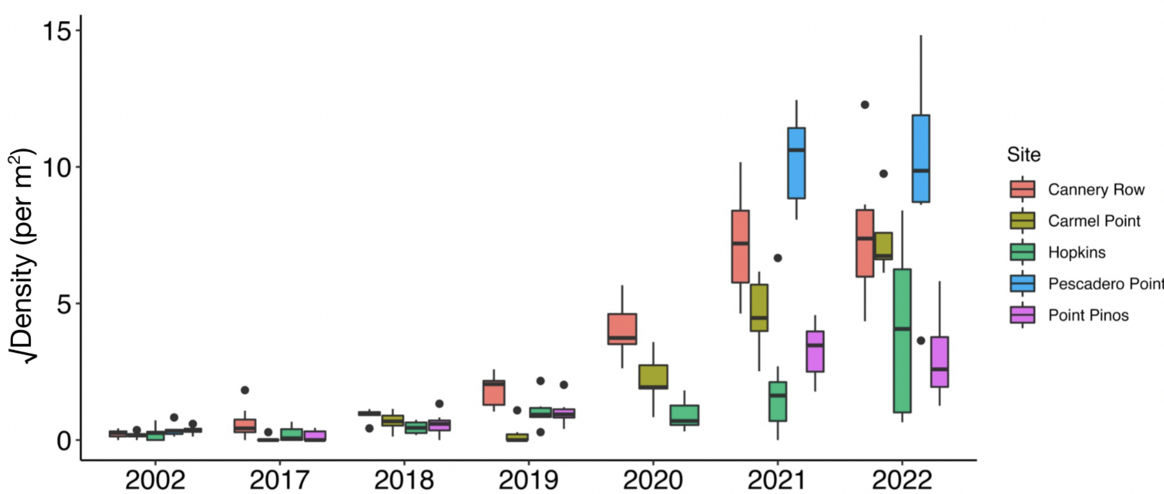

Figure 2. This figure shows urchin population increases over time across the Monterey Peninsula. Data from 2002 were collected by PI Haupt and others in the Micheli lab at Hopkins Marine Station. Data from 2017 to 2020 were collected by PI Haupt's Projects in Marine Ecology capstone class.

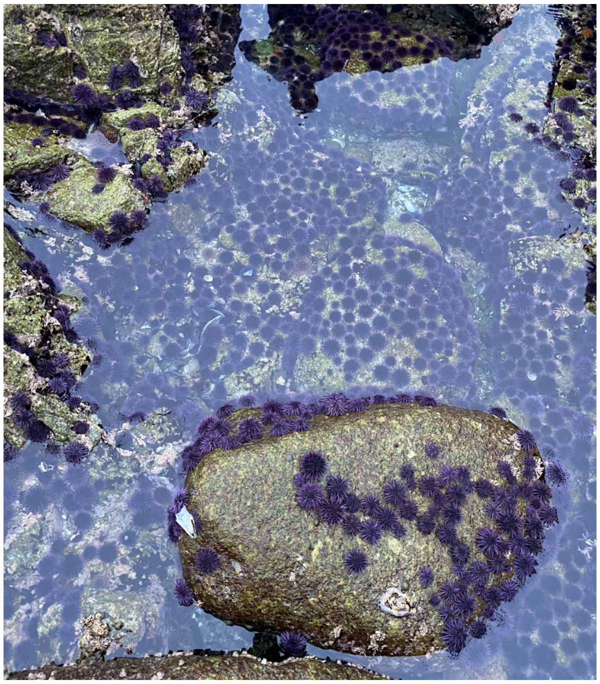

Figure 3. Example of a high density urchin site at Pescadero Point in Pebble Beach. When this site was surveyed in 2002, there were an average of 10 urchins per 30x2m transect.

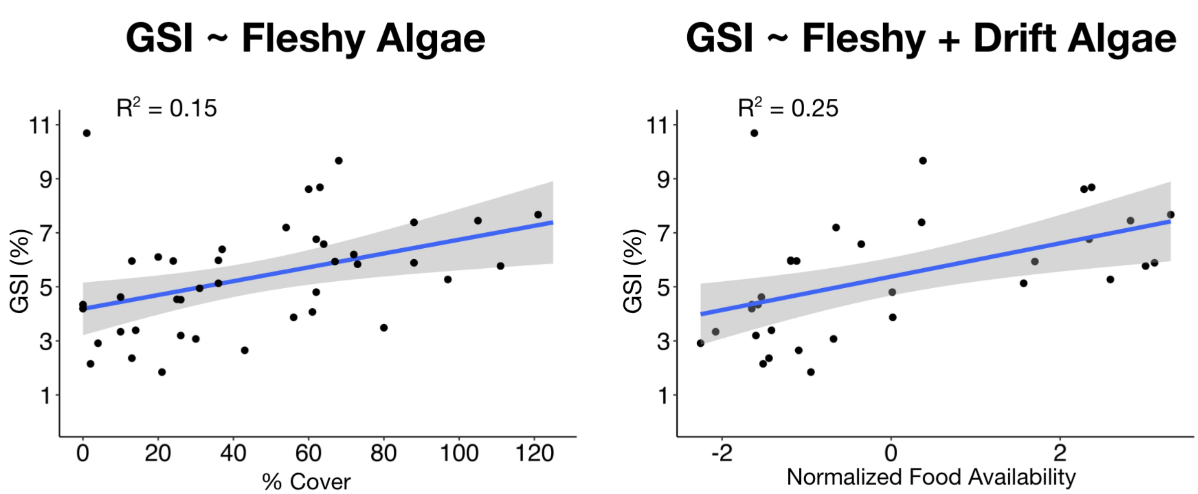

Figure 4. Data collected as part of Isaak Haberman's masters project. The panel on the left shows the relationship percent cover of fleshy algae in a quadrat and the average GSI of five urchins collected in that quadrat. The panel on the right integrates data on biomass of drift algae at each site and shows a stronger relationship between food availability and reproductive capacity when we include drift algae.

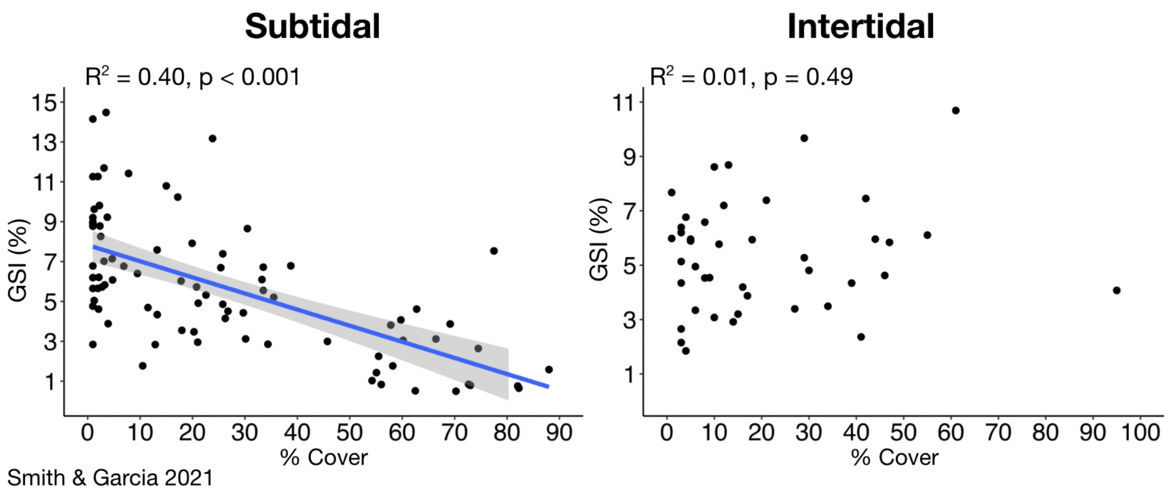

Figure 5. Data collected as part of Isaak Haberman's masters project. These two figures show the relationship percent cover of coralline algae in a quadrat and the average GSI of five urchins collected in that quadrat. The panel on the right is a re-analysis of subtidal data collected by Josh Smith at UCSC (Smith and Garcia 2021). We see a clear negative correlation between percent cover of coralline algae and urchin GSI in the subtidal but no correlation in the intertidal.

Table 1. Comparison of drivers of urchin reproduction in the subtidal vs intertidal.

	Subtidal		Intertidal	
GSI ~ Predictors	Relationship	R^2	Relationship	R^2
Fleshy Algae	+	0.36	+	0.15
Coralline Algae	—	0.40	None	0.01

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COVID impacts the project

This project was significantly delayed due to covid impacts on research which resulted in not completing Objective 2. We plan to continue working on this objective beyond the timeline of this grant. At CSU Monterey Bay set up and start of the grant was delayed. Due to a hiring freeze in 2020, we were unable to hire Daniel Pureco as a research technician until January 2021 and he wasn't able to move and start until March 2021. CSUMB's required return to research plans were not approved until April 2021. Because of this the start of the project was delayed. Additionally PI Haupt was on partial maternity leave through June 2021.

Disproportionate impacts of covid in science

In addition to COVID impacts on research, like many women in science, PI Haupt has felt the disproportionate impacts of COVID on mothers in science. Early in the pandemic there were many anecdotal reports of decreasing paper and grant submissions by female scientists and these observations were eventually borne out by data. One paper found that women had a 5% decrease in research productivity, having at least one child under 5 resulted in a 17% reduction, and having more than one child further reduced productivity by 3% (Myers et al. 2020). Another study in Italy found that article submissions by men stayed steady (or slightly increased) from 2017 – 2020 whereas submissions from female researchers were steady from 2017 – 2019 and dipped in 2020 (Inno et al. 2020). A more recent analysis published in Nature found that while many impacts of covid on research had rebounded there are long-lasting impacts on female faculty and parents of young children (Gao et al. 2021). An NSF program officer recently relayed that grant submissions had been moving close to gender parity, but recently had been moving backwards for the first time in decades (Daniel Thornhill *pers comm)*.

Introduction

Foundational species create complex habitats and support marine ecosystems, which make them an important target for restoration and recovery. However, effective restoration and recovery is challenging and requires an understanding of the direct and indirect effect of environmental changes on foundation species. Kelp ecosystems have undergone historic shifts and changes globally (Krumhansl et al. 2016; Steneck et al 2014). Currently kelp ecosystems face unprecedented loss in the face of increasing temperatures and rising urchin populations (Rogers-Bennett and Catton 2019). Changes in sea urchin behavior plays an important role in shifting kelp forests to urchin barrens through alternation of stable states (Steneck et al. 2002; Hart and Scheibling 1998).

For restoration efforts to be effective and to prioritize spatial areas most likely to be successful, managers and policy makers need complete information especially about herbivores like urchins that can precipitate large scale changes in kelp abundance. Sea urchins in urchin barrens devoid of food for them often have highly reduced gonadosomatic index (GSI) and virtually no gonads (Eurich et al. 2014). How urchin populations reproductively sustain themselves when there is so little biological effort put towards reproduction is not well understood. Increases in urchins have been well documented in the subtidal, and we have also seen corresponding increases in intertidal urchins adjacent to barren subtidal areas (Haupt unpublished data). Though reproductive capacity of urchins within urchin barrens is fairly well understood, reproductive capacity of intertidal areas adjacent to urchin barrens has not been well studied and intertidal areas may serve as reproductive refugia for subtidal urchin barrens.

Effective restoration and recovery of kelp requires spatial prioritization of areas that are most likely to be successful. Sea urchins have a larval duration of around five weeks (Strathman 1978) and are thought to have relatively open populations though there is some evidence of local adaptation along the west coast (Pespeni 2012). Identifying potential areas that act as sinks for recruitment and better understanding temporal patterns in recruitment can improve decision making about where to prioritize restoration efforts. Past work has found temporal and spatial patterns in urchin settlement across the west coast (Ebert et al 1994). There is some indication that wave exposure may play a role in urchin recruitment by forcing urchin larvae into competency (Ferner et al. 2019; Gaylord et al. 2013), but whether or not this leads to an increase in recruitment in more wave exposed areas is not well understood. Mere presence of an urchin barren may not be an indicator of high urchin settlement: past work found lower in recruitment inside than outside kelp forests but concluded this was likely due to post settlement mortality differences rather than differences in recruitment (Schroeter et al. 1996). Further emphasizing the need to understand where high levels of urchin recruitment might hinder restoration efforts.

For this study, we identified three objectives that will help inform management decisions about kelp recovery and restoration:

- **Objective 1: Assess reproductive capacity of intertidal sea urchins as a reproductive refuge for urchin barrens.**
- **Objective 2: Identify spatial and temporal patterns in recruitment of sea urchins**

Summary of methods

This project supported involvement by many undergraduate, post graduate, and graduate students. Many who presented at a conference and many not included in the table who were provided entry-level research experiences. Many of the students who participated in the program are now heading to graduate school programs in Fall 2023 (Table 1).

Table 1. List of student participants in the research funded by this grant. This does not include many undergraduates who participated in entry-level research experiences sorting recruitment samples or helping out in the field.

Student	**Status**	**Project**	**Directly funded**	**Other leveraged funding**	**Fall 2023 Status**
Alicia Del Toro	Undergraduate /Post-bac	Abalone density	Yes	CSUMB UROC	CSUMB grad student
Cristian Martinez	Undergraduate	Spatial patterns of urchin reproduction	Yes (SURE)	CSUMB UROC	MLML grad student
Daniel Lopez	Undergraduate	Project assistant	No		UM Boston grad student
Daniel Pureco	Technician	Urchin recruitment	Yes		Aquarist for Aquarium of the Bay
Emily Chui	Post-bac	Project assistant	Yes		CSUMB staff

Emily Vidusic	Undergraduate	Sampling method comparison	Yes	CSUMB UROC	OSU lab tech
Isaak Haberman	M.S. student	Drivers urchin reproduction	Yes	CSU COAST	MLML grad student
Jonah Grier	Undergraduate	Patterns of sea star recovery	No	NSF REU	MLML grad student
Josie Wrinkle	Undergraduate	project assistant	No	CSUMB UROC	Current CSUMB ugrad
Josue Ortiz	Community College	Patterns of urchin biomass	Yes	CSUMB/MPC iCARE	Current MPC student
Leta Dawson	Undergraduate	Abalone size structure	No	NSF LSAMP	CSUN grad student
Lilah Wise	Undergraduate	Urchin recruitment	Yes	NSF LSAMP	Current CSUMB ugrad
Lizbeth Amador	Post-bac	Drivers of urchin spatial variation	No	NSF GeoBridge	U Maine PhD student
Mariana Jimenez	Undergraduate	Project assistant	No	Anthropocene program	Current CSUMB ugrad
Megan Staton	Undergraduate	Project assistant	No	CSUMB UROC	Current CSUMB ugrad
Otto Martinez	Post-bac	Storm impacts on intertidal communities	No	NSF GeoBridge	Current NSF GeoBridge
Paige Siegel	Undergraduate	Drivers of sea star recovery	Yes	CSUMB UROC	Eastern Carolina grad student
Randi Barton	Graduate Student	Project assistant	Yes	CSU COAST/NSF	MLML grad student
Sofia Gluskin	Undergraduate	Fine-scale spatial patterns of urchin reproduction	No	NOAA Hollings Scholar	USF student
Zachary Vaydar	Undergraduate	Project assistant	No	CSUMB UROC	Current CSUMB ugrad

Objective 1: Assess reproductive capacity of intertidal sea urchins as a reproductive refuge for urchin barrens.

Field Methods: During Summer 2021 and 2022, we surveyed intertidal populations at nine sites along the Monterey Peninsula (Figure 1). At each site we conducted 6-8 20m x 2m transects. Along each transect we counted all sea urchins, sea stars, and abalone. We placed 5 1m^2 strung quadrats even spaced along the transect to measure 1) percent cover of algae by functional group, 2) percent cover of sessile invertebrates, 3) percent cover of habitat substrate,

4) measure (1 cm bins) and count all sea urchins. We also used a 10m long piece of chain to assess rugosity at each site.

To further assess food availability, at select sites we conducted drone surveys to assess lower intertidal algal abundance. Seasonally, we also counted and weighed all drift algae at each site across a 20x20m quadrat.

To examine community-level changes before and after the rise of intertidal sea urchins, we used MARINe photoquadrat data.

<u>GSI Methods:</u> As part of Isaak Haberman's M.S. thesis project and Cristian Martinez' CASG SURE project, we collected urchins at each site seasonally. At each site we randomly laid out 5 $1m^2$ strung quadrats in urchin habitat and collected data in the same manner above. Then we collected five urchins from this quadrat (25 urchins total per site across 5 quadrats). Urchins were brought to the lab where they were weighed and dissected. Urchins were dissected by cutting the tests and gonad tissue was separated (Figure 2). Students let gonad tissue dry on paper for five minutes and then weighed gonad tissue separately. GSI was calculated by dividing gonad weight/urchin weight * 100. As part of Sofia Gluskin's NOAA Hollings Scholar project we took a closer look at spatial variation across one site, we sampled 17 quadrats at Hopkins Marine Station and collected 85 urchins using the same sampling methods above and same lab processing methods

<u>Analyses:</u> To look for changes in urchin density over space and time, we ran an ANOVA and a Kruskal-Wallace test. To examine drivers of spatial patterns of urchin density we used a structural equation model approach (Figure 3). We used a multivariate approach to look at impacts of increases in urchin herbivory on intertidal communities.

To examine drivers of intertidal urchin reproductive capacity we used a series of linear regressions. Took look for variation across space and time we used an ANOVA and we visualized GSI patterns across small spatial scales using ArcGIS.

Objective 2: Identify spatial and temporal patterns in recruitment of sea urchins

<u>Methods:</u> We have monitored weekly or bi-weekly urchin recruitment levels using the scrub brush technique with mooring lines hung off of piers in the Monterey Harbor and Stillwater Cove. Mooring lines were hung from existing piers with a mushroom anchor attached that rested on the seafloor. Two lines were hung from each pier and four scrub brushes were attached to each line for a total of 8 scrub brushes per site (Figure 4). Scrub brushes were swapped every two weeks and placed in zip lock bags. Brushes were then taken to Hopkins Marine Station and individually placed in a sonicator with seawater for five minutes. Samples were processed at Hopkins Marine Station so we could use flow through sea water since we do not have access to sea water at CSUMB. After sonication, scrub brushes are sprayed with a sea water hose and then removed from the sonicator. All sea water in the sonicator is sieved through a 250 micron sieve to collect potential urchin recruits. Samples were stored in 70% EtOH and sorted under a dissection scope and urchin recruits.

<u>Future Methods:</u> As stated above Objective 2 has not been completed. PI Haupt has a graduate student (Audrey Sarin) starting in the fall 2023 who will take the lead on the subtidal urchin recruitment project. The Haupt lab currently has permits to do urchin recruitment work at Tankers Reef, Hopkins Marine Station, Lovers Point, and Point Pinos. Audrey will lead a project

to establish recruitment collection at these four sites to assess levels of recruitment and also impact of wave exposure on urchin recruitment. Audrey is funded through an NSF Graduate Research Fellowship and will be able to work on this project after funding through CASG is over. Recruitment collectors will be deployed on subsurface buoys anchored to cinder blocks. Brushes will be swapped every other week and processed same as above.

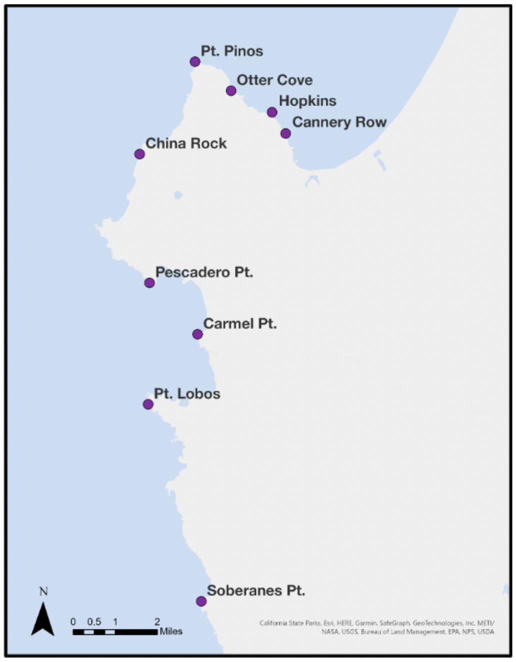

Figure 1. Sampling sites across the Monterey Peninsula

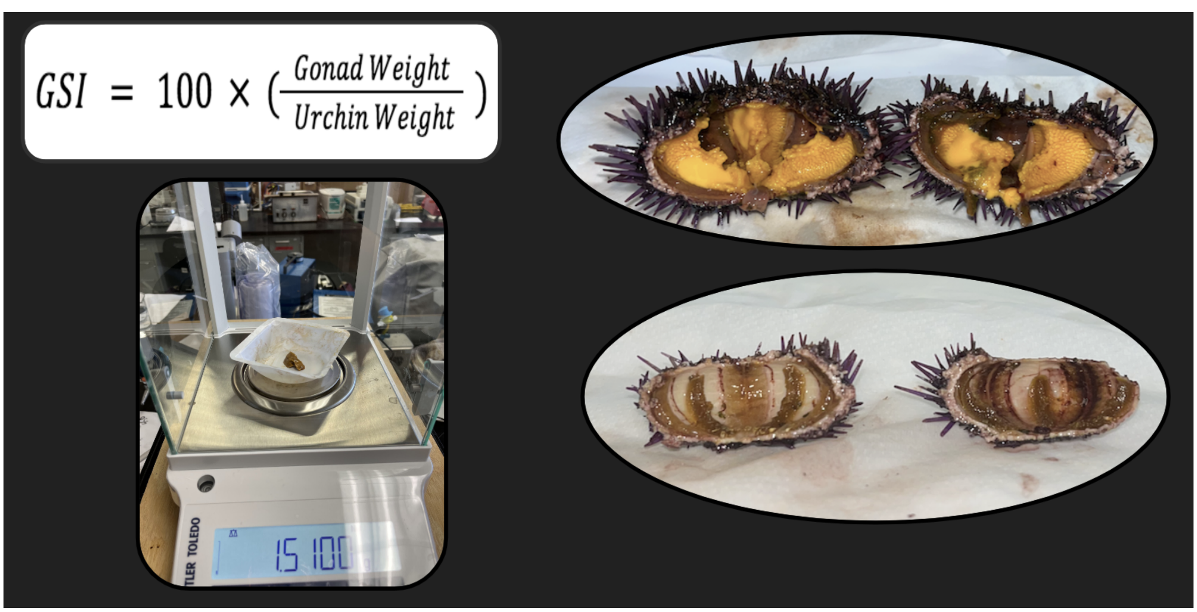

Figure 2. Urchin GSI sampling. Example (top) of a high GSI urchin and (bottom) a low GSI urchin.

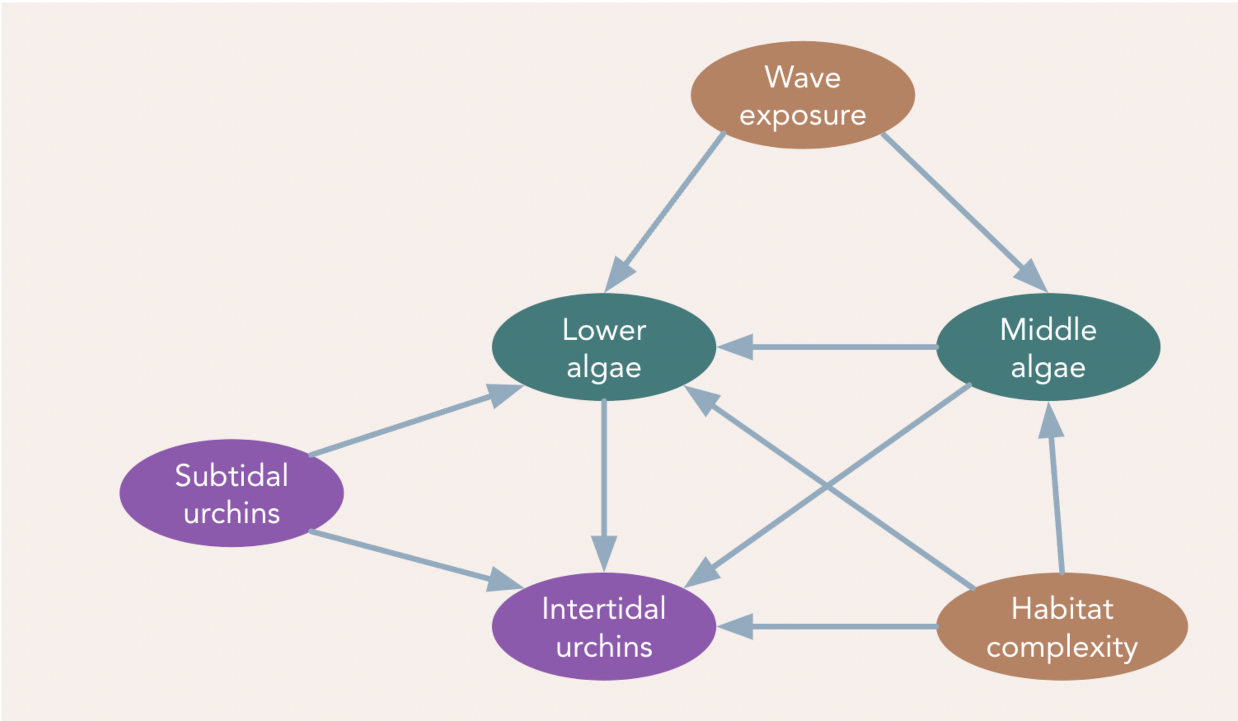

Figure 3. Structural Equation Model (SEM) framework to determine drivers of spatial distribution of urchins. This SEM model combines the following linear models 1) Middle algae ~ wave exposure + habitat complexity, 2) Lower algae ~ wave exposure + habitat complexity + subtidal urchins + middle algae, and 3) Intertidal urchins ~ subtidal urchins + lower algae + middle algae + habitat complexity

Figure 4. Schematic of urchin recruitment sampling. Lines are hung off of piers (left) with four scrub brushes attached. After processing with a sonicator, samples are sieved into a vial (middle). Samples are then sorted under a dissecting microscope (right).

Data summaries, analyses, figures, tables, and interpretation

Urchin population patterns

Urchin population patterns: Urchin populations have increased dramatically since 2002 with the increase beginning around 2019 or 2020 - much later than the increase in subtidal systems (Figure 5). Intertidal urchin densities are high yet variable across sites (Figure 6). Liz Amador, funded through the NSF GeoBridge program, used an SEM approach to examine potential drivers of urchin densities. Neither intertidal algae had a significant relationship with intertidal urchin abundance, where habitat complexity seems to be a strong driver of intertidal urchin density in this mode (Figure 7)l. Overall characteristics other than the main food source may be driving intertidal urchins densities across the sites. Liz presented this work as a poster at WSN in 2022 and a talk at the Benthic Ecology Meeting in 2023.

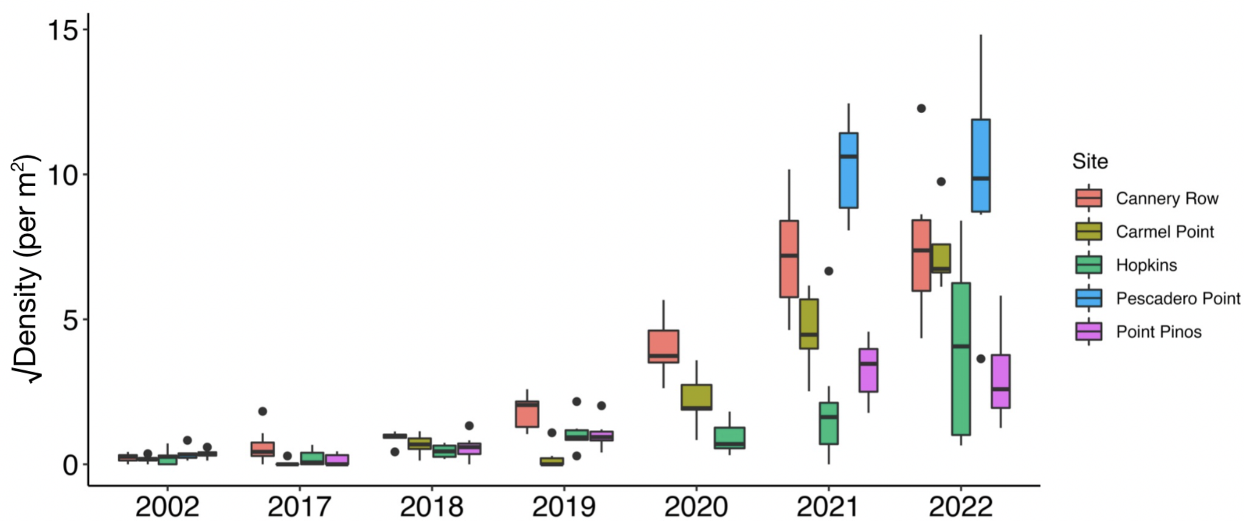

Figure 5. This figure shows urchin population increases over time across the Monterey Peninsula. Data from 2002 were collected by PI Haupt and others in the Micheli lab at Hopkins Marine Station. Data from 2017 to 2020 were collected by PI Haupt's Projects in Marine Ecology capstone class. There is a dramatic trend of increasing density over time that occurs a few years after the rise in subtidal urchins, which began in 2015. Two way crossed ANOVA (site*year) significant $p < 0.0001$.

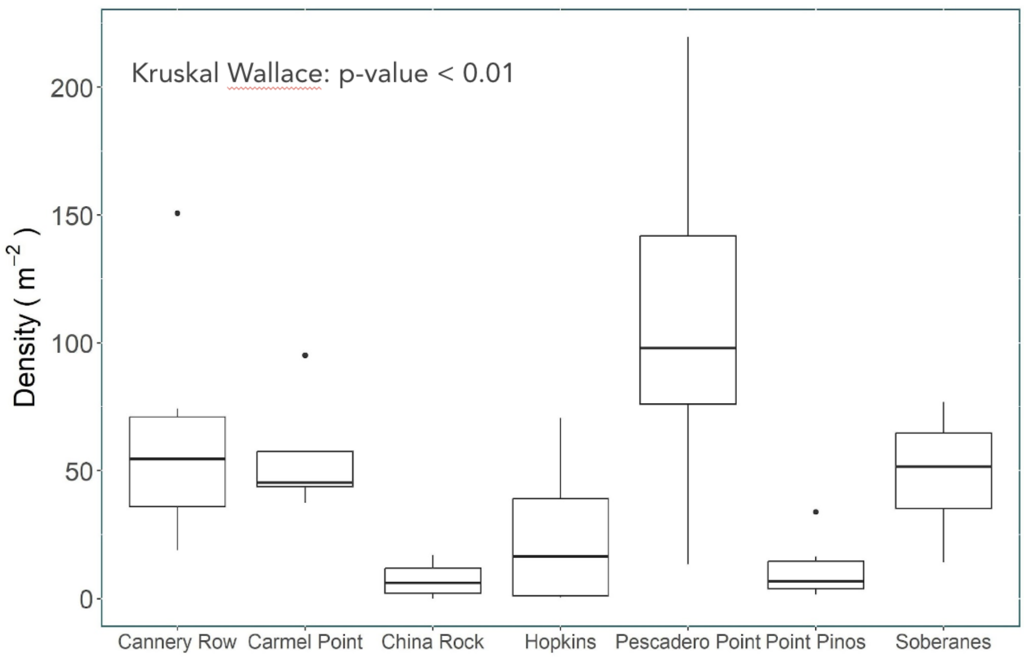

Figure 6. Density of urchins across sites in Summer 2022. All sites have high densities of urchins (at least an order of magnitude higher than data form 2002) but there is significant spatial variation across sites (KW $p < 0.01$).

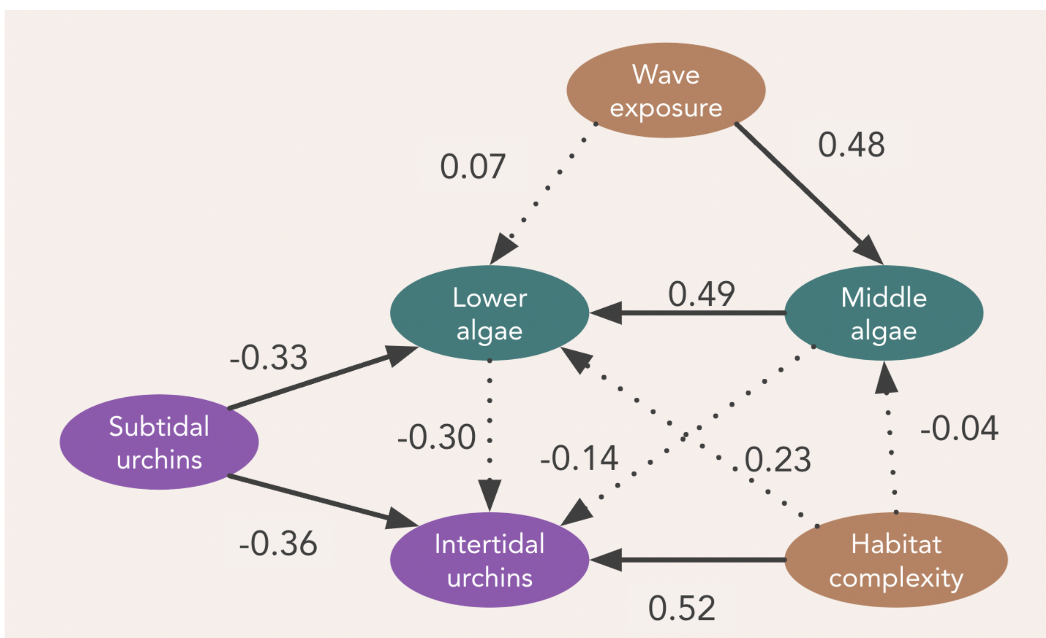

Figure 7. SEM results. Dashed lines refer to insignificant relationships and solid lines refer to significant correlations. Numbers indicate the strength and direction (positive or negative) of the relationships. We see a surprising negative correlation between subtidal urchins and intertidal urchins. Habitat complexity has a strong positive correlation with intertidal urchin density which suggests high rugosity sites may have higher urchin densities. Surprisingly we do not see a relationship with intertidal algal abundance.

CSUMB student Emily Vidusic conducted a comparison of quadrat and transect methods to measure urchin densities. She found that at the aggregate level when comparing all transects and all quadrats there were not significant differences in density estimates (Figure 8 and 9; ANOVA p-value = 0.126). However when comparing transect density estimates to the density estimates from the quadrats done on the same quadrat there were significant differences (Figure 10; Paired t test: t = 3.9018, p-value = 0.0004). Further analysis using a poisson mixed effects model by Emily found that density estimates from quadrats were 1.4 times higher than transects (95% CI 1.39 - 1.44). Long-term monitoring often requires combining data sets using different methods and this analysis will be useful to create best methods for looking at population changes over time using different sampling methods. Emily preesnted this work as a poster at WSN in 2021 (and won best undergraduate poster), a talk at WSN in 2022, a talk at the Benthic Ecology meeting in 2023, and a talk for her Honors capstone project at CSUMB.

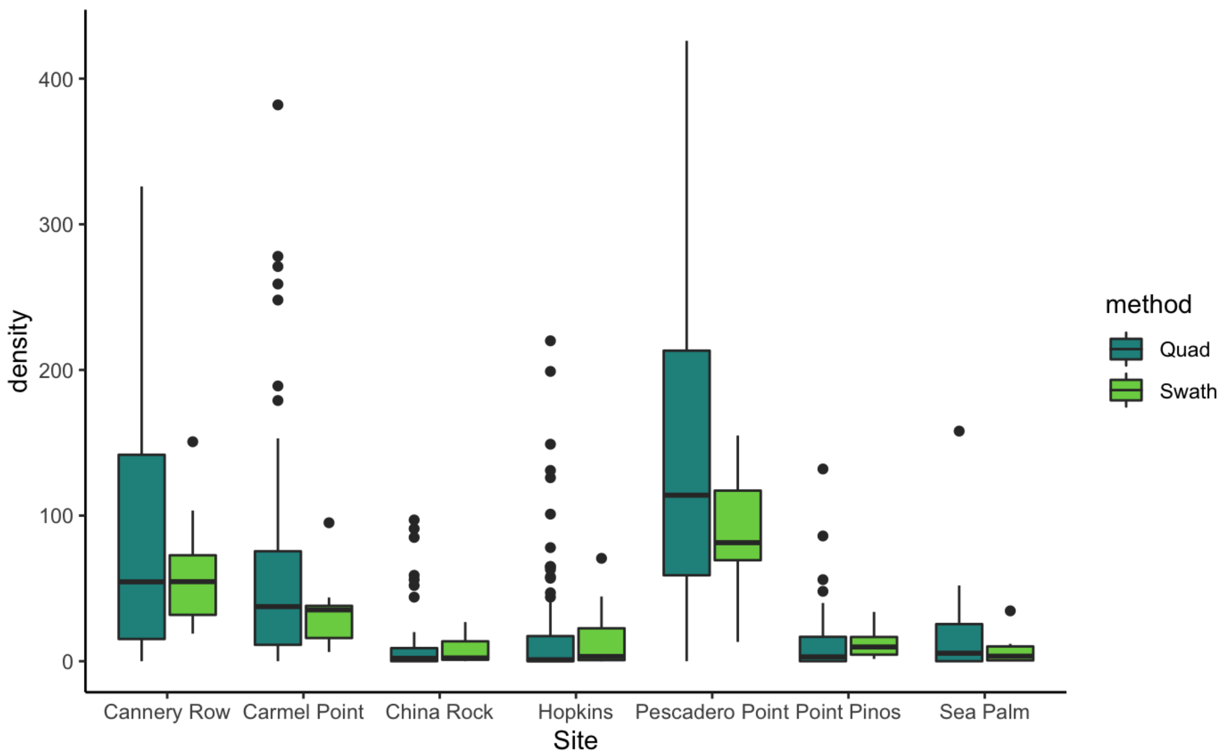

Figure 8. Figure 1. A comparison of urchin density boxplots calculated across seven sites in the Monterey peninsula. Teal boxplots represent quadrat data and green boxplots represent swath data. Differences by method not significant (ANOVA: F-value = 28.230, p-value = 0.126)

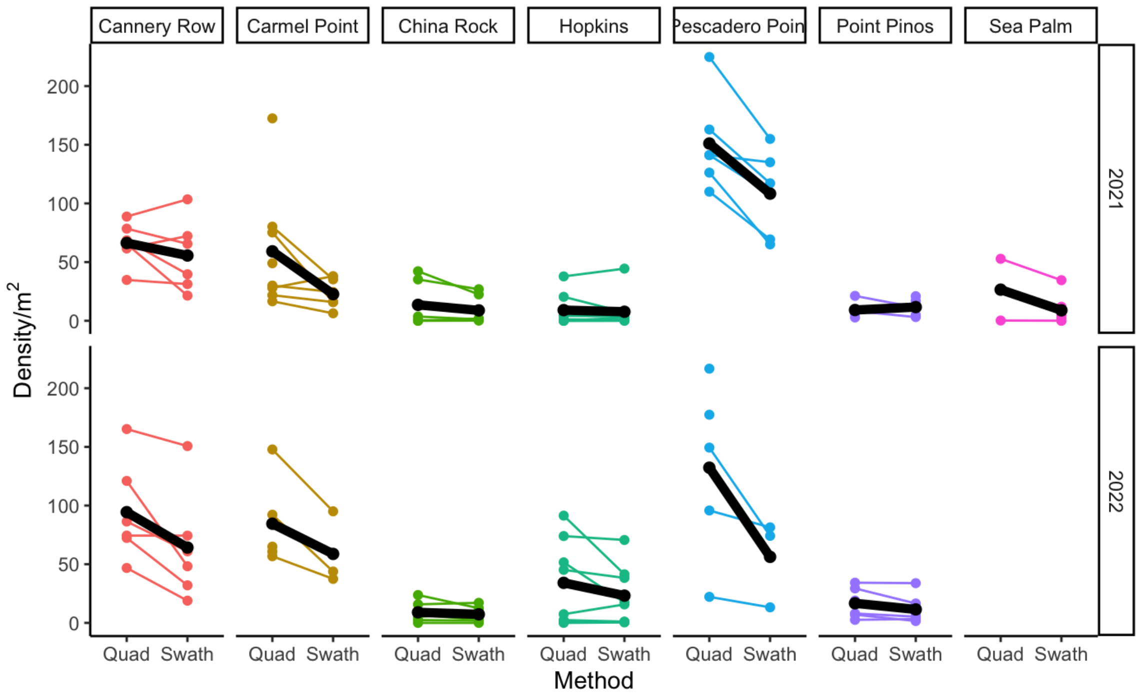

Figure 9. Comparison of density estimates for purple urchins at each site and for each year. Quad represents urchin densities estimated from $1m^2$ quadrats and swath are density estimates from $40m^2$ transects.

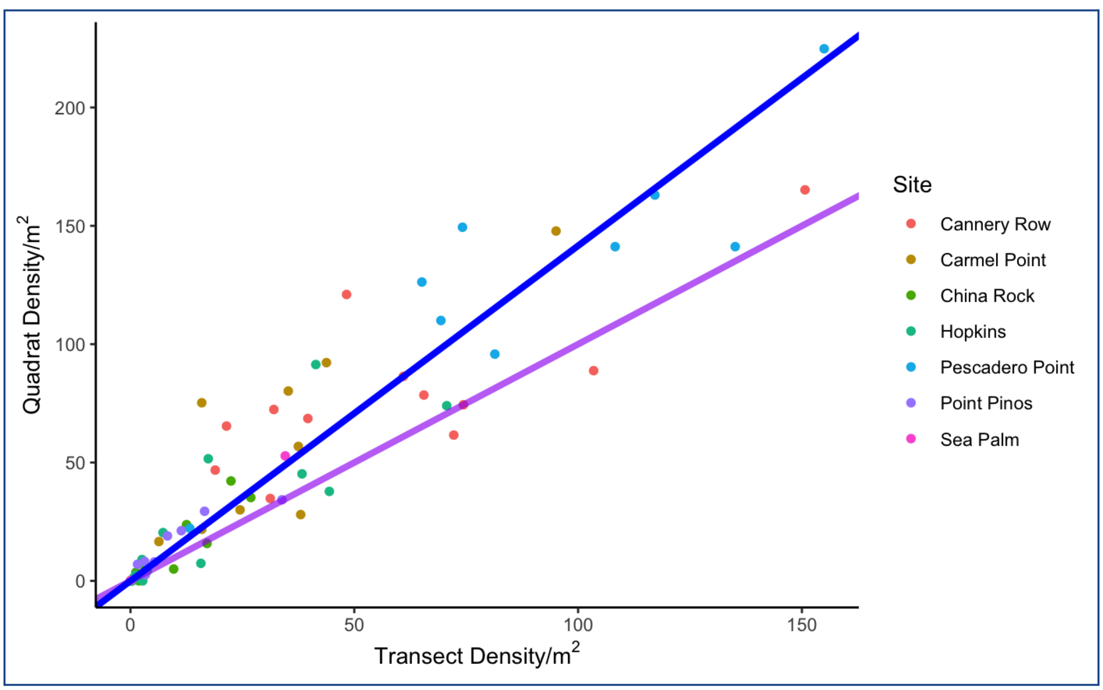

Figure 10. Each point is the density/m² from the transect and the average of the 5 quadrats from the same transect. The purple line represents the 1:1 ratio of urchin densities between transect and quadrat. Quadrat and transect density estimates are significantly different (Paired t test: t = 3.9018, p-value = 0.0004)

Urchin reproduction patterns:
We found high levels of spatial and temporal variability in urchin GSI (Figure 11 & 12). As found with previous studies GSI was highest at all sites in the fall and lowest in the winter. Cristian Martinez (funded through the CASG SURE program) focused on spatial patterns of urchin GSI for his honors capstone honors project. There were high levels of variation across sites and some sites, like Point Pinos were, one of the lowest GSI site in the summer but then the highest in the fall (Figure 12 & 13). Point Pinos appeared to be an outlier in this sense and could be due to high levels of fleshy algae at this site and potential lack of drift algae may make the urchins more reliant on local levels of food. Cristian presented this work as a poster at WSN in 2022, a talk at the Benthic Ecology Meeting in 2023, and as his Honors Capstone presentation at CSUMB. Sofia Gluskin (a NOAA Hollings Scholar) also examined spatial variation of sea urchin GSI at a small spatial scale. Sofia found high levels of variation across the small scale of one site - Hopkins Marine Station (Figure 14).

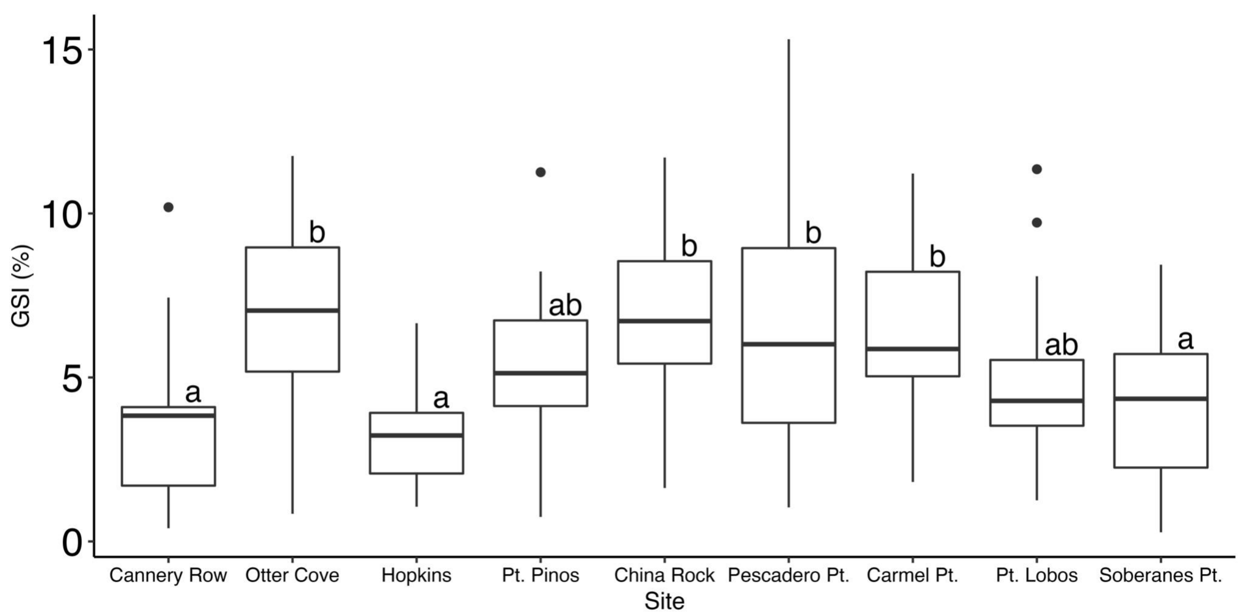

Figure 11. GSI of urchins during summer 2022 across the Monterey Peninsula.

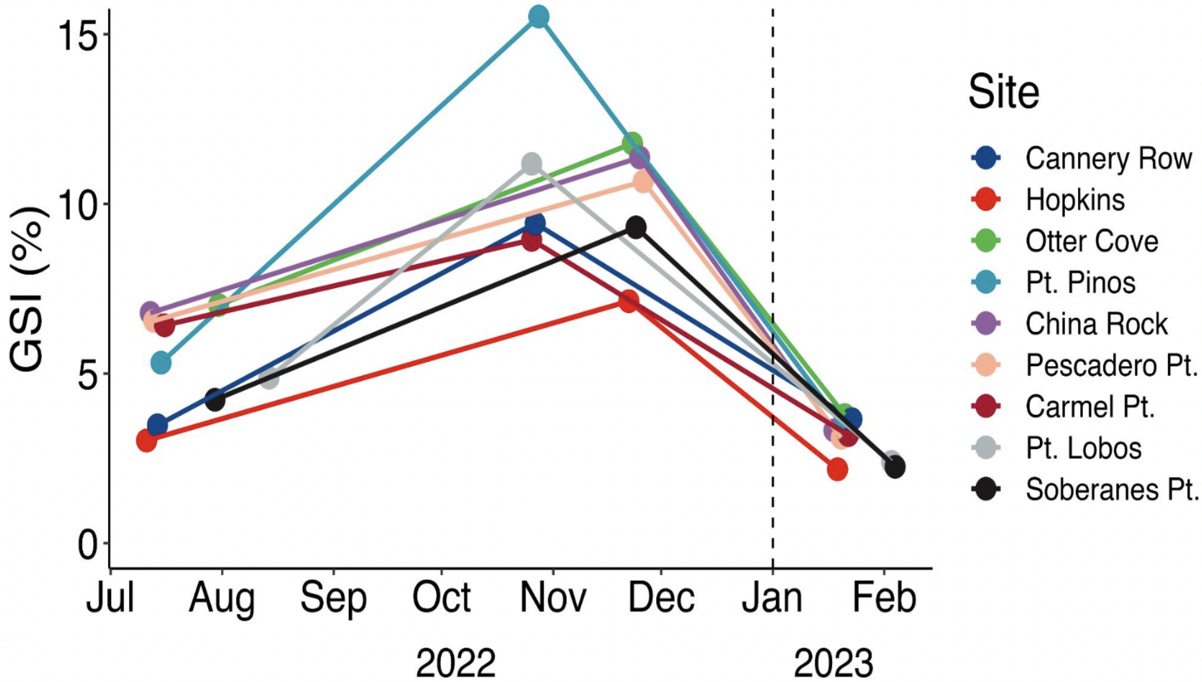

Figure 12. Average GSI of each site (n = 25) across Summer, Fall, and Winter.

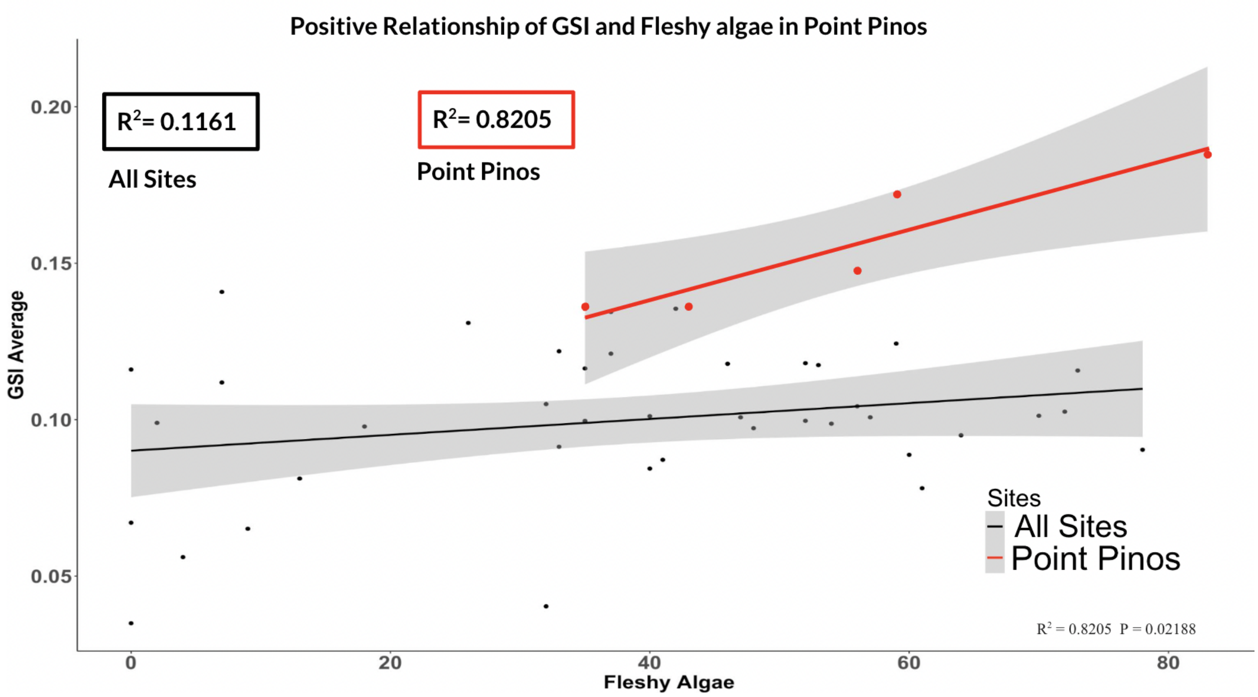

Figure 13. Relationship of urchin GSI and fleshy algae at all sites. The ride trendline indicates the relationship at Pt Pinos only where we see a much stronger relationship between algae and GSI (R^2 = 0.82) compared to all other sites (R^2 = 0.11)

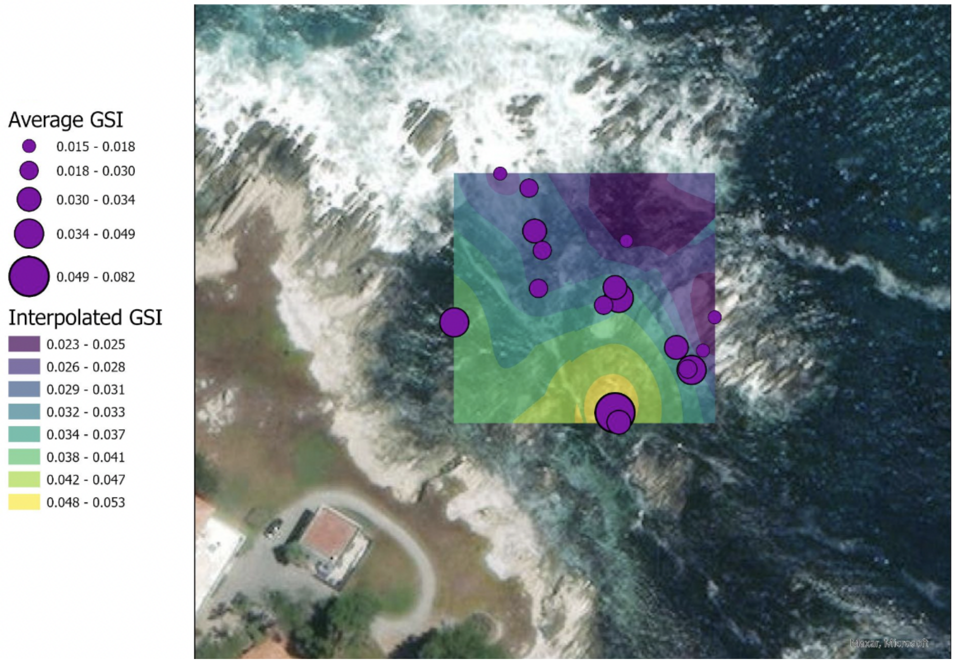

Figure 13. GSI of urchins from one time point in summer 2022 at Hopkins Marine Station. We surveyed 85 urchins across one site and found high levels of variation across a small spatial scale.

As part of his M.S. thesis project, Isaak focused on drivers of intertidal sea urchin GSI and how they might be different than subtidal drivers. We compared our data to GSI data collected by Josh Smith at UCSC and found that drivers of urchin reproduction in the intertidal were found to be different than drivers in the subtidal (Table 2). We found that intertidal urchin reproductive capacity is not only driven by the algae growing in the intertidal, but likely also drift algae that is washing onto the intertidal from subtidal kelp forests and other areas (Figure 15). Even in areas of high urchin density, low fleshy algae growth, and high coralline algae cover, intertidal urchins show relatively high reproductive capacities, indicating that they must be getting food from an outside source: likely drift algae (Figure 16). This indicates that intertidal urchin populations represent a high reproductive output for purple urchin populations, and they must be monitored as a potential source population for urchin barren urchins.

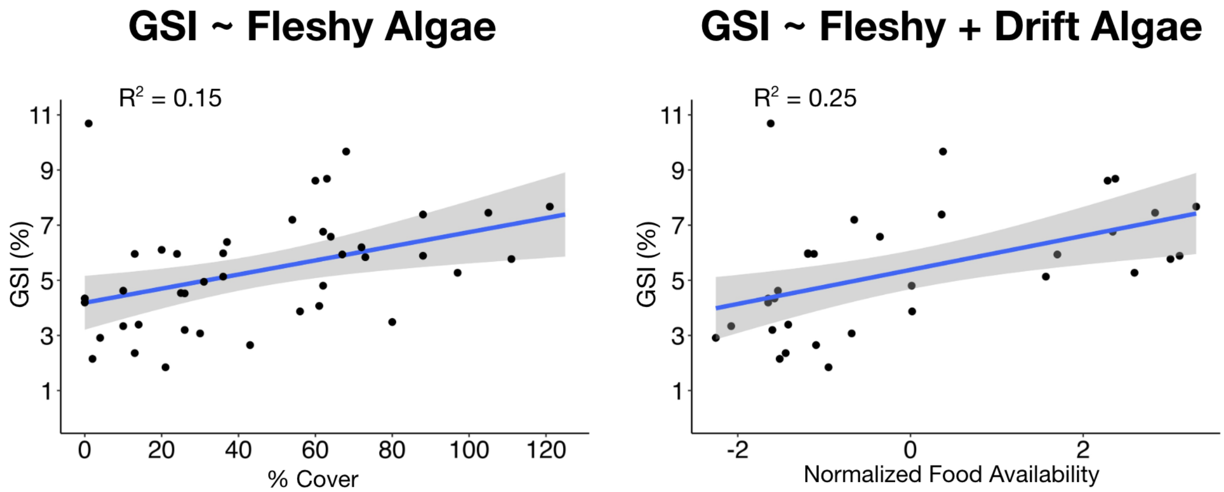

Figure 14. Data collected as part of Isaak Haberman's masters project. The panel on the left shows the relationship percent cover of fleshy algae in a quadrat and the average GSI of five urchins collected in that quadrat. The panel on the right integrates data on biomass of drift algae at each site and shows a stronger relationship between food availability and reproductive capacity when we include drift algae.

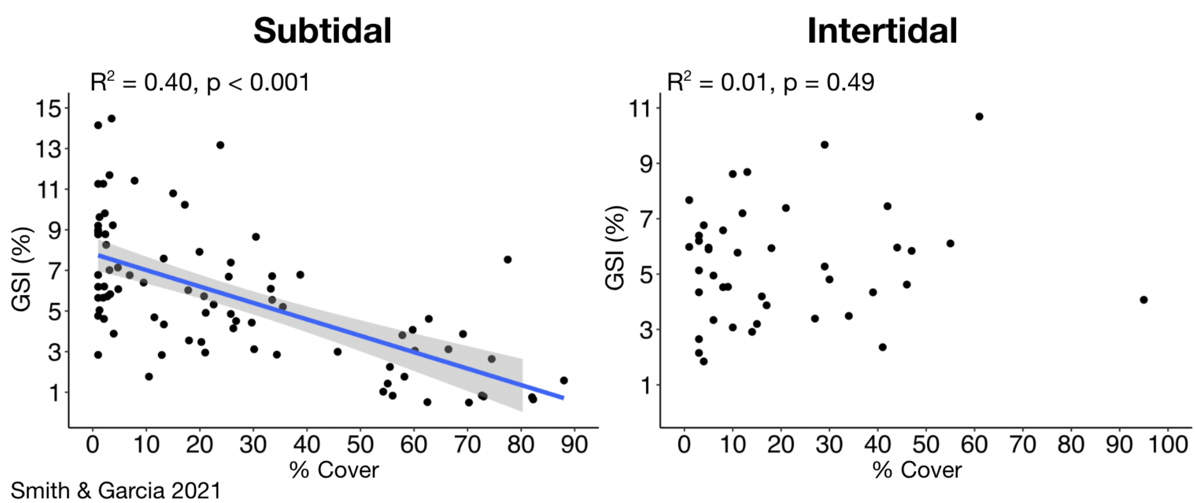

Figure 15. Data collected as part of Isaak Haberman's masters project. These two figures show the relationship percent cover of coralline algae in a quadrat and the average GSI of five urchins collected in that quadrat. The panel on the right is a re-analysis of subtidal data collected by Josh Smith at UCSC (Smith and Garcia 2021). We see a clear negative correlation between percent cover of coralline algae and urchin GSI in the subtidal but no correlation in the intertidal.

Table 2. Comparison of drivers of urchin reproduction in the subtidal vs intertidal.

	Subtidal		Intertidal	
GSI ~ Predictors	Relationship	R^2	Relationship	R^2
Fleshy Algae	+	0.36	+	0.15
Coralline Algae	—	0.40	None	0.01

Intertidal communities:
We found that intertidal communities were largely resilient to large increases in urchin populations (and likely urchin herbivory; Figure 16). This is in contrast to subtidal systems that see extreme shifts in algal communities.

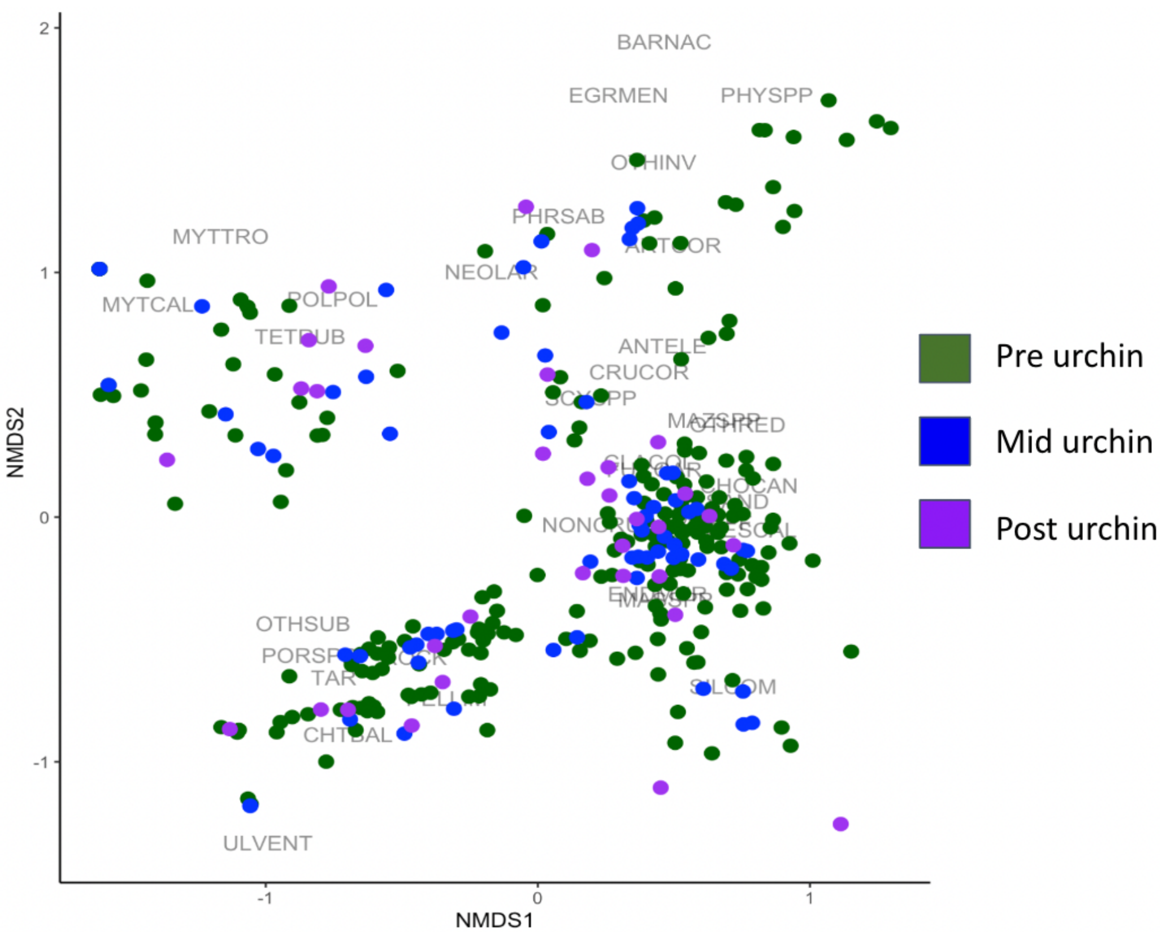

Figure 16. nMDS plot of MARINe photoquadrat data. Colors indicate if the time sampled was pre urchin increase (green), during the urchin increase (blue), or post urchin increase (purple) in the intertidal. We do not see any clear differentiation of intertidal sessile communities between

these different time points suggesting that the intertidal community pre and post urchin increase are not very different despite a drastic increase in urchin densities.

Objective 2 Urchin recruitment: This objective of the study was most impacted by covid delays on field work and research. The Haupt lab is continuing to monitor urchin recruitment at Stillwater Cove and the Monterey Harbor. Because of these delays due to covid, we will continue to work on this objective beyond the timeline of this grant. Haupt lab has a graduate student starting in Fall 2024 with funding from another source who will be able to take the lead on expanding this study to complete this full objective. This objective provided the basis for countless entry-level undergraduate research experiences at CSUMB.

Recommendations for restoration efforts

Many kelp restoration efforts are reasonably focused on subtidal kelp forests or urchin barrens. Many of these efforts emphasize reducing urchin herbivory on kelp plants. These efforts including Tankers Reef in Monterey Bay and Noyo Bay and Albion Cove in Mendocino County have been successful at mitigating impacts of urchins on small areas. However, many restoration efforts ignore the intertidal as a potential source of herbivory or sea urchin reproduction. Studies have shown that urchins inside of subtidal urchin barrens have very low GSI and thus low levels of reproduction. However, in the intertidal even at very high densities or when food availability is very low, urchin GSI can be very high and comparable to GSI inside a kelp forest. We recommend that kelp restoration efforts include intertidal sea urchin populations in restoration and management plans. Especially those that focus on reducing urchin reproduction or herbivory.

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