Accelerating North Coast Kelp Recovery

Year 2 Report
OPC Project: R/HCEOPC-45

Suggested Citation:

McHugh, T.A., Grime B., Bugbee, B., Karm, R., Downie G., Hamilton, S., Hughes B., Leuschel, M., Iselin, J., Bauer-Civiello, A., Freiwald J., Springborn M., Smith, J. Accelerating North Coast Kelp Recovery. The Nature Conservancy, Mendocino, CA. February 2026.

The Nature Conservancy

Acknowledgements:

The Accelerating North Coast Kelp Recovery Project was made possible through the dedication of many individuals and organizations.

We thank the commercial sea urchin divers—*Patrick Downie*, *Tom Trumper*, *Thomas John Trumper*, *Adam Bremer*, *Marcos Aban*, *Bernie Sauls*, *Jamie Wilson*, *Robert Smith*, *Dave Rudie*, *Byron Koehler*, *Gary Trumper*, *Ken Gerkin*, and *Mickey Kitahara*—for their commitment in the field. In addition, we acknowledge the local support from folks at the Noyo Ocean Collective, City of Fort Bragg, Noyo Harbor District, and processors at Ocean Fresh, Pacific Rim, and Zephyr. We are also grateful to *David Goldenberg* and *Dave Rudie* of the California Sea Urchin Commission for their technical expertise and drive to develop a pathway to utilize urchins landed for restoration.

Our appreciation extends to Moss Landing Marine Laboratories and Sonoma State University graduate students and technicians—*Andrew Kim*, *Madi McKay*, *Laney Hall*, *Dominik Fett*, *Joel Huckeba*, *Eliana Bower*, *Brynn O'Hara*, *Shirah Strock*, *Saul Cervantes*, *Emily Hascall*, *Sabrina Grant*, *Noah Kolander*, *Jessica Franks, and Nate Spindel*—for their contributions to Objective 1, with special thanks to *Diana Steller* for diving safety support and *John Douglas* for boating safety support.

We also thank the CSU COAST interns with The Nature Conservancy, *Laney Hall*, *Joanie Hardcastle*, *Rafael Cribley and Parker Getz* as well as the Reef Check interns and volunteers—*Cassidy Daniels*, *Kyla Marcello*, and *Kylee Michaud*—for their valuable assistance. We also thank Reef Check intern *Dylan Hutchinson* for her senior thesis work featured in Objective 2. Further, we extend gratitude to *Annie Bauer-Civiello*, *Morgan Murphy Cannella*, and *Ian Norton* at Reef Check for their subtidal and educational expertise.

We are indebted to the *KelpFest!* Steering Committee including *Marianna Leuschel* of Above/Below as committee chair, *Monique Sonoquie*, *U'ilani Wesley* and *Xa Kako Dile*, *Dav Bell* and the Mendocino Art Center, *Trey Petry* and the Noyo Center for Marine Science, *Torrey Douglass* and Word of Mouth Magazine/Lemon Fresh Design, *Jami Miller* and the Blue Economy Initiative, *Tanya Ayala* and *Jeff Totsch* of Flockworks, as well as the Mendocino Film Festival, MendoParks, Visit Mendocino, and the Community Foundation of Mendocino. A special thanks to *Josie Iselin* for her artistry in making seaweed visible through storytelling.

Our gratitude also goes to *Izzi Volonte*, *Bryan DeAngelis, and Norah Eddy* at The Nature Conservancy for their guidance in shaping this report, and to Ocean Protection Council staff *Pike Spector* and California Department of Fish and Wildlife staff *Kristen Elsmore*, *Andrew Weltz*, *Derek Stein*, and *Shelby Kawana* for their technical expertise. Finally, we thank the Ocean Protection Council and California Sea Grant for their foundational support of kelp recovery across California.

- Co PIs: Tristin Anoush McHugh, Benjamin Grime, Scott Hamilton, Grant Downie, Brent Hughes, Marianna Leuschel, Jan Freiwald, Michael Springborn, and Joshua Smith

This project report was supported in part by The Nature Conservancy under Grant Agreement Number C0874016, Project Number R/HCEOPC-45 through California Ocean Protection Council and California Sea Grant at the University of California San Diego with technical support from California Department of Fish and Wildlife. The views expressed herein do not necessarily reflect the views of any of those organizations and no official endorsement should be inferred.

Table of Contents

Executive Summary

This report provides an update on progress made during the 2024–2025 implementation year of the *Accelerating North Coast Kelp Recovery* project (OPC-HCE 45). It summarizes major activities, scientific advancements, and outcomes achieved to date, building on the detailed methodologies, program development, and technical findings documented in the Year 1 report (McHugh et al. 2025a). Support from the Accelerating Kelp Research Program (AKRP) continues to serve as a critical driver of innovation, enabling the development and refinement of restoration strategies that will inform statewide kelp recovery efforts through 2026.

This update highlights accomplishments by the primary awardee and all subawardees for California Sea Grant, the Ocean Protection Council, and California Department of Fish and Wildlife, with the intent of supporting adaptive management and contributing to the emerging *Kelp Restoration and Management Plan.* A comprehensive final report will be delivered in early 2027 and will include research findings from the 2026 field season.

Goals:

Our project advances an integrated and scalable approach to kelp restoration at a recently deforested location by:

- implementing a strategic sequence of restoration and protection techniques (grazer suppression and kelp enhancement) to stimulate kelp recovery
- investigating urchin fishery adaptation and its implications for kelp restoration and blue economy opportunities
- creating community participation methods to increase the likelihood of restoration success

Objectives:

1. Implement a strategic sequence of techniques to optimize kelp restoration success at Big River, expanding kelp ecosystem recovery to larger scales
    a. Target a reduction in sea urchin density at or below threshold of < 2 sea urchins/m2
    b. Target > 60% sea urchin transition from destructive to passive grazing and > 40% increase in bull kelp canopy following kelp enhancement

2. Investigate sea urchin fishery adaptation to effectively direct kelp restoration efforts and to evaluate blue economy opportunities in purple urchin removal
    a. Understand kelp forest and red sea urchin fishery feedbacks to guide urchin harvest for guarding remnant forests
    b. Assess historical and future capacity for red sea urchin diver adaptation in response to the collapse of the red sea urchin fishery
    c. Create a framework to assess downstream economic opportunity for various market uses of purple sea urchins

3. Ensure long-term kelp restoration success and stewardship by providing opportunities for the local community through experience and art
    a. Provide internships for local divers to build diver workforce capacity and engage previously underrepresented groups in monitoring and restoration

b. Develop a series of tangible and replicable art/science products and events to engage and communicate project goals and outcomes

Integration of OPC HCE-45 with the Pacific Coast Ocean Recovery (PCOR) Initiative

In spring 2025, The Nature Conservancy received NOAA funding to launch the Pacific Coast Ocean Restoration (PCOR) Initiative, comprising workstreams in Workforce Development, White Abalone, Sunflower Stars, and Kelp. Under PCOR, the proposed kelp restoration footprint at Big River increased from 5 to 25 acres, with additional restoration planned at a second site, Noyo Cove in Fort Bragg. Building on the partnerships, methods, and outcomes established through the AKRP award, PCOR restored 12 additional acres of kelp forest in 2025, bringing the Big River total to 17 acres by year's end. An additional 8 acres are planned for 2026. This report integrates outcomes from both the ANCKR and PCOR initiatives to represent the combined impact of these complementary investments. More information in the PCOR initiative can be found here.

Ultimately, the transformative aspects of this research are centered around refining highly scalable, robust, and climate-ready restoration techniques through a coordinated community-based approach that ensures restoration is ecologically, socially, and economically viable throughout California and beyond.

Key outcomes of the work to date (2024-2025) include:

Objective 1

- **Restoration is amplifying kelp abundance beyond natural drivers-** We detected a 921% increase (from 1,211m^2 to 12,366m^2) in kelp canopy following restoration interventions at Big River from 2023 (pre-intervention) to 2025. A non-restored control site (Van Damme) also experienced a 245% increase (from 8,105m^2 to 27,947m^2), indicating broadly favorable oceanographic conditions, yet the restoration site's canopy growth was 3.75× greater than the control, strongly suggesting restoration is accelerating recovery beyond natural drivers.
- **Sea Urchin Divers continue to participate and lead in harvest and marketing of purple sea urchins-** Commercial Sea Urchin divers harvested over 96,000 lbs of purple sea urchins (2024-2025). Additionally, 4,800 lbs of purple and red sea urchins have been commercially harvested from the site for the food market.
- **Arrays to Recover Kelp Ecosystem Vegetation (ARKEVs) continue to impress as a novel kelp outplanting strategy-** We grew kelp from the size of a pencil to reproductive adult size in 47 days. Kelps were reproductive and dropped spores for at least 3 months, which we estimate to be tens of billions of spores. Additionally, we documented nearly 4 times more juvenile rockfish associated with ARKEVs with bull kelp than control plots or blank ARKEVs (without spliced kelp). ARKEVs have been exported and tested in Oregon with success and *A Blueprint to the Array to Recover Kelp Ecosystem Vegetation (ARKEV), Version 1* was developed and available upon request (McHugh et al 2025b)

Objective 2

- **A secure data environment was created allowing receipt of confidential CDFW data-** Despite numerous delays in acquiring data, the analysis has been initiated.

- **Innovative non-food product development (led by Primitives Biodesign) has created viable and scalable uses for landed purple urchins-** Uses include pigments, leather, 3D-printing filament, and *Urchinite™ engineered stone*, which has demonstrated strong customer demand, high performance, and feasibility for commercial-scale production.

Objective 3

- **The New York Times attends *KelpFest!*-** The project was showcased in their "50 states, 50 fixes" segment- Reviving California's Kelp Forests, One Dive at a Time. October 2025.
- **Local internships strengthen long-term kelp restoration capacity-** A robust two-year community workforce and monitoring effort, trained six local interns (plus supporting four additional COAST interns at match), and expanded multi-agency restoration research. Interns gained hands-on experience (participation in Objective 1), with several earning dive certifications, presenting at scientific conferences, and developing independent research projects.
- **Kelp community is growing and supporting sustained restoration success-** Engagement expanded across 2024–2025 through the growing success of *KelpFest!* and the Bull Kelp Webstory. Across both years, *KelpFest!* delivered 32 events and reached 4,052 participants, supported by 17,100 unique website visitors. Steering Committee capacity increased by 40%, positioning the festival for continued growth and success in the coming year. The Mysterious World of Bull Kelp Webstory continues to evolve and deliver as a regional hub for kelp ecosystem knowledge (e.g. Big River Project , Eastern Pacific Kelp Congress) and has engaged over 40,000 active users.
- **Kelp ecosystem changes documented through visual records-** A multi-year, high-resolution archive (2020–2025) documenting seaweed and sea urchin assemblages within Big River, providing a powerful visual tool for tracking ecological change, and supplying widely used assets for scientific reporting, public communication, fundraising, art exhibits, signage, and programming.

The Nature Conservancy is excited to be collaborating with multiple private, academic, nonprofit, and community stewards to execute the work under this AKRP award. Because of these collaborations, our efforts through years 1 and 2 have been tremendously successful. We are thrilled to report on those results here and look forward to working with The Ocean Protection Council, California Sea Grant, California Department of Fish and Wildlife, and others to ensure we utilize the learning outcomes from OPC HCE-45.

Objective 1

1. Implement a strategic sequence of techniques to optimize kelp restoration success at Big River, expanding kelp ecosystem recovery to larger scales
    a. Target a reduction in sea urchin density at or below threshold of < 2 sea urchins/m^2
    b. Target > 60% sea urchin transition from destructive to passive grazing and > 40% increase in bull kelp canopy following kelp enhancement

Objective 1a

Grazer suppression: Sea urchin harvest by commercial sea urchin divers

The California Sea Urchin Commission (CSUC) led commercial sea urchin harvester (CUH) participation in kelp-restoration–driven grazer suppression at Big River in 2024–2025. The CSUC is a state recognized marketing agency for the CA sea urchin fishery and was tasked with managing the harvest of purple sea urchins from Big River and purchasing the landings from CUH. This project marked the first time North Coast divers were formally represented and coordinated through their own agency, demonstrating a scalable model for industry-led restoration. It also provided modest but meaningful economic support to a fishery experiencing prolonged disaster declarations (2016–present) with federal declaration in 2016-2017 and 2018-2019.

CUH operated under existing commercial permits, minimizing administrative burden and maximizing potential to develop a commercial purple sea urchin fishery through sea urchin harvested for restoration. Purple sea urchins were landed at three processors (Ocean Fresh, Zephyr, and Pacific Rim) using standard fee structures.

The site was mapped into 50m × 50m blocks and 25m × 25m underwater quadrants for systematic clearing. As part of OPC HCE 45, CUH completed 93 workdays (56 in 2024; 37 in 2025) and removed 59,507 lbs of purple sea urchins. Note that in Summer 2025, once OPC HCE award funds had been spent down, we transitioned to PCOR funding where an additional 73 workdays were completed and 37,238 lbs of urchin were harvested for a total of 96,745 lbs at Big River.

Strategically, CUH targeted remnant kelp along the north and east site boundaries. Clearing purple sea urchins up to 50 meters away from canopy edges led to rapid ecological improvements (Downie pers. Comm). Within weeks, understory algae and bull kelp recruits expanded across newly cleared reef. By 2025, kelp naturally re-established in blocks cleared the previous year, validating the effectiveness of initial grazer suppression. CUH then shifted effort to addressing new feedlines formed by small sea urchins. In 2024, Big River experienced unprecedented recruitment of small purple sea urchins far exceeding initial density estimates (McHugh et al 2025). Redirecting Year 1 sea urchin trapping funds enabled 15 additional workdays at the start of Year 2. Although reducing densities to <2 sea urchin/m^2 was not feasible given these extreme densities and small sea urchin size, we found the removals were sufficient to substantially reduce grazing pressure and support positive ecosystem recovery (Figure 33-34).

Visual assets to demonstrate ecosystem response to sea urchin harvest: pre-urchin removal and 1-month post-urchin removal.

Two-year financial summary:

- Direct purchase of purple sea urchin landings from CUH: $239,900
- Processor landing fees ($0.25/lb): $14,827.25
- CSUC assessment fees collected ($0.03/lb): $1,779.27
- Total cost of harvest operations: $256,506.52

These funds supported both the restoration effort and a fishery sector facing historically low food-market landings.

Harvest Rates:

- Year 1: 834 lbs/day per vessel
- Year 2: 358 lbs/day (dominated by small-sized sea urchins)
- Two-year average: ~639 lbs/day

Despite lower poundage in Year 2, CUH removed high numbers of individual sea urchins due to the density of small recruits.

Advancing a Restorative Economy- A major outcome was recognizing that many restoration-harvested sea urchins contained market-quality uni. This is especially true as we strategically harvested sea urchin from the kelp edges. Together, CSUC, TNC, and CDFW developed a mechanism allowing processors to legally purchase restoration-funded sea urchins and return proceeds to restoration without "double dipping."

Year 1 ANCKR pilot:

- 198 lbs processed at $3.30/lb
- $654 reinvested directly into restoration

Another successful outcome from defending the kelp edge and establishing food market purple sea urchin quality was that as vessels finished up their number of allocated workdays on the restoration project, some then targeted the restoration site solely to harvest large purple or red sea urchins for the commercial food market (on their own time and not paid for by the restoration project). Restoration-directed site exposure revealed commercially viable purple and red sea urchins:

- **2024:** 8 commercial harvest days, ~4,000 lbs removed
- **2025:** 2 commercial harvest days, ~800 lbs removed

This approach reduces waste, extends restoration capacity, and supports processors during low natural harvest periods. These removals likely would not have occurred without CUH involvement in the Big River project. CUH participation remained strong, but funding limitations, especially in 2025—restricted total available workdays. Divers consistently expressed interest in expanding restoration participation which fortunately also gave way for PCOR funding to leverage OPC HCE 45 award by providing additional harvest days to expand from 5 to 25 acres.

CSUC maintained regular communication through meetings, email updates, and vessel-level check-ins. Fast payment turnaround was highlighted as a significant operational improvement from past operating models. In addition, CO-PI Downie coordinated closely with TNC, Sonoma State University and San Jose State University (Moss Landing Marine Laboratories), integrating CUH activities with ecological monitoring, kelp outplanting, and drift enhancement. This strengthened alignment between science and industry and improved harvest efficiency.

The greatest challenge was the unprecedented density and small size of purple sea urchins, which slowed harvest progress and lowered poundage. CUH adapted using smaller mesh bags and fine-scale tools such as hand rakes. We also strategically left small sea urchins on site as it was observed that the "tide of kelp return" was overpowering their destructive grazing (Downie and McHugh pers comms.).

Conclusion, Regional Significance and next steps - The Big River project produced some of the most rapid and extensive kelp recovery observed on the North Coast to date, and has demonstrated: 1) the effectiveness of industry-led kelp restoration, 2) strong ecological gains from targeted grazer suppression, and 3) the viability of a restorative economy that reinvests value from harvested sea urchins into continued restoration. This two-year effort lays the groundwork for expanded restoration under the PCOR initiative and highlights a scalable model for future industry–science collaboration.

As of Summer 2025, the CSUC subaward in OPC HCE 45 is completely spent down. As such, for the remainder of 2025 through 2027, all sea urchin harvesting at Big River will be supported by PCOR funding.

Grazer suppression: sea urchin trapping

This section provides an interim update on the sea urchin-trap component of OPC HCE 45. Progress has been slower than anticipated due to permitting delays and environmental conditions, and field operations are expected to continue through 2026.

Previous research by TNC, Grant Downie, UCSB, and CDFW has demonstrated that benthic urchin traps are an effective tool for capturing purple sea urchins, particularly in conditions where diver-based removals are limited by poor visibility, winter conditions, or lack of diving infrastructure (Evaluating the effectiveness of benthic urchin traps for removing overpopulated purple sea urchins from degraded kelp forest habitat, *in prep*). Building on this work, the current phase of OPC HCE 45 evaluates whether traps can function as a maintenance tool—keeping purple sea urchin densities low inside restoration blocks that were previously cleared by commercial hand harvest. This focus represents a shift from the original design (which aimed to defend restoration boundaries and identify grazing hotspots) to address more immediate questions identified by CDFW to support development of the Kelp Recovery and Management Plan (KRMP).

Following approval of the Scientific Collecting Permit on August 20, 2025, fieldwork began with a redesigned deployment strategy. Rather than placing traps along the edges of restoration sites, traps were installed directly inside cleared blocks to intercept remaining sea urchins. Site selection also shifted from Big River to Noyo Bay. By late summer, Big River had regained substantial kelp canopy and natural drift, which reduced sea urchin responsiveness to bait and made it difficult to isolate trapping effects from other ongoing restoration methods, including ARKEVs and drift kelp deployment. Noyo Bay, where drift is limited, provided more reliable conditions to measure trap effectiveness.

To date, the team has spent 16 of 30 on-water trapping days, with all days expected to be completed by Summer 2026. Preliminary results show that catch rates are notably lower than earlier trapping phases (2021-2023), which is consistent with the updated experimental design of trapping in cleared blocks. From an operational standpoint, this also reinforces a known limitation: when densities are low, catch per unit effort may be less efficient than hand harvesting. Limited wrack kelp availability during the winter has also constrained bait supply as seasonal canopy declines. We will continue to evaluate this tool throughout the no-cost extension period using landings data and subtidal monitoring data.

Objective 1b

Aquaculture

Over the past two years, we have maintained multiple generations of all bull kelp life history stages from Albion Cove (hereafter referred to as Albion), Big River, and Noyo River in Mendocino, California. We have two main spaces for kelp culturing at Moss Landing Marine Laboratories (MLML) that include the aquaculture facility as well as multiple spaces at the main lab.

At the main lab, we utilized the aquarium room, cold room, and multiple incubators to perpetuate our sterile and non-sterile microscopic bull kelp cultures. In the aquarium room, we continued to utilize the semi-recirculation chilled water tables we established in 2024. On the side mounted table, we grew juvenile sporophytes for splicing into ARKEVs utilizing static 1 L and 5 L beaker cultures along with flow-through 15 L carboy tumble culture tanks (Figure 1). We tested inoculating rock substrates and dried sea urchin tests to increase sporophyte production along with conducting pilot studies on arrested sporophyte development in static culture using variable light intensities (Figure 2). We can implement these findings to arrest large quantities of <1 cm macroscopic sporophytes ensuring a consistent, on demand stock for outplanting. Additionally, we continued use of four 40-gallon (135 L) tumble culture tanks fitted with adjustable spectrum

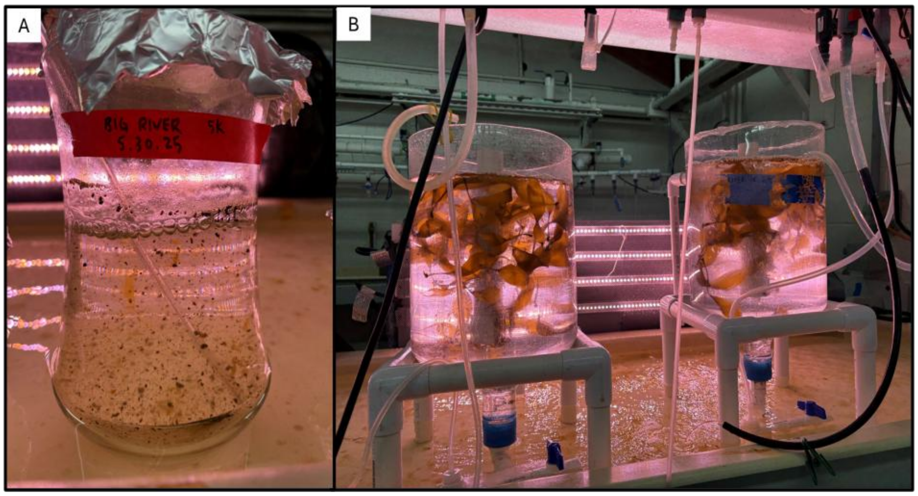

Figure 1. Static beaker (A) and flow-through (B) tumble culture in the aquarium room on the semi-recirculating seawater system

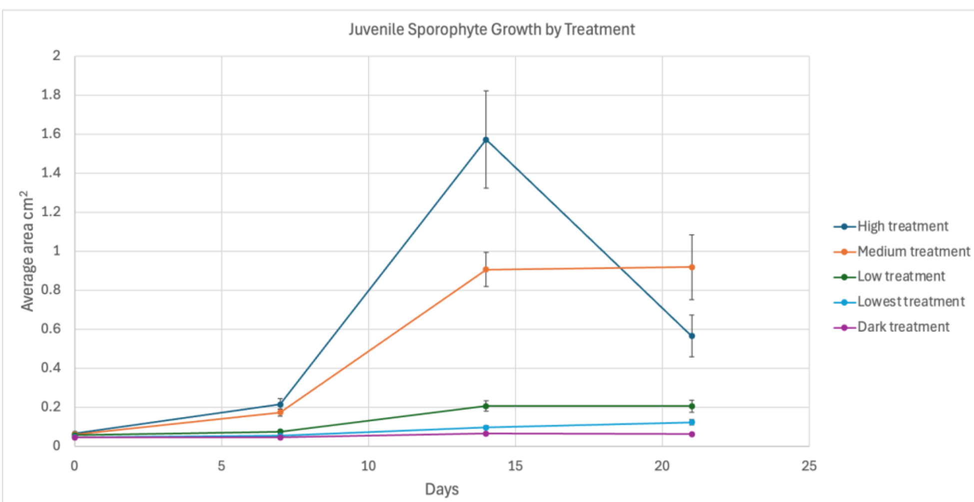

Figure 2. Pilot study quantifying juvenile sporophyte area across light treatments in static culture. Mean (+/- SE) sporophyte area (cm2) was calculated each week across light treatments for 3 weeks.

core lights (Figure 3). To control light intensity and wavelength, we wired core lights to external controllers, which allowed us to grow vegetative, unfertilized gametophytes (red light) and sporophytes in quantities significantly larger than our previous methodologies. We retro-fitted tanks from ambient flow-through seawater to semi-recirculating seawater controlled by an external chiller to mitigate elevated seawater temperatures coming through the MLML intakes. On September 20th, 2024, we established cultures harvested from the reproductive kelp on the Albion ARKEV pilot deployments. On October 21st, 2024, we collected and isolated cultures from reproductive kelp on the Big River ARKEV pilot deployments. These cultures provided the juvenile sporophytes that we outplanted at Big River in April 2025. In the cold room and white light incubator, we expanded and maintained petri dish and beaker cultures of Albion and Big River microscopic stages up to 1 cm macroscopic blades in static, no-aeration conditions (Figure 4). For beaker cultures with microscopic stages in suspension, we grew sporophytes up to 5 cm. At that size, we transferred sporophytes to larger beakers or 15 L carboys and eventually to the shore lab to be grown out in 40-gallon and 100-gallon (379 L) tumble culture tanks. Additionally, we wound 12 2″ x 12″ PVC tubes with Kuralon Japanese twine and seeded with Albion spores between January 27th and March 18th, 2025 for grow out at Sunken Seaweed's farm in Humboldt Bay, California to supply kelp biomass for drift enhancement (Figure 5). We continued red-light petri-dish cultures in our small incubator for 2024 Albion and Big River populations, with new cultures established with reproductive material from 2025, to maintain a small seed bank that could be readily available for growth or experimentation.

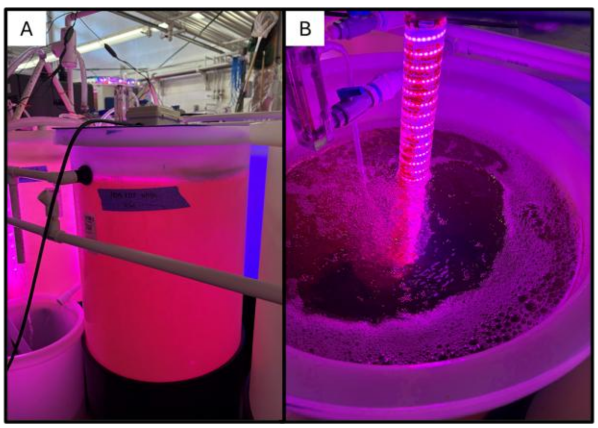

Figure 3. Core-lit 40-gallon tumble culture tanks

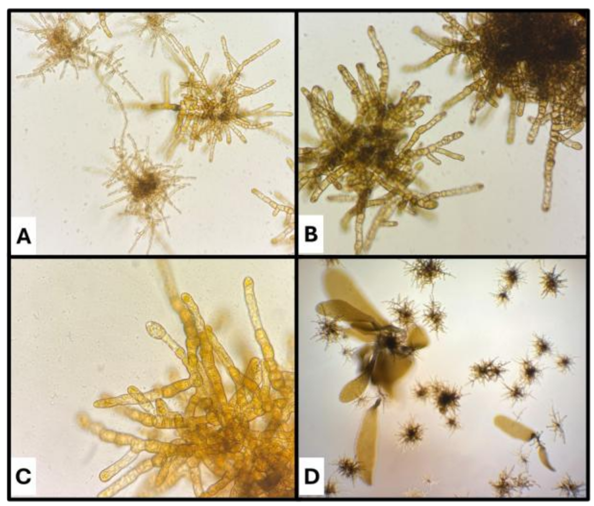

Figure 4. Images of sterile microscopic cultures. (A) Male and female gametophytes. (B) Close up of female gametophyte. (C) Close up of female gametophyte with egg. (D) Male and female gametophytes with numerous female gametophytes bearing large sporophytes.

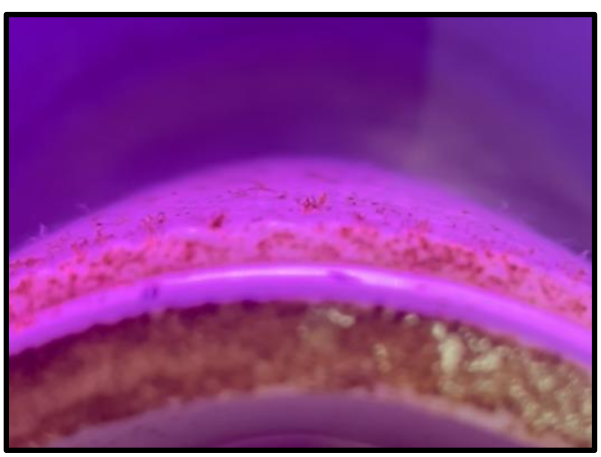
Figure 5. Top-down view of macroscopic sporophytes grown on seeded twine.

In 2024, we purchased and installed four 1000-gallon (3,785 L) tanks which were installed at the shore lab facility to increase the capacity for growing bull kelp biomass, primarily for the purpose of drift enhancement (Figure 6). We fabricated each tank for bottom-supplied air using the system-wide air supply, flow through sand-filtered seawater, and partially submerged the tanks in the ground for accessibility. We stocked tanks with Albion blades on January 10th, 2025 and weighed approximately every week to quantify growth and biomass production. We conducted a pilot study to determine light conditions for 1000-gallon tanks by quantifying kelp growth (kg) and soral production (percent of blades bearing sori) across six light treatments (Figure 7). On March 20th, May 13th, June 18th, and July 6th, we weighed out blades into 10 kg bags and froze them in the MLML walk-in freezer to neutralize any reproductive material on the blades. By July 6th, we had produced and frozen 250 kg of bull kelp tissue for our first drift enhancement deployment on July 8th. In addition to scaling up drift kelp production, we expanded our tumble culture of splicable juvenile sporophytes by utilizing existing 300-gallon (1,135 L), 100-gallon, and 40-gallon tumble culture tanks. Prior to our target April ARKEV outplanting date at Big River, we transferred juvenile sporophytes from Albion and Big River cultures >4 cm total length from the temperature controlled aquarium room to the outdoor, ambient flow-through tanks at the shore lab over multiple batches. To minimize mortality from the significant increase in light and changing seawater temperatures, we added multiple layers of garden shade cloth at initial translocation. Over a two week period, we slowly increased light to near ambient conditions, such that juvenile sporophyte growth was minimized to keep sporophytes at the ideal spliceable size.

Figure 6. Four 1000-gallon bull kelp tanks for drift enhancement production.

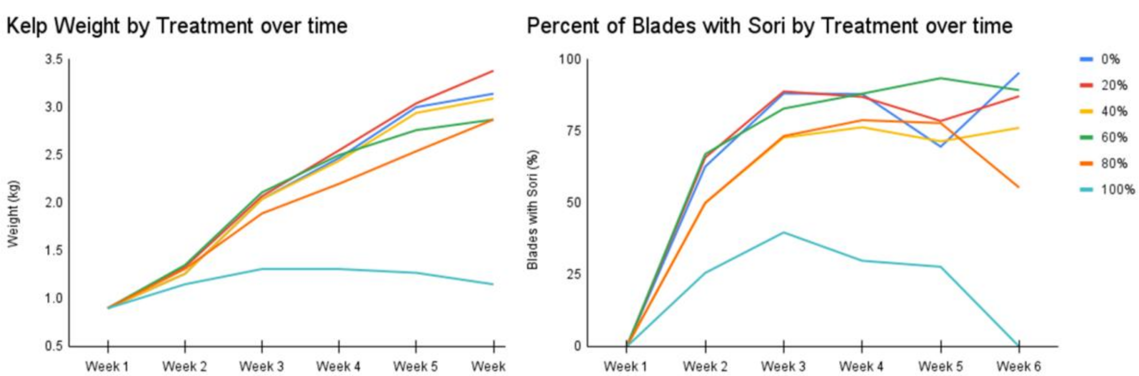

Figure 7. Pilot study quantifying single-blade bull kelp growth and soral production in tumble culture across six light treatments.

Kelp Outplanting

ARKEV assembly

In 2025, we scaled up ARKEV production to meet the demand of the increasing kelp enhancement footprint at Big River from 900 m^2 to 3000 m^2. To assemble 60+ ARKEV modules, we cut over 160 ft of aluminum strut, 360 ft of 1" PVC, and 1,620 ft of blue steel line (Figure 8). Each ARKEV consists of ⅜" and ¼" blue steel line, two 1m lengths of 1" PVC capped on either end, two 1 ft lengths of 1" aluminum strut, four aluminum strut clamps, one stainless steel swivel jaw and eye, and a 45lb kettlebell. We assembled all components apart from attaching the ARKEVs to the kettlebells prior to the April deployment date. For specific dimensions and assembly instructions, see the ARKEV blueprint here.

Kelp enhancement

Due to permitting delays in 2024, we were only able to deploy ARKEVs at Albion (n=12) in early spring, with the Big River ARKEV (n=9) deployment occurring in the summer. When we compared survivorship and growth rate of spliced sporophytes on ARKEVs between sites in 2024, we found increased survivorship and rapid growth to reproductive adult thalli when deployed earlier in the calendar year (Figure 9). Thus, for 2025, we targeted an April ARKEV deployment at Big River. Notably for 2025, we significantly scaled up the number of ARKEVs and total number of kelp outplanted with 50 ARKEVs deployed to test the effects of kelp enhancement, 5 blank ARKEVs to assess the effects of the kelp and the ARKEV structure on fish recruitment, 5 additional ARKEVs to grow kelp biomass for drift enhancement, and 2 ARKEVs testing more sustainable materials. On April 24th, 2025, we deployed 30 ARKEV modules off the F/V Cyndi Lynn at Big River and deployed the remaining 30 ARKEVs the following day in approximately 8 hours total; the 2 ARKEVs made of sustainable material were deployed in July.

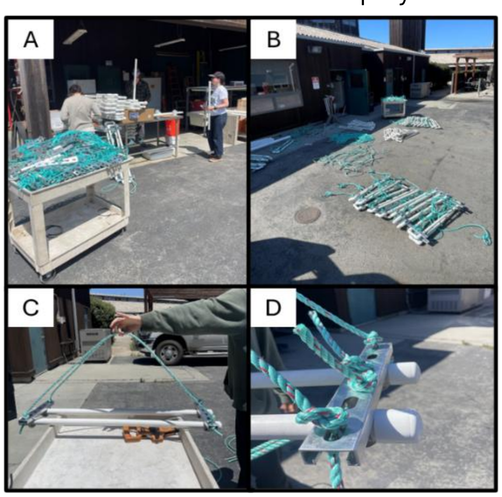

Figure 8. Images from ARKEV assembly day. (A) Construction. (B) ARKEVs ready for deployment. (C, D) Demonstrating the appropriate line height.

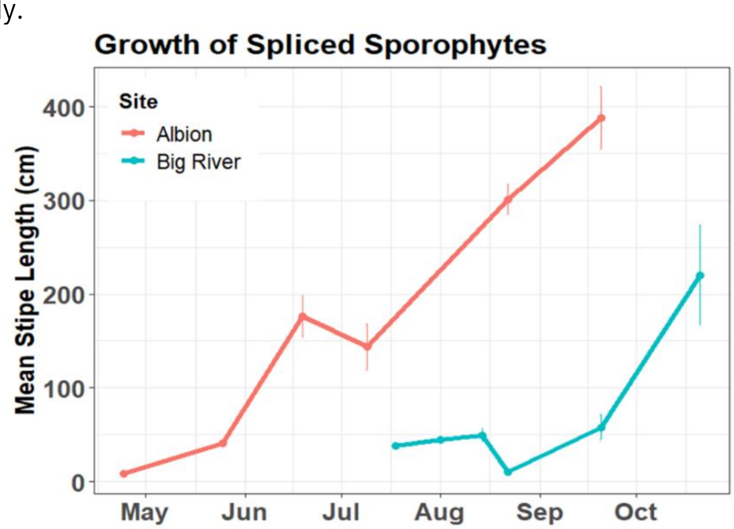

Figure 9. 2024 mean (+/- SE) stipe length for ARKEV pilot deployments at Big River and Albion Cove.

We spliced each kelp enhancement ARKEV module with 10 lab-reared bull kelp individuals of 25.59 +/- 3.77 (mean +/- SE hereinafter) cm stipe length, split equally among two lines on the ARKEV. For modules growing drift kelp biomass, we spliced them with as many individuals as were available,

Figure 10. Image of a random sample of splicable sporophytes and the associated numbered bag. Meter tape was used as a scale bar for analyses.

while fish recruitment ARKEVs had no kelp spliced. Prior to being transported and outplanted, we hand-picked spliceable individuals from numerous tumble culture tanks at the MLML shore lab facility. Slight delays in outplanting due to unfavorable forecasts, along with elevated seawater temperatures coming through the MLML seawater intake, led to having fewer sporophytes than initially intended. As a result, we needed to use some sporophytes (>20 cm stipe length) that were larger than the ideal size for splicing. To combat this change, we also used some smaller sporophytes but kept them separately as a smaller size class (<5 cm stipe length). We selected, photographed, and placed 10 random sporophytes by size class in a prelabelled bag then stored them in a cooler for 24 hours during the transport to Mendocino (Figure 10). We later used the photographs to size sporophytes, eliminating the need to measure sporophytes during splicing or immediately after outplanting. We separated bags into two distinct size class bins based on if the sporophytes were predominantly smaller or larger than desired. On board the F/V Cyndi Lynn, we arranged and tagged kettlebells (anchor weights for each ARKEV) according to the respective plots (Figure 11). Each ARKEV had a specific GPS point which enabled us to accurately deploy from the boat with modules within each ARKEV plot spaced 5 m apart. On-site, five ARKEV modules for a

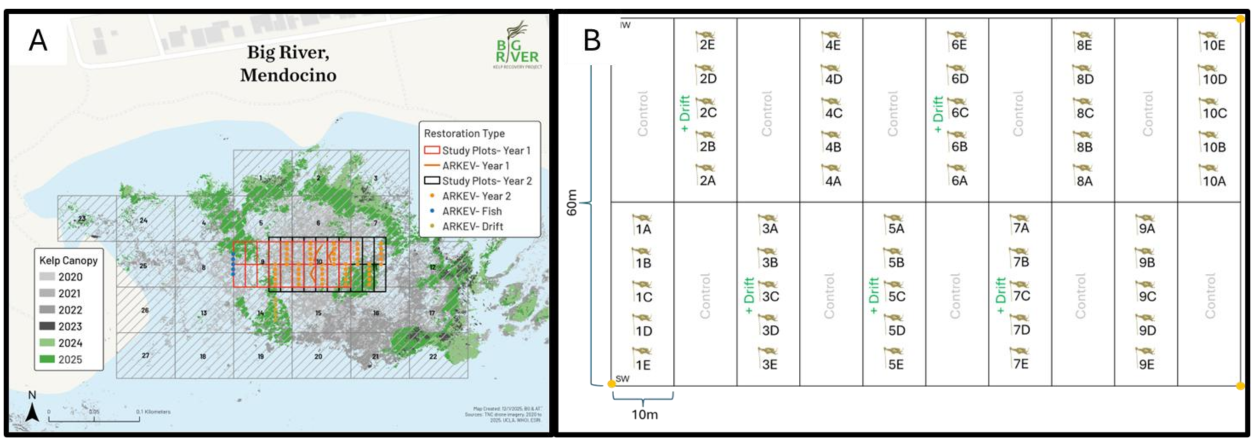

Figure 11. (A) Overview of Big River with kelp canopy colored by year. The black 100m x 60m grid is the restoration grid where ARKEVs (orange dots) were deployed in 2025. The orange grid is the proposed restoration grid in 2024 with pilot ARKEV deployments (lines). Blank fish ARKEVs (blue dots) were deployed outside of the restoration grid to minimize the effect of outplanted and natural kelp presence on fish recruitment. Drone-imagery of annual kelp canopy cover is overlaid by year. (B) Schematic of ARKEV outplanting and drift kelp enhancement design. Ten 60m x 10m plots are split into a 30m x 2m ARKEV plot and control plot.

single plot (i.e. 1A, 1B, 1C, 1D, 1E) contained 10 spliced kelp individuals attached to the pre-assembled modules (see ARKEV assembly section) to the kettlebell. Five people each took an ARKEV and a pre labeled bag, alternating between large and small size classes by ARKEV, and spliced all 10 individuals across both lines; we noted pre-labeled bags and ARKEV plot tags at the time of splicing (Figure 12). A sixth person connected the ARKEV module to the respective tagged kettlebell by attaching a stainless steel swivel jaw and eye to a 1 m length of ⅜" blue steel line tied in a loop around the handle of the kettlebell, then secured the shackle with stainless steel seizing wire (see ARKEV blueprint linked above). Once we spliced and attached all five ARKEVs to their respective tagged kettlebells, the vessel transited across the plot over each respective GPS point with each module deployed in order according to the direction of the transit. Each person carried their ARKEV whilst another person carried the kettlebell, with both simultaneously letting go when queued to "drop" the module off the side of the boat (Figure 12). On May 25th, we spliced in sporophytes on SCUBA to replace individuals lost in the first month, totaling approximately 600 bull kelp individuals spliced at Big River. We anticipated a higher incidence of mortality on account of needing to use some larger and longer sporophytes, which likely increased the likelihood of mechanical breakage from drag forces. Based on survivorship counts from the previous sampling period, we pre-labeled bags with photographed sporophytes and spliced them onto modules with less than 10 individuals.

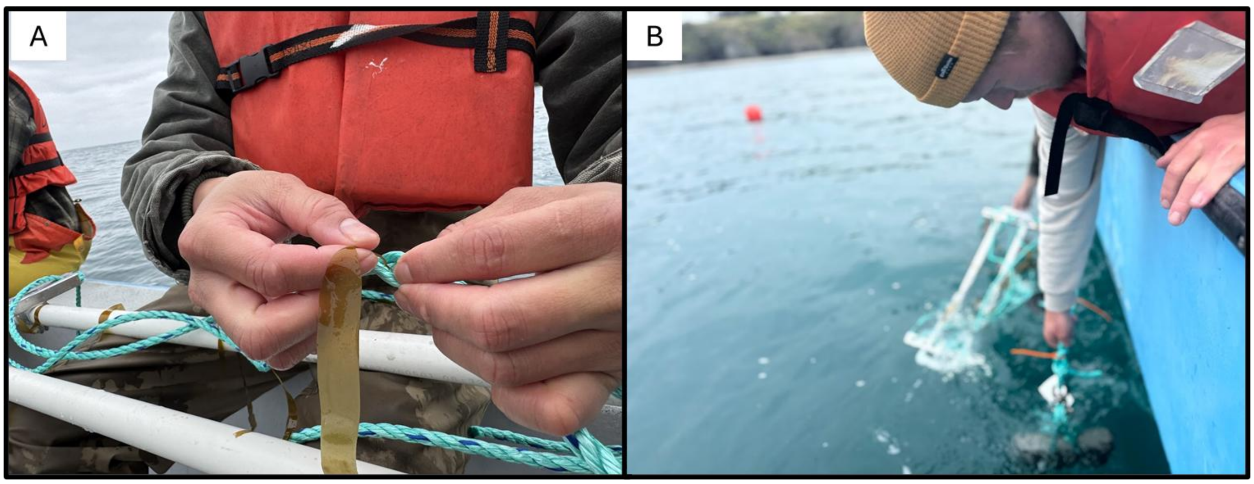

Figure 12. (A) Splicing kelp into the ¼" blue steel rope. (B) Two people holding the kettlebell and spliced ARKEV module waiting to deploy it off the side of the vessel.

Drift enhancement

In 2024, we piloted three 20 kg drift enhancement deployments at Big River and noticed significant and immediate aggregations in larger purple sea urchins. Moving into 2025, we planned to scale up both the biomass of drift deployed, along with the number of plots receiving drift kelp biomass. Beginning in January 2025, we started batching and freezing lab-grown blades and crowns that were grown in the newly installed 1,000-gallon tanks. Our first drift deployment occurred on July 8th, 2025, one month after our ARKEV kelp became reproductive. By that deployment date, we had grown and frozen 250 kg of drift kelp biomass (50 kg per drift enhancement plot), approximately half of what we proposed to deploy monthly at Big River. We harvested nearly all bull kelp biomass from the MLML shore lab for drift, meaning that subsequent drift biomass would need to be predominantly sourced from wild drift kelp collections. Despite this significant logistical hurdle, we were able to source 250 kg of drift kelp biomass for an August and September deployment respectively, totaling 750 kg of drift kelp deployed for drift enhancement.

To quantify changes in grazing behavior in response to drift enhancement, we measured 24 hour grazing rates and conducted before and after surveys for each drift deployment. We determined grazing rate by deploying 30 distinct 3 ft aluminum grazer assay bars, each with six pieces of pre-weighed bull kelp tissue clipped on, simulating kelp recruits on the reef. We deployed two grazer assay bars in 15 plots: 5 +ARKEV +drift, +ARKEV -drift, and 5 -ARKEV -drift (Figure 13b). We deployed the grazer assay bars simultaneously with drift deployments to ensure grazers had equal opportunity to consume either drift kelp or kelp on the grazer assay bar, then retrieved 24 hours later. If there was any remaining kelp on the grazer assay bar, we bagged by plot *in situ* then weighed it. Concurrently, we conducted surveys completing a series of 1m quadrat surveys quantifying percent drift algal cover (both natural or added drift), percent fleshy (attached to the reef) algal cover, purple, and red sea urchin densities. We conducted quadrat surveys around the grazer assay bar, 1 m, and 3 m in all cardinal directions from the grazer assay bar. We completed the surveys at the time of drift and grazer assay bar deployment and then again 24 hours later. Additionally, we deployed six GoPro camera traps to capture time-lapse photos to quantify grazer movement in relation to drift presence or absence; video analyses are ongoing (Figure 13).

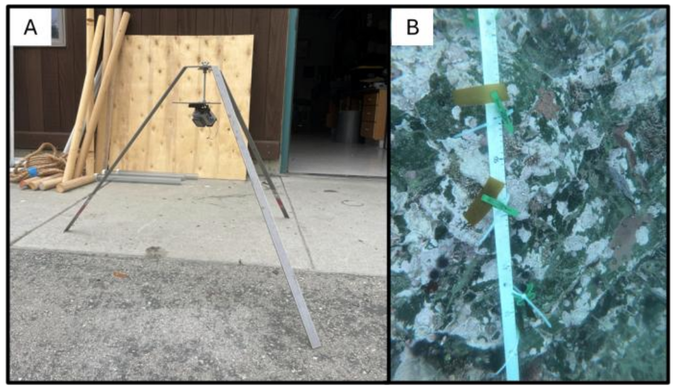

Figure 13. (A) GoPro collapsible camera trap. (B) view from deployed camera trap with grazer assay bar centered

Outplanting grid and survey methods

Following the 2024 field season, we evaluated the habitat within and around the initial outplanting grid and determined that a large sand channel bisecting Block 9 could limit recruitment from ARKEV kelp. To avoid this feature, we shifted the outplanting grid approximately 30 m east for the 2025 season, positioning the ARKEVs on contiguous rocky reef substrate. Figure 11 shows the location of the original 9 ARKEVs in 2024 overlaid with the modified grid and ARKEV locations for 2025.

The updated grid consists of ten 60x10 m plots split into paired 30x10 m subplots. We labeled plots from west to east (1-10) and each plot contains a control (containing no ARKEVs) and an ARKEV section. Within each ARKEV plot, we deployed five ARKEV modules starting at the midline and extending either north or south, alternating among adjacent plots, and placing modules within an ARKEV plot 5 m apart (Figure 11). This standardized layout created a consistent series of paired ARKEV and control areas across the grid. In addition, we designated five ARKEV plots as drift plots, where drift kelp enhancement occurred July through September. We added five "blank" ARKEV modules (i.e., the ARKEV structure itself with no spliced kelp) outside of the restoration grid, across the previously mentioned sand channel, intersecting between blocks 8 and 9. These allowed us to test whether fish responses were driven by the ARKEV structure itself rather than the presence of attached kelp. We deployed fish ARKEVs farther away from the restoration grid to maximize treatment interspersion and minimize the effect of outplanted and natural kelp recruitment that could facilitate increased fish recruitment.

Survey methods also differed between years in ways that reflected this transition from a pilot deployment to a full outplanting array. In 2024, ecological monitoring relied on broad spatial surveys designed to characterize background community structure and grazers throughout the entire grid. To accomplish this, we conducted a combination of fish swath transects and quadrat surveys on the benthic community in each plot. Three 1 m^2 quadrats were placed 10 m apart within each plot, and within each quadrat, purple (*Stronglycentrotus purpuratus)* and red sea urchins (*Mesocentrotus franciscanus)* were counted as well as indicator kelp and invertebrate taxa. At each quadrat corner, the primary substrate holder was recorded, providing a crude percent cover of major algal cover.

In addition to eco-monitoring, fine scale ARKEV surveys were conducted in 2024 around each of the nine pilot ARKEVs to assess kelp growth, fish abundance, and local benthic community structure. For each ARKEV, we counted and measured the spliced kelp individuals, conducted a paired fish survey recording individuals on (within 1 m) and off (1-2 m) the ARKEV, quantified purple and red sea urchin densities as well as indicator kelp and invertebrate species within a 1 m radius around the unit. These surveys provided higher resolution information on ARKEV performance and on species interactions directly adjacent to each ARKEV.

Figure 14. Bottom-up view of ARKEV module surrounded by an emerging kelp forest. Photo: Marco Mazza

With the expansion to 50 ARKEVs in 2025 and the establishment of a standardized outplanting grid, we refined our survey methods to focus directly on ARKEV specific dynamics (Figure 14). We conducted all surveys in 2025 around each ARKEV module and its corresponding control location. We surveyed each ARKEV using the same method above with the addition of separating the purple sea urchin counts by size class (<2 cm and >2 cm) as we recognized the importance of quantifying the small cryptic recruits. We added percent algal cover on the reef to quantify the relative percentage of cover on the 1 m radius around the ARKEV. During each survey period (monthly to twice monthly), we surveyed two out of five ARKEVs and their paired control sections within each plot. ARKEVs were not sampled in successive months to limit repeated measures and quantify any variability among ARKEVs within replicate plots. We converted the count data collected within the 1 m radius to densities (individuals/ m^2) by dividing by π.

Indicator invertebrate species include Turban snails (*Tegula funebralis and Tegula brunnea),* abalone (*Haliotis Kamtschatkana*, *Halitois rufescens*, sea stars (*Pisaster ochraceus*, *Pisaster* *miniata*, *Pisaster brevispinus*, *Pisaster giganteus*, *Dermastarias imbricata*, *Pycnopodia helianthoides*, *Stylasterias forreri*, *Leptastarias hexactus*), crabs (*Cancer spp.*), and sea cucumbers (*Apostichopus californicus*). Kelp species included *Laminariales* recruits, *Nereocystis luetkeana* juvenile and adults, *Pterogophora californica*, *Desmerestia spp. Alaria marginata*, *Laminaria setchelii*, *Costaria costata*, *Dictyotales spp.*, *Laminariales* stump (stipe only).

ARKEV performance

In 2024, we experienced elevated losses, most notably losing four of the six ARKEVs at Albion following shackle failure and drag induced breakage. This was largely due to permitting constraints that meant we had to initially deploy ARKEVs using existing infrastructure (eyebolts) at the site. Once we moved the remaining modules to anchor weights, we lost no further ARKEV infrastructure. On the remaining ARKEVs, kelp exhibited ~40% survivorship, rapid growth, and continuous reproductive output for at least 3 months (see Figure 9). At Big River, we experienced higher kelp losses, predominantly due to deploying in the summer months when temperatures were elevated. However, we were able to get five individuals across three ARKEVs reproductive for at least 1 month. Knowing we could deploy ARKEVs at Big River as we initially proposed, we anticipated elevated survivorship, biomass, and reproductive output in 2025 relative to our results in 2024.

We deployed 60 total ARKEVs at Big River in April 2025 and retrieved 57 in October, with losses due to storm-induced mechanical damage to either the rope attaching to the kettlebell or the shackle failing. One ARKEV was lost in September following a long-period swell event; two additional ARKEVs were lost during the first large winter storm in early October that delayed our retrieval operations by a week. Despite these losses, the remaining ARKEVs remained in the same location they were deployed 6 months prior.

Retrievals took two vessel days (~7 hours each, 4 researchers/divers and two vessel operators), each day with a different approach given the natural kelp abundance at the site and its spatial orientation in relation to the ARKEVs. On day 1, we started by removing ARKEV modules far from emerging natural kelp forests. We pulled up 7 ARKEVs by the spliced kelp growing on the unit. One person began by grabbing the pneumatocyst/stipe and started pulling it up with a second person grabbing the ARKEV structure and a third person grabbing the kettlebell once it was within reach. This method proved easier than expected and would've been the preferred method had the tide height not prevented us from reaching the pneumatocysts. We removed the remaining ARKEVs using a combination of SCUBA, snorkel, and vessel teams. On day 1, two dive teams worked to separate the ARKEVs from the kettlebell and arrange them by their respective plots. This involved one diver cutting the ⅜" blue steel rope loop around the handle of the kettlebell. The second diver then connected the removed ARKEV to a second length of line where all 5 ARKEVs within each plot would be tied together. Next, we attached a surface float to the kettlebell to pull it up from a winch on board the vessel. Swimming with multiple ARKEVs proved to

Figure 15. Picture of ARKEV kelp on board the F/V Cyndi Lynn following retrievals.

be very challenging, thus we modified our removal technique on day 2. One dive team went down and removed the ARKEVs from the kettlebell utilizing the same technique as day 1. The second diver connected a surface float to the kettlebell. Instead of swimming at depth with the ARKEV, divers let the module float up to the surface for a second snorkel team to retrieve, arrange by plot, then swim over to the boat. This method was much more efficient, with the exception of the ARKEVs that were located within the dense natural kelp forest that emerged in the southeast corner of the restoration grid. Using the modular nature of the ARKEVs, we determined that if there is an emerging kelp forest developing in the near proximity to an ARKEV, it is best to relocate outside to aid in retrievals. We also observed that the naturally emerging kelp outcompeted some kelp on the ARKEV, further supporting relocation in the event of kelp recruitment in the footprint of the module.

Once we retrieved ARKEVs (see video), we selected 2 out of 5 modules in each plot for final morphometric data including stipe length, total blade number, total number of reproductive blades, and total weight (kg) (Figure 15). We cut all kelp on ARKEV modules from the splicing line above the holdfast then dropped it on the restoration grid as drift.

Results and analysis of kelp outplanting

We initially started with 500 kelp across all kelp enhancement ARKEV modules and ended with 179 reproductive adults at the time of harvest, equating to a 35% survivorship rate. When considering the average number of spliced kelp surviving on each ARKEV, we saw 3.8 +/- 0.34 kelp per ARKEV (Figure 16). Survivorship across years was similar when comparing Albion in 2024 with Big River in 2025, however, we outplanted 41 more modules in 2025, translating to a dramatic increase in reproductive kelp on site.

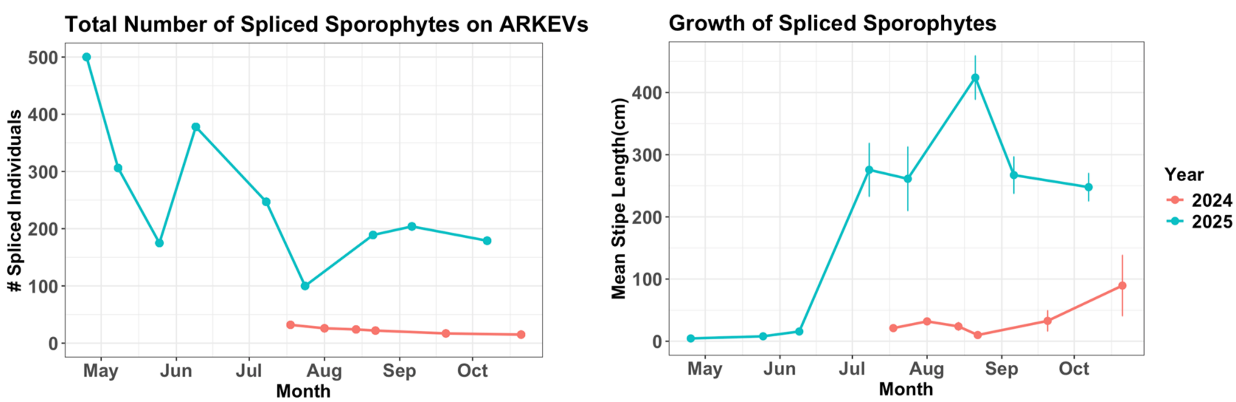

Figure 16. (left) Total number of spliced sporophytes on ARKEVs in Big River. (right) Growth of spliced sporophytes (mean stipe length +/- SE) at Big River from the date of outplanting to harvest.

Spliced sporophytes at Albion in 2024 grew from an average 8.5 +/- 0.59 cm at the time of outplanting to 176.6 +/- 22.4 cm in two months, at which individuals were reproductive. In 2024, Big River outplants performed markedly worse compared to Albion outplants due to the combined effects of increased ocean temperatures at the time of outplanting and a prolonged time spent in culture both emanating from previously described permitting delays. In addition, we observed increased grazing pressure at Big River including kelp crabs cutting the stipes of our spliced sporophytes. However, the sporophyte replenishment on August 22nd, 2024 showed increased survivorship following decreased ocean temperatures with 33% of those individuals surviving for the subsequent two month outplanting period. Spliced sporophyte stipes grew from ~10 cm to 220.4 +/- 53 cm at which individuals were at or near the surface. Across both sites, we estimated that approximately 24 million spores were released per individual every ~4 days, equating to approximately 204 million spores released over three months at Albion, and Big River individuals had released approximately 94 million spores for the month they were reproductive.

In 2025, sporophytes at Big River grew from 25.59 +/- 3.77 cm to 62.45 +/- 18.26 cm between April 25th and June 9th, 2025, and then grew to greater than 4 m on average by mid-August. From ARKEV deployment, it took only 45 days for spliced kelp to become reproductive. Spliced sporophytes were reproductive on site for 91 days until modules were removed on October 7th, 2025 (Table 1). On average, kelp on ARKEVs produced 51 blades, 14 of which were reproductive (Table 1). We estimate that 68-103 sori were released per kelp every 4-6 days, with approximately 1,034-2,343 sori produced on average per plant on the modules (Table 1). Based on these estimates, we expected 10.5-15.7 million spores released every 4-6 days per plant and for the 91 days the kelp were reproductive on site, equating to 158-358 million spores released per plant at Big River just from ARKEV modules (Table 1). At harvest, kelp on ARKEVs weighed a total of between 764.51 and 1005.4 kg (22.85 +/- 2.73 kg per ARKEV). Comparatively, we produced a total of 113.75 kg of kelp biomass at Albion in 2024 (7.355 kg per ARKEV) and 32.95 kg of kelp biomass at Big River in 2024 (4.17 kg per ARKEV). See table 1 for a summary of ARKEV outplants across years.

Table 1. Reproductive data for 2024 and 2025 ARKEV outplants.

	2024	**Big River 2025**
Mean # blades per kelp individual	**54 (Albion) 40 (Big River)**	**51**
Timing from outplanting to first sori	**76 days (Albion) 60 days (Big River)**	**45 days**
Percent of blades fertile	**49% (Albion) 27% (Big River)**	**26%**
# sori released per kelp every 4-6 d	**49-73 (Albion) 55-82 (Big River)**	**68-103**
# spores released per kelp every 4-6 d	**7.4-11.2 Million (Albion) 8.3-12.5 Million (Big River)**	**10.5-15.7 Million**
# days kelp was reproductive	**73 days (Albion) <31 days (Big River)**	**91 days**
Total number of sori produced per plant	**596-1343 (Albion) 275-618 (Big River)**	**1034-2343**
Total number of spores released per plant per reproductive season	**90.6-204 Million (Albion) 41.8 – 94 Million (Big River)**	**157-358 Million**

Our results from 2025 further support outplanting kelp sporophytes earlier in the calendar year to facilitate increased survival and growth, as also shown from our 2024 Albion growth data. Additionally, we were able to have reproductive kelp on site continuously seeding the surrounding reef for 91 days. Comparing growth, biomass, and reproductive data between years for Big River suggests that temperature, and likely nutrient availability, are driving factors determining the success of kelp outplants and likely natural kelp forests.

Fish recruitment to ARKEVs

In 2024, we observed an immediate and pronounced recruitment of fish on the ARKEVs at Albion, which highlighted the potential role of these structures in attracting fish and motivated a clear investigation of this interaction. We noted a similar trend at Big River in 2024, though it was weaker likely due to the delayed kelp outplanting that year at that site. Based on these observations, we designed the 2025 field season to quantify how fish respond to both the structural presence of the ARKEVs and the kelp attached to them. During each survey period, divers conducted standardized fish counts around ARKEVS within the restoration grid, recording fish either "on" the ARKEV (within a 1 m radius) or "off" the ARKEV (1-2 m away). We performed identical surveys at paired control locations within the restoration grid lacking ARKEVs and conducted additional surveys around five blank fish ARKEVs. This sampling design allowed us to disentangle whether fish recruitment was driven by the physical structure of the ARKEV or the presence of kelp on ARKEVs.

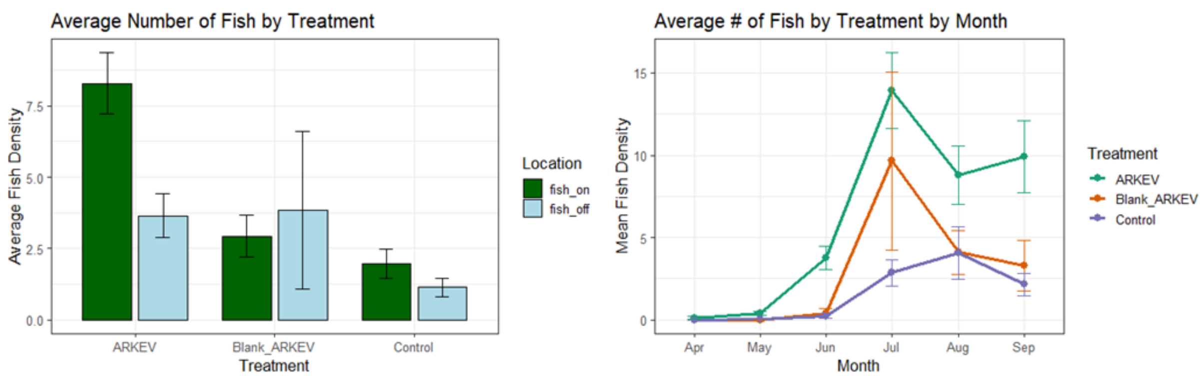

Figure 17. (left) Mean (+/- SE) number of juvenile rockfish by ARKEV treatment. Fish ON were deemed to be more strongly associated with the ARKEV/kelp than fish OFF the ARKEV. (right) Monthly mean (+/- SE) number of rockfish ON/OFF ARKEVs

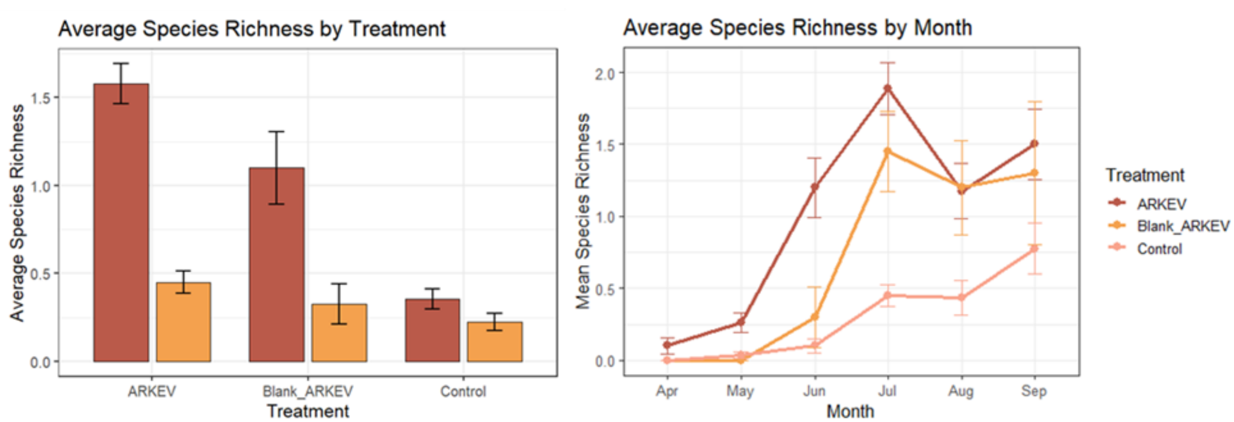

Figure 18. (left) Mean (+/- SE) species richness across treatments and location. (right). Monthly mean (+/- SE) species richness across treatments.

A generalized linear mixed model (GLMM) was used to analyze differences in fish counts and species richness across treatment types and months using a negative binomial distribution with treatment and location (fish on vs fish off) as fixed effects. Fish surveys revealed that ARKEVs attracted substantially more fish than surrounding reef habitat, with the strongest response occurring on ARKEVs with spliced kelp (Figure 17). Fish recruitment response was strongest in the presence of an ARKEV (higher counts in fish on) than away from ARKEV modules (fish off) (estimate = -1.416, $p < 0.001$). The increase in fish densities was strongest in the presence of ARKEV modules with kelp (estimate = +1.488), with a smaller increase for blank fish ARKEVs (estimate = +0.451, $p = 0.055$) and controls (estimate = +0.591, $p = 0.013$). Fish densities on ARKEV were consistently higher than fish densities off ARKEV for all months, except for July (Figure 17). Mean fish abundance increased nearly 3 times between late May and early June then again in early July to the peak of fish recruitment for 2025 (Figure 17). Further, fish abundances on ARKEV were twice that of fish off abundances for July (Figure 17). Species richness on ARKEV modules was three-times greater than species richness off ARKEVs ($p < 0.001$). Species richness was significantly higher for ARKEV modules with spliced kelp than control plots (Figure 18, $p < 0.001$). There was no significant difference in species richness between ARKEVs with kelp and blank fish ARKEVs ($p = 0.424$). However, species richness was driven more by time (SD = 1.277) than ARKEV treatment (SD = 0.087). Monthly mean rockfish species richness was greatest across all treatments all months except in August where blank fish ARKEVs had 0.03 higher average species richness (Figure 18). We also saw the highest species richness for ARKEVs and blank ARKEVs in July, with control plots steadily increasing in richness throughout the year and peaking in September (Figure 18). By June, kelp sporophytes on ARKEV modules had grown to canopy and were beginning soral production. This peak in fish abundance and species richness associated with kelp canopy formation further highlights the importance of outplanting earlier in the calendar year. Moreover, these recruitment patterns indicate that fish were responding to both the structural complexity provided by ARKEVs and the added habitat value of attached kelp. Overall, these patterns demonstrate that ARKEVs function as small scale habitat features that enhance local abundance with kelp spliced onto ARKEVs further amplifying this trend.

Results and analysis of drift enhancement

In 2024, we piloted multiple drift deployments at Albion and Big River, both demonstrating a significant reduction in the kelp consumed on the grazer assay bar when drift kelp was present across a range of grazer densities. Additionally, we anecdotally noticed a 5m sphere of influence, predominantly with larger purple sea urchins and red sea urchins, from our 20 kg drift kelp additions in August at Big River. Grazer suppression at Big River in 2024 was focused outside of the restoration grid, seeking to defend existing kelp patches and facilitate expansion outward. Thus, the drift pilot studies and observed sea urchin behavioral shifts from 2024 involved a population with a larger size class than in 2025, when grazer suppression focused on the restoration plot. We anticipated a smaller sphere of influence with smaller purple sea urchins as they are less mobile. However, it is possible that we could satiate smaller sea urchins with less drift biomass, potentially shifting their behavior quicker than with larger, hungrier sea urchins.

We wanted to scale up the quantity and frequency of drift deployments in 2025 to test the singular and additive effects of drift supplements in the same plots over time. We sought to deploy up to 500 kg of drift biomass monthly, supported by lab-grown tissue at MLML aquaculture facility, collecting natural drift kelp from nearby sites, and predominantly from seeded twine grown at Sunken Seaweed. Unfortunately, due to late permitting miscommunications, we were unable to transport and grow seeded twine we had in culture for ~4 months. Thus, we were only able to supply drift kelp from lab cultures, naturally occurring drift, and 5 ARKEVs deployed specifically for growing drift biomass. We were able to supply 250 kg of drift biomass from MLML cultures for our first July drift enhancement experiment. We predominantly supplied August and September drift deployments (250 kg each) by collecting drift with some biomass coming from drift ARKEVs. Due to the limited quantity of drift biomass, we opted to deploy drift only in a subset of ARKEV plots to maximize the amount of drift deployed in each replicate plot. This design gave us three levels of drift supplementation 1) deployed drift plus any biomass sloughed off of the ARKEV (+drift +ARKEV), 2) drift only supplemented by material from ARKEV (-drift +ARKEV), and 3) minimal to no drift additions (-drift -ARKEV). Each treatment had 5 replicate plots containing 2 grazer assay bars to quantify 24-hour grazing rate.

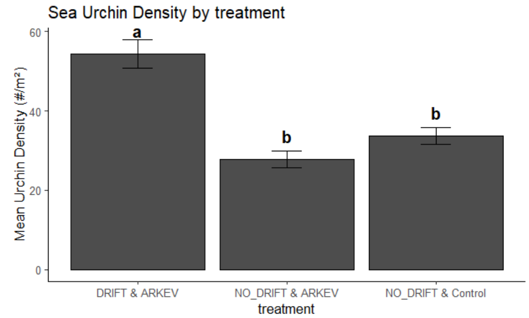

Figure 19. Mean (+/- SE) sea urchin densities by treatment.

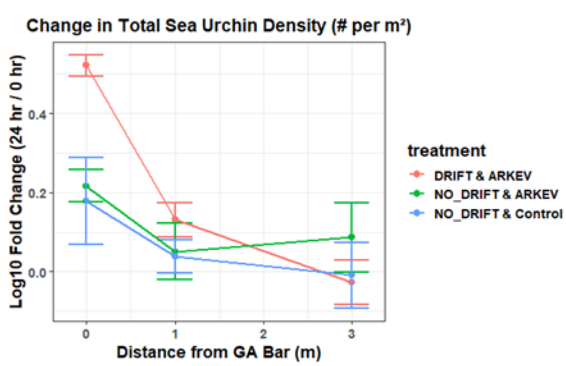

Figure 20. Log-transformed mean (+/- SE) 24-hour change in sea urchin densities (#/m^2) by distance from the grazer assay bar.

Sea urchin densities overall were significantly higher in plots for ARKEVs with drift added than ARKEV and control plots that had no drift supplementation ($F(2,1010) = 18.76$, $p<0.001$; Figure 19). This suggests that the addition of drift kelp attracted sea urchins more than the sloughed kelp material from ARKEVs independently. The slight increase in sea urchin density in control plots compared to ARKEV plots is likely due to grazer suppression techniques focusing around the ARKEV modules to defend any microscopic stages that may have settled on the reef. To attempt to quantify this change in sea urchin density across treatments, we compared the log-transformed change in sea urchin densities for each plot using the quadrat surveys conducted at increasing distances from the grazer assay bar. We found no significant differences in the change in sea urchin densities among treatments ($p=0.57$). Additionally, there were no significant differences in the change in sea urchin densities within ARKEV ($p=0.72$) and control plots ($p=0.54$), although there was a slight increase in sea urchin densities at the grazer assay bar quadrat (distance = 0, Figure 20) compared to 1 m and 3 m away (Figure 20). For ARKEV plots with drift added, we saw significantly different densities of sea urchins 24 hours after the drift and grazer assay bar was deployed ($p<0.001$). Specifically, we saw an increase in sea urchins at the grazer assay bar quadrat relative to the 1 m ($p=0.015$, Figure 20) and 3 m ($p<0.001$, Figure 20) distances. There was a slight difference in the 24-hour change in sea urchin density between 1m and 3m distance ($p=0.076$, Figure 20). This increase was correlated with the presence of drift and not the kelp on the grazer assay bar as there was significantly less kelp consumed on the grazer assay bars when drift was added ($F(1, 28) = 4.389$, $p = 0.045$; Figure 21). There was no significant difference in percent kelp consumed on grazer assay bars among treatment types, however, there was the most kelp consumed in control plots, the least consumed in ARKEV plots with drift, and intermediate

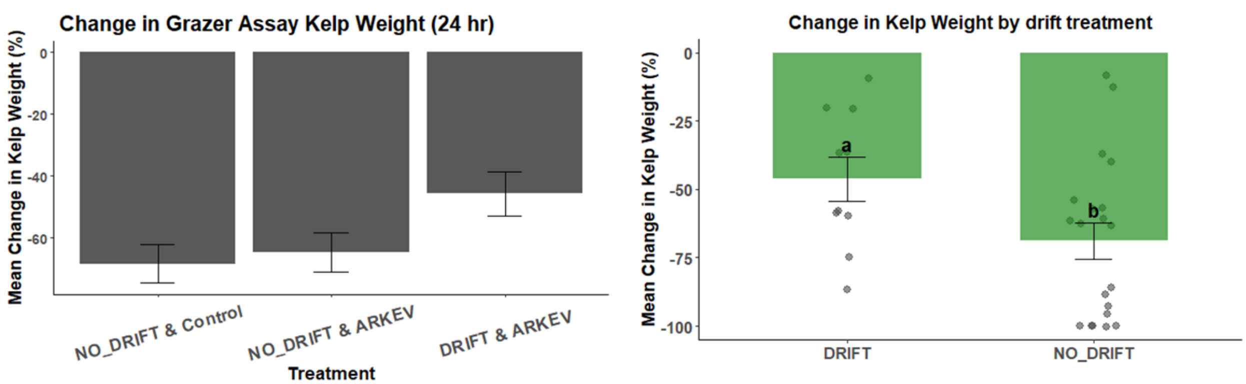

Figure 21. (left) Mean (+/- SE) percent change in grazer assay kelp weight across treatments after 24 hours. (right) Mean (+/- SE) percent change in grazer assay kelp weight between drift and no drift treatments for July and September.

consumption in ARKEV plots (Figure 21). Analyses on percent change in kelp weight excluded the August drift enhancement trial as the kelp quality for the grazer assay bars was significantly worsened due to field operation delays caused by unfavorable conditions. These data demonstrate that remaining sea urchins in these systems are still demonstrating destructive grazing behavior and will move towards kelp subsidies whether small pieces of kelp or large quantities of drift. Importantly, we found a pronounced behavioral change with increasing kelp presence (drift additions) where sea urchins were moving and aggregating from as far as 3 m to seek food. This varies slightly from our observed 5 m sphere of influence from drift additions in 2024, which could be due to the decrease in dominant sea urchin size class between years.

Results of sea urchin density and behavior

As previously mentioned, sea urchin size class in 2024 was much larger as commercial sea urchin divers had not begun grazer suppression in the restoration plots. Prior to the start of the 2025 drift enhancement trials, divers had begun grazer suppression in the site, driving down the dominant size class as it is less efficient to collect smaller sea urchins due to their cryptic and concealed nature. This shift to smaller sea urchins could explain the reduced sphere of influence, as smaller sea urchins are less mobile than larger sea urchins. Further, we observed shifts in sea urchin behavior, with an increasing frequency of individuals residing in cracks, crevices, and under the kettlebell following repeated drift deployments (pers. obs.). This observed rapid change in behavior could have been facilitated by the small size class of sea urchins that could be satiated at a lower kelp biomass. Importantly, we saw that kelp on grazer assay bars was consumed at a significantly lower rate when drift was present, suggesting that sea urchins will preferentially feed on drift kelp than kelp recruits on the reef and may serve as a temporary distraction. This finding follows our 2024 findings that we observed across a range of sea urchin densities. Further studies are needed to quantify the duration that drift can persist and may distract sea urchins across a variety of size classes.

Sea urchin dynamics differed between years in ways that reflect grazer suppression strategies implemented in each season. In 2024, the primary objective was localized purple sea urchin removals around remnant kelp patches as a part of a "protect and expand" approach intended to facilitate natural kelp recovery. As a result, only limited removal effort occurred within the outplanting blocks (4 days in Block 10 and one day in Block 9), and this effort was focused narrowly around the original 9 ARKEV deployments (see Figure 11). Consistent with this limited intervention, purple sea urchin densities increased during the 2024 season (Figure 22). We also observed numerous small juvenile sea urchins (<1 cm) throughout the summer, which likely contributed to the apparent rise in density as both recruit appearance and potentially observer awareness increased over time.

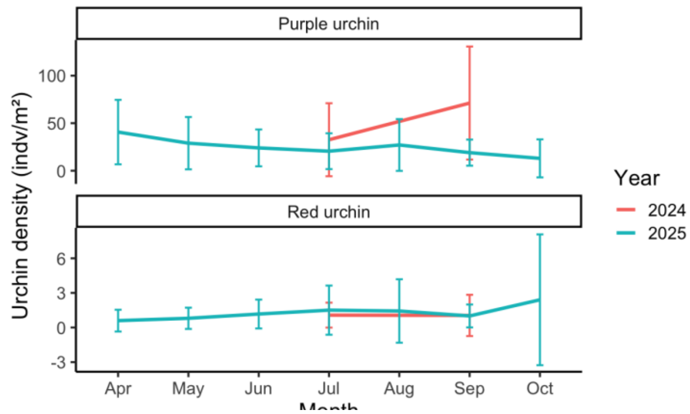

Figure 22. Monthly mean (+/- SE) purple and red sea urchin counts in the outplanting grid for 2024 and 2025.

In contrast, the commercial dive group substantially expanded grazer suppression efforts in 2025, with more consistent and broader purple sea urchin removals across the outplanting blocks compared to the previous year. Although early season densities (e.g. July) appear somewhat similar between years, this similarity may partly reflect the increasing awareness of very small (<1 cm) juveniles stemming from surveys late in 2024, rather than a lack of difference between years. Consistent with the expanded removal efforts implemented in 2025, purple sea urchin densities declined through the 2025 season, whereas they increased during the 2024 season. Red sea urchins, which were not removed for restoration purposes, remained at low and relatively stable densities across both years (Figure 22). Because red sea urchin abundance showed little variation and is not directly affected by grazer suppression, we focused subsequent analyses on purple sea urchins.

Learning from observations during the 2024 field season, which revealed a high abundance of small purple sea urchins on the site, we quantified purple sea urchins in two size classes: <2 cm and >2 cm in 2025 to better understand the contribution of these small individuals to overall grazing pressure. We quantified purple sea urchin densities within a 1-m radius surrounding the base of each ARKEV or control location and then converted to individuals per m^2.

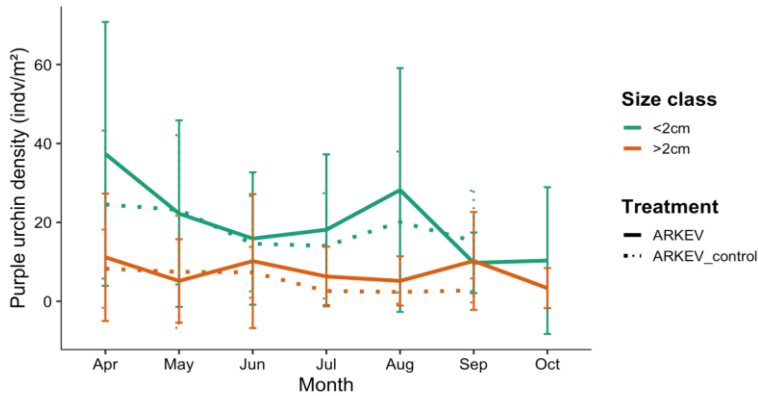

Figure 23. Monthly mean (+/- SE) purple sea urchin densities between ARKEV and control plots. Purple sea urchins were separate into two size bins: <2cm test diameter and >2cm test diameter.

Purple sea urchin densities varied throughout the monitoring period, with small individuals (<2 cm) consistently occurring at much higher densities than larger individuals (>2 cm; Figure 23). Densities of both size classes generally declined from spring into early summer, showed a slight increase in August, and then stabilized through the fall (Figure 23). Across all months, ARKEV and ARKEV control plots followed similar trends, indicating no clear treatment effect on purple sea urchin abundance (Figure 24). October surveys were paired with ARKEV removals; thus, we prioritized surveying the ARKEV plots given the limited weather window for diving and removal efforts (Figure 24).

To further evaluate size and treatment specific patterns, we compared average purple sea urchin densities across size classes and ARKEV treatments using a non-parametric Aligned Rank Transformation ANOVA (Figure 24). Small purple sea urchins (<2 cm) occurred at significantly higher densities than large individuals (>2 cm) ($p < 0.0001$). In contrast, ARKEV treatment had no significant effect on purple sea urchin density, and no interaction was detected, indicating that treatment did not modify the relationship between size class and density. Post-hoc Tukey tests similarly showed that small purple sea urchins were consistently more abundant than larger ones under both ARKEV and control conditions. This lack of a treatment effect is expected, as sea urchin removals were conducted across the entire outplanting grid rather than restricted to ARKEV treatment areas, minimizing the potential for treatment-level differences in sea urchin densities.

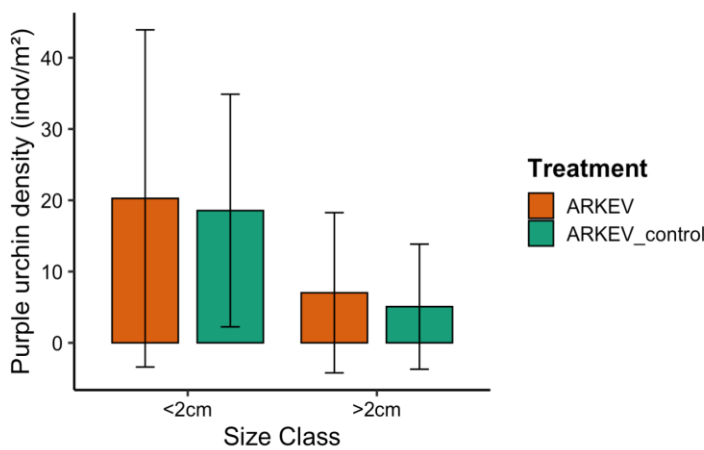

Figure 24. Mean (+/- SE) purple sea urchin densities by ARKEV treatment by size class.

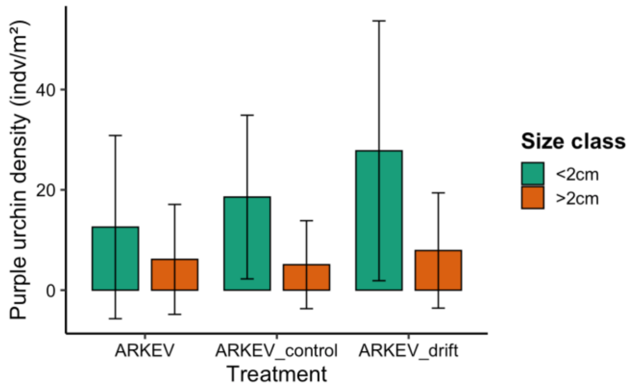

Figure 25. Mean (+/- SE) purple sea urchin densities by treatment type.

We did not take categorical data to quantify sea urchin behavior relative to its position (actively foraging on the reef versus passively grazing in a crevice). However, 2024 observational evidence highlighted that the drift kelp additions quickly aggregated large numbers of purple sea urchins within a matter of hours, particularly larger and more mobile sea urchins. To further evaluate how drift enhancement influences grazing pressure, we compared 2025 purple sea urchin densities by size class across the ARKEV, ARKEV controls, and the ARKEV plots which were given drift treatments using a non-parametric Aligned Rank Transformation ANOVA (Figure 25). Average purple sea urchin densities differed across treatment and size classes, with small individuals (<2 cm) consistently occurring at much higher densities than larger ones (>2 cm). There were significant effects of both ARKEV treatment type and size class on sea urchin density, as well as a strong interaction between the two factors ($p < 0.0001$). Small purple sea urchins were significantly more abundant than large sea urchins in all treatments; however, their densities varied by treatment, with the lowest in the ARKEV plots, intermediate in the controls, and the highest in the ARKEV plots with drift enhancement. In contrast, densities of larger purple sea urchins did not differ significantly across treatments. These results suggest that drift addition influences the abundance of small sea urchins, potentially altering grazer pressure in areas where drift accumulates. As noted previously, the consistently higher densities of small sea urchins likely reflect the difficulty divers face in locating and removing individuals <2 cm. In contrast, larger sea urchins are more visible and are likely removed at a higher rate, which reduces their overall abundance and may limit the ability to detect movement or aggregation patterns in the large size class. Given the results from both 2024 and 2025, it is beneficial to combine drift deployments with sea urchin removals given the potential ease of harvesting aggregated sea urchins and potentially lowering the size class of remaining sea urchins in the process. Further, sea urchin density may not be the best predictor for kelp recovery, but rather sea urchin biomass (size class and density) and/or behavior may be more accurate metrics.

Synthesis of kelp enhancement and community response monitoring

To understand changes in community composition among and within years, we used non-metric multidimensional scaling (NMDS) based on the full suite of kelp and invertebrate species recorded during our ARKEV and benthic surveys (see outplanting grid and survey methods section). NMDS provides an integrated view of the ecological community by analyzing all of these taxa simultaneously, where communities (represented by points on the figure) that are more similar to each other are closer together in ordination space. Additionally, we used the *envfit* model to overlay species that are significantly correlated with community patterns, represented by the vector arrows. This multivariate approach captures changes in species assemblages that could be indicative of shifts from sea urchin dominated systems to emerging kelp forest systems.

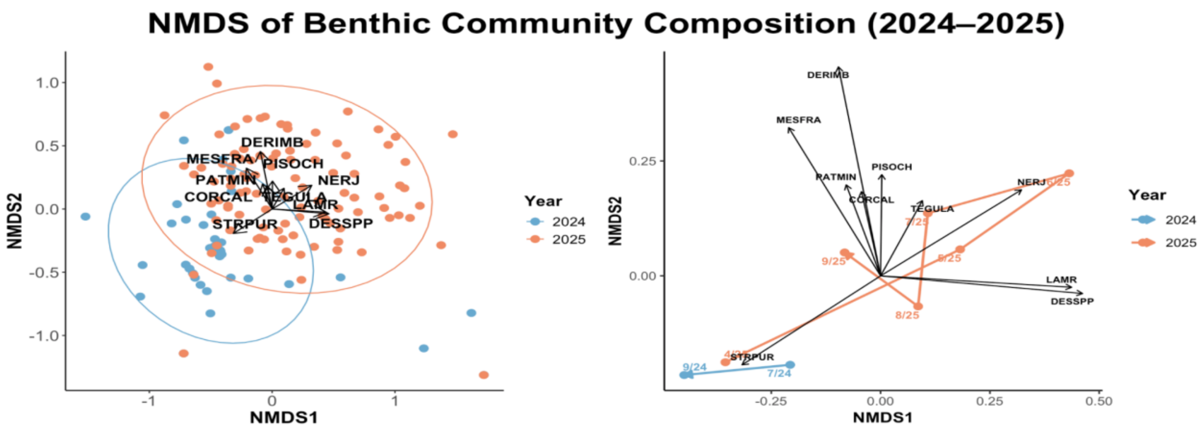

Figure 26. NMDS ordination illustrating patterns in community composition between 2024 and 2025 at Big River. Ellipses represent 95% confidence intervals around group centroids. Vectors indicate the top 10 species most strongly correlated with community composition. (Left) community composition across individual ARKEV units. (Right) community composition aggregated across months.

The NMDS revealed clear differences in community composition between years (PERMANOVA: R^2 = 0.088, p = 0.001). Points from 2024 and 2025 formed partially distinct clusters in ordination space, with relatively little overlap between the 95% confidence intervals (Figure 26). The purple sea urchin vector was oriented toward the 2024 cluster, indicating that higher purple sea urchin abundance was associated with the 2024 community state (Figure 26). In contrast, several invertebrate and macroalgae vectors pointed toward the 2025 cluster, suggesting a shift away from sea urchin-dominated conditions. This pattern is consistent with field operations described above in that sea urchin removals in the restoration grid did not begin until after July 2024. Furthermore, the efforts initiated in 2024 were limited and concentrated around the ARKEV structures.

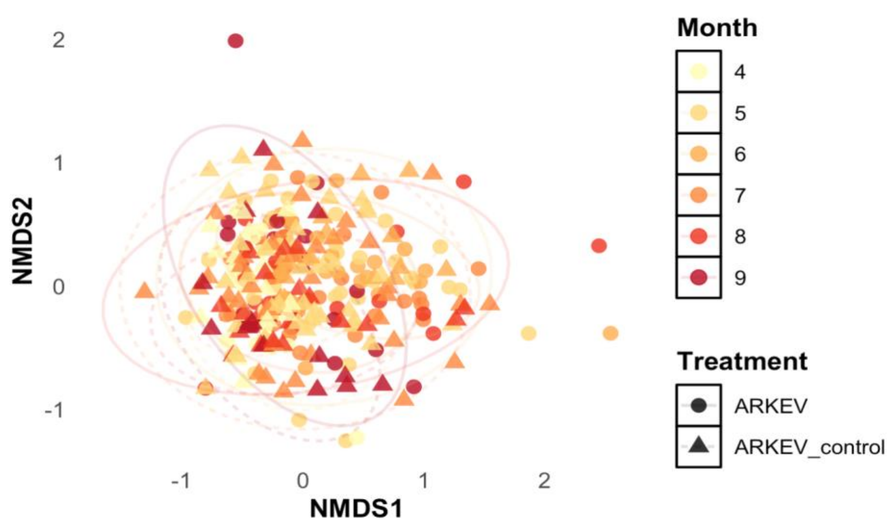

Figure 27. NMDS ordination illustrating patterns in community composition in 2025 at Big River. Ellipses represent 95% confidence intervals around group centroids. Points represent the community at individual ARKEV units. Colors represent different months. Shapes represent different treatments.

To track changes in community composition at Big River in 2025 between ARKEV treatments, we applied this NMDS ordination to examine patterns in community composition across months and treatments. The ordination revealed strong temporal variability in community composition, with samples from the same month clustering closely together. In contrast, ARKEV and control plots showed substantial overlap within each month, with no consistent separation between treatments (Figure 27). PERMANOVA results supported the NMDS visualizations that community composition differed significantly through time ($p < 0.05$), while ARKEV treatment had no significant effect on community composition from April to August ($p > 0.01$). A small but significant treatment effect was detected in September ($R^2 = 0.068$, $p = 0.015$), suggesting that minor treatment-related differences emerged late in the sampling period. Overall, temporal dynamics were the primary driver of benthic community structure, with only limited evidence for treatment effects. This is expected for a community that is naturally dynamic in nature, given the annual life history of bull kelp and its affinity for disturbance-prone habitats.

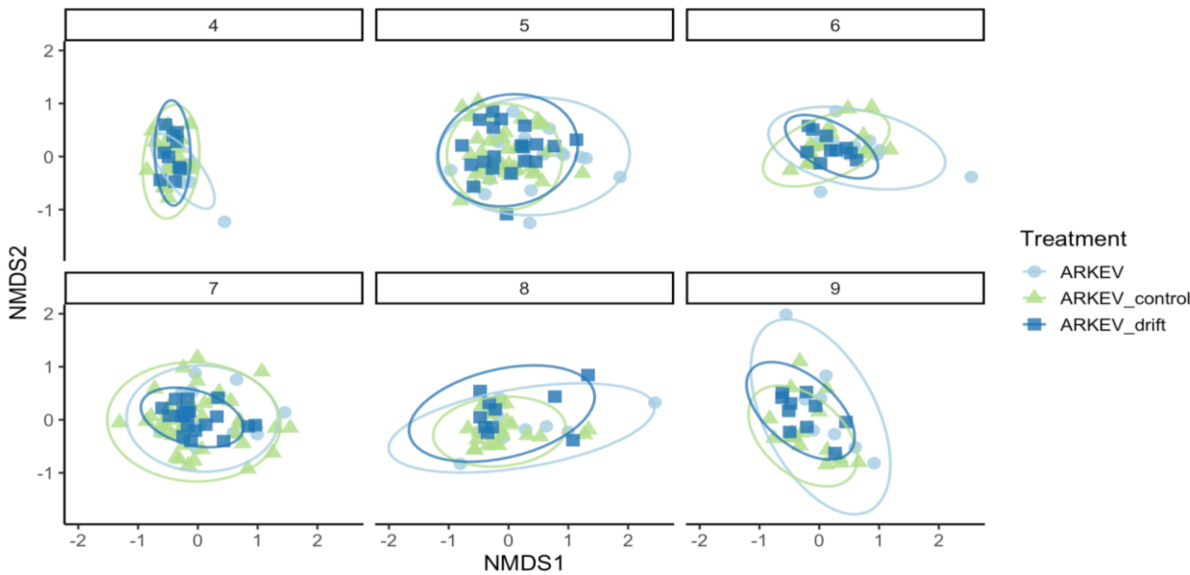

Figure 28. NMDS ordination illustrating patterns in community composition in 2025 at Big River separated by month. Ellipses represent 95% confidence intervals around group centroids. Points represent the community at individual ARKEV units. Colors and shapes represent different ARKEV treatments (ARKEV, ARKEVs with drift added, controls).

To evaluate whether benthic communities responded to treatment level differences, including drift enhancement, we examined an NMDS ordination grouped by ARKEV, control, and the ARKEVS within plots where drift was added over time (Figure 28). In most months, there was no significant difference in community composition between treatment types. However, in May, ARKEV treatment explained 7.2% of the variation in community composition (Pairwise PERMANOVA: $p = 0.004$). In July, drift kelp was introduced to the plots, and by the end of the season, ARKEV treatment explained 9.3% of the variation in community composition (PERMANOVA: $p = 0.049$). While ARKEV deployment alone did not produce detectable community shifts, drift enhancement may have contributed to subtle, late season divergence in benthic assemblages.

Because natural habitat conditions varied across the site, we also examined benthic community structure at a finer spatial scale by dividing the outplanting grids into four quadrants (NE, NW, SE, and SW; Figure 29). Although the NMDS ordination indicated some overlap in community composition among quadrants, a PERMANOVA test revealed a significant effect of quadrant on benthic community structure, with quadrant identity explaining 10.7% of the total variation ($p = 0.001$).

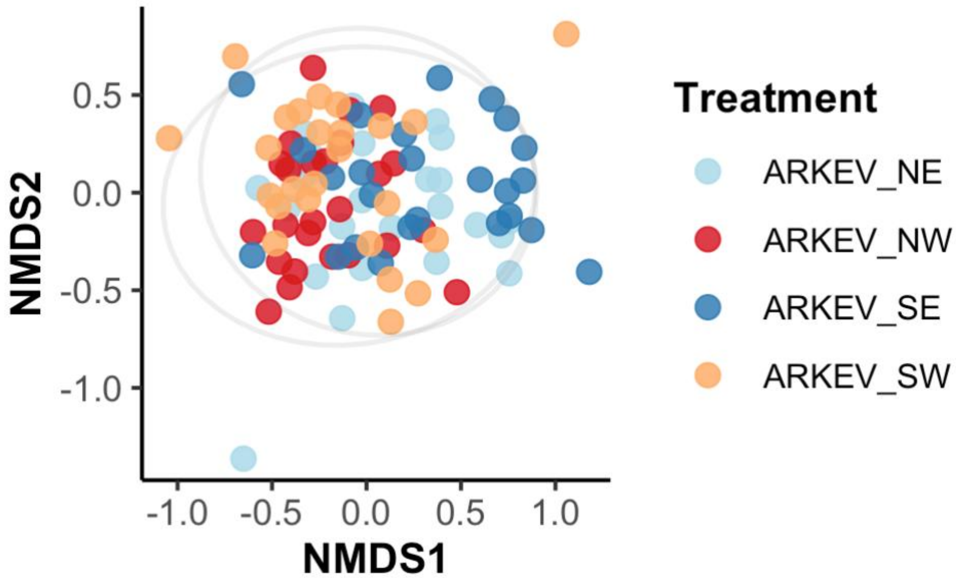

Figure 29. NMDS ordination of benthic community composition (invertebrates, urchins, kelp, and Tegula) across site quadrants (NE, NW, SE, SW) in 2025. Points represent individual sampling units, colored by quadrant, with ellipses representing 95% confidence intervals around group centroids.

Pairwise comparisons revealed that this spatial variation was driven primarily by differences involving the southeastern (SE) quadrant, which differed significantly from both the northeastern (NE) ($R^2 = 0.052$, $p = 0.03$), northwestern (NW) ($R^2 = 0.175$, $p = 0.001$), and southwestern (SW) quadrants ($R^2 = 0.109$, $p = 0.002$). Additional contrasts indicated strong variation between the NE and NW quadrants ($R^2 = 0.054$, $p = 0.033$).

This pattern is consistent with observed differences in natural kelp cover across the site (Figure 19). These spatial differences provide important context for interpreting variation in community composition and may help explain why some treatment contrasts appear weaker or more variable across the grid. Taken together, the temporal, treatment, and spatial ordinations indicate that benthic community composition was shaped primarily by seasonal dynamics and to a lesser extent by underlying spatial patterns, with drift enhancement potentially contributing only localized and modest effects later in the season. Importantly, this multivariate tool pools all kelp taxa, therefore, cannot detect species specific response, thus univariate analyses are required to analyze treatment effects on kelp recruitment.

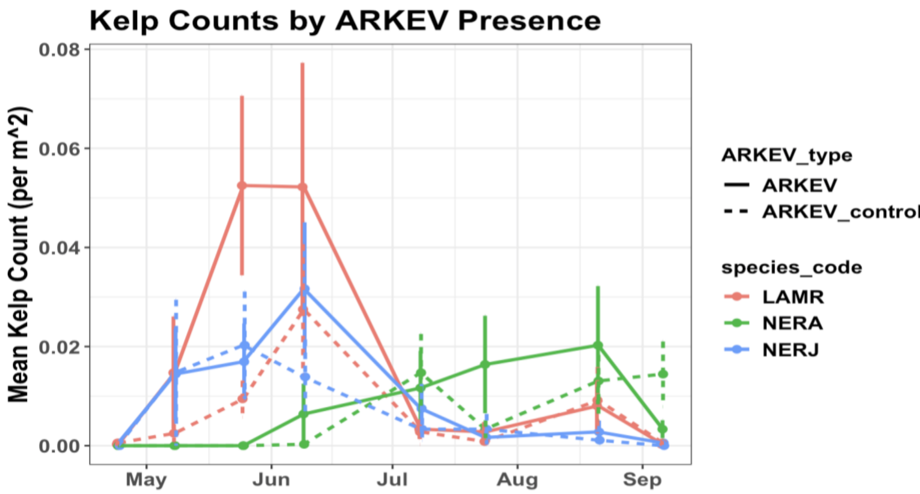

Figure 30. Mean kelp counts per m2 of Laminariales recruits, bull kelp recruits, and bull kelp adults across ARKEV types over time.

To evaluate whether ARKEVS influenced bull kelp, we specifically examined Laminariales (an Order of brown alga that includes all of the kelps) recruits, which refers to kelp recruits which could not yet be identified down to species, bull kelp juveniles, and adults separately (Figure 30). Laminariales recruits were significantly more abundant around ARKEVs (t=2.1941, df=40701, p=0.028). However, this trend appears to be driven mostly by temporal and spatial patterns as this was early in the season prior to ARKEVs having reproductive kelp, and in the plots nearest the emerging kelp bed (Figure 31).

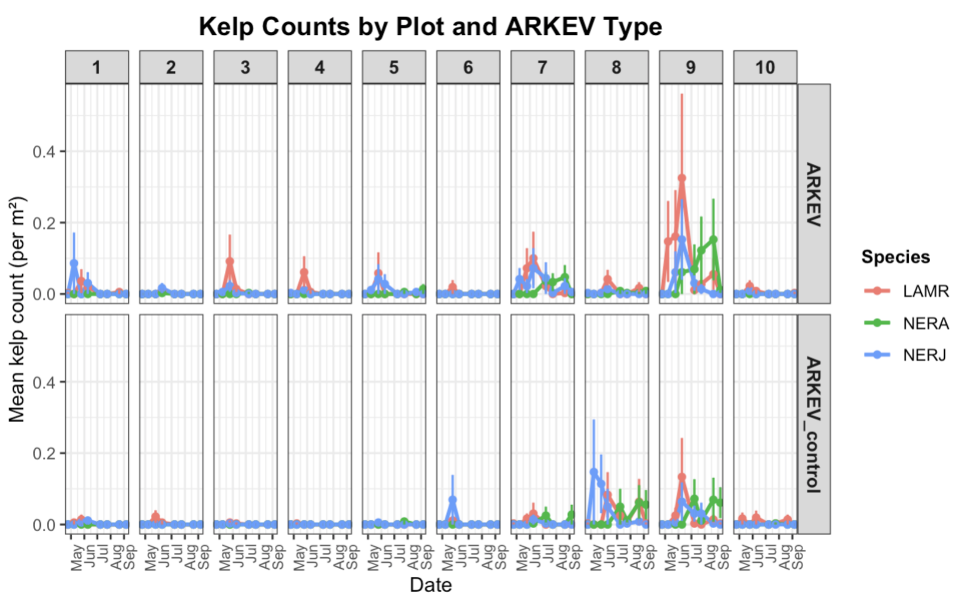

Figure 31. Mean kelp counts per m2 of Laminariales recruits, bull kelp recruits, and bull kelp adults across sampling months, ARKEV type, and ARKEV blocks.

Although Plots 4-6 were farthest from the emerging natural kelp beds, several ARKEV plots in this region showed early season laminaria recruits, which may reflect localized recruitment from the 2024 ARKEV deployment (Figure 11, 31). However, this pattern was not consistent across all plots near 2024 ARKEV deployments. For example, Plot 3 and 1 showed an increase in laminaria recruits as well, highlighting that recruitment was spatially patchy and likely shaped by multiple drivers (Figure 30). Juvenile and adult bull kelp displayed strong spatial structure with higher abundances in plots located closer to these beds, independent of ARKEV presence. We would expect to see signals from the reproductive kelp on the ARKEVs to become clearer in 2026 given bull kelps annual life history, in which the majority of recruitment and juvenile growth are not observable until the following year.

To assess early signs of benthic recovery following grazer suppression and kelp outplanting, we examined changes in the relative percent cover of major algal groups across ARKEV and control plots. Benthic cover patterns indicate early successional shifts following grazer suppression across both ARKEV and control plots (Figure 32). In April, communities were dominated by encrusting red algae (ER), scum (brown fuzz covering the reef), and bare rock (BR), all conditions characteristic of heavily grazed sea urchin barrens. By September, both treatments showed clear increases in fleshy red algae and crustose coralline algae (CCA), along with substantial reductions in scum and encrusting algae. The decline in scum could suggest improved benthic stability and reduced fouling accumulation, as CCA colonizes freshly cleared substrate (decrease in bare rock and increase in CCA). Successional trajectories were broadly similar between ARKEV and control plots, although ARKEV plots exhibited a larger increase in fleshy red algae. Overall, these patterns indicate that reduced grazing pressure could have initiated early stage transition away from grazer dominated states and allowed for some regrowth of fleshy algae and increased coralline cover.

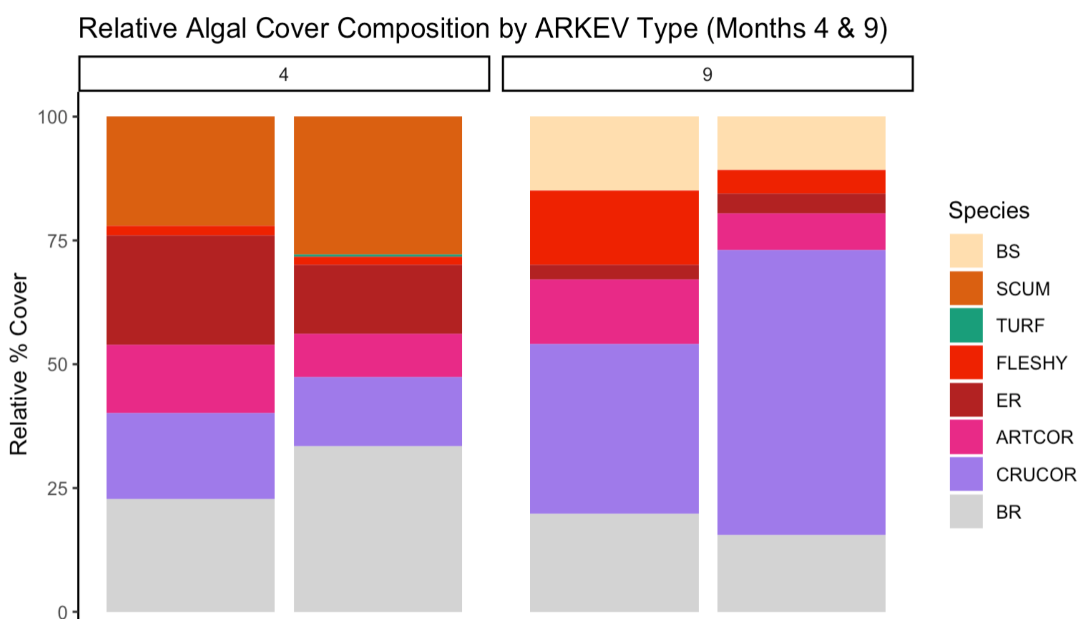

Figure 32. Relative percent cover of species across treatment types recorded in UPC surveys at the beginning of the season (month 4) and end of the season (month 9) in 2025.

Ecosystem response to Objective 1

Aerial Data:

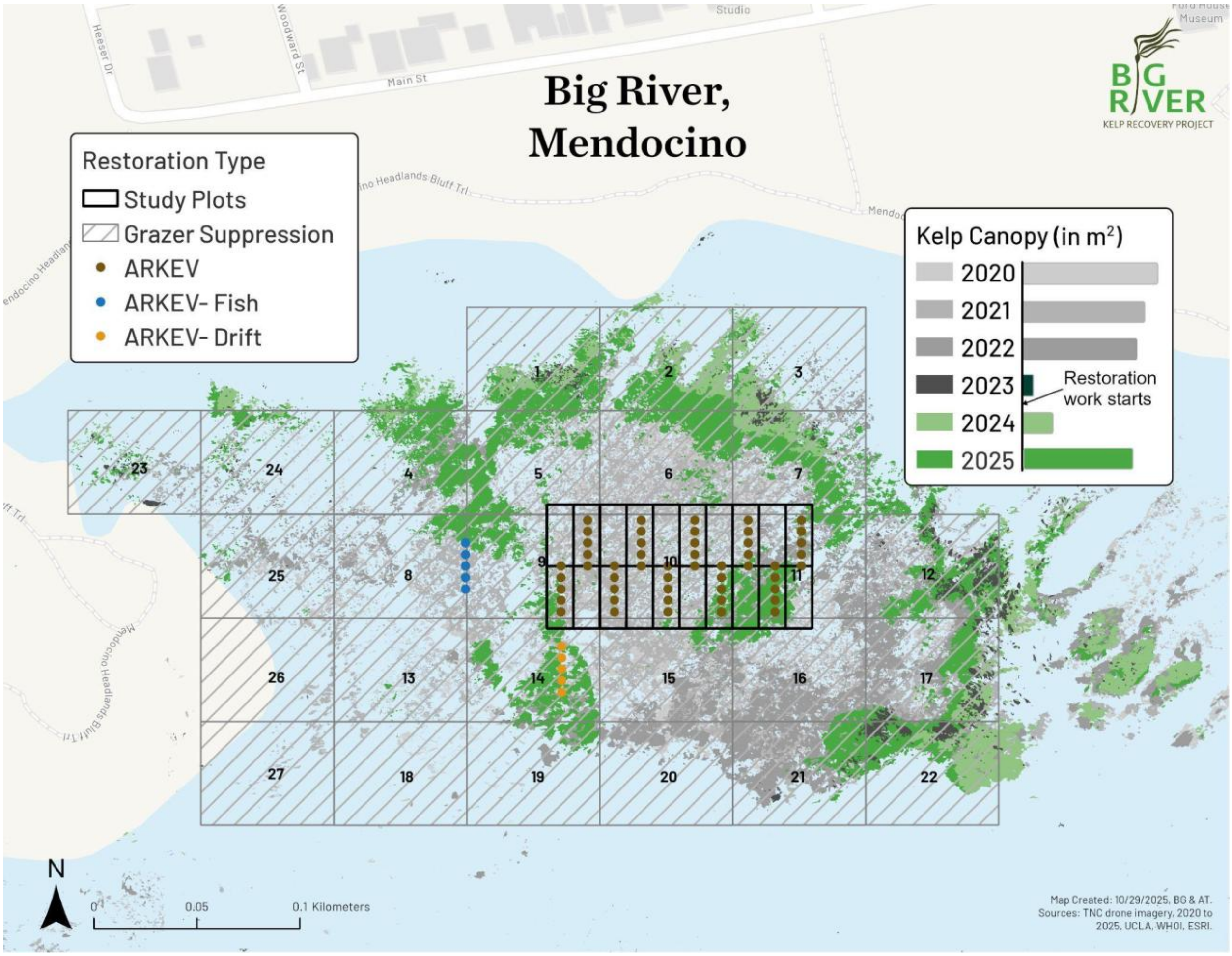

Figure 33. Site map for kelp restoration efforts at Big River, Mendocino. Kelp canopy area is designated by color. Kelp canopy was measured at 13,683m^2 in 2020, 12,348m^2 in 2021, 11,672m^2 in 2022, 1,211m^2 in 2023, 3,299m^2 in 2024, and 12,366m^2 in 2025. Kelp enhancement activities occurred in blocks 9, 10, and 11, and ARKEV units are designated by color.

Between 2023 (pre-restoration) and 2025 (during-restoration), kelp canopy at the Big River restoration site increased 921% (Figure 33). The control site (Van Damme), where no restoration interventions occurred, also experienced growth, with canopy showing a 245% increase. This signal likely means that oceanographic conditions were favorable for kelp at both of these locations. Yet, the percent increase in kelp canopy at the restoration site was approximately 3.75 times greater than the control site between 2023 and 2025, suggesting that restoration efforts may have been transformative in accelerating kelp rebound well beyond baseline environmental improvements. For final reporting (January 2027), we plan to incorporate additional sites throughout the region into this analysis to differentiate natural versus restoration-based recovery.

Subtidal Data:

A brief summary of kelp and sea urchin density changes based on restoration activities, provided by Reef Check, can be found in Figures 34-37, below. Preliminary results of subtidal surveys show an increase of bull kelp starting in July 2025 within the restoration site, whereas no changes were observed at the control site (Figures 34-35). Since the initiation of removal efforts in 2024, sea urchin densities have declined at the restoration site, while they have remained high at the control site (Figures 36-37). At the restoration site, it should be noted some areas with patchy densities were seen in July 2025 (shown by high error bar) (Figure 36).

A series of videos from the October 2025 survey can be found here.

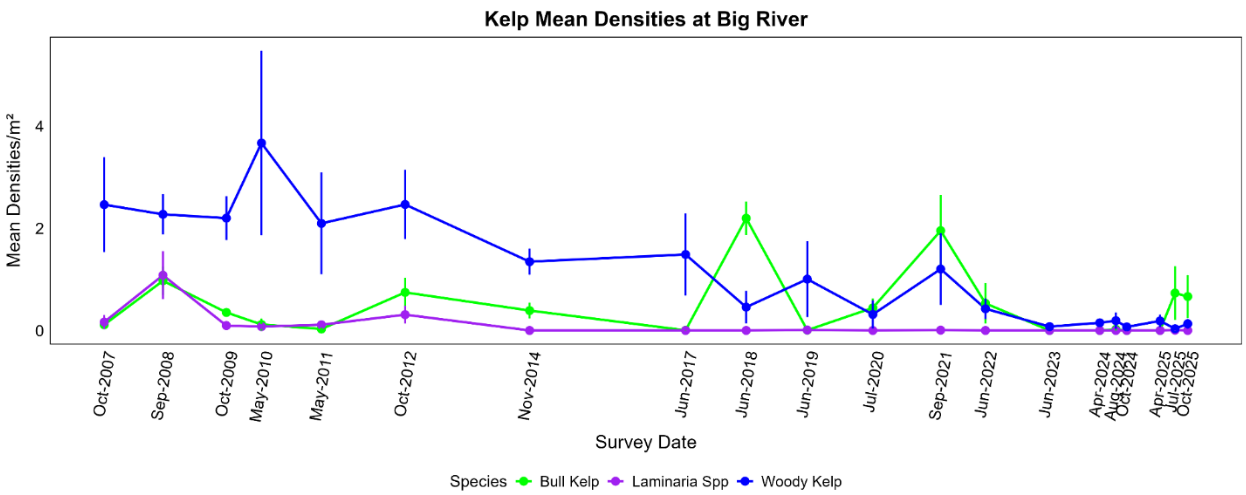

Figure 34. Mean kelp densities per square meter with standard error for canopy and subcanopy species at Big River from 2007-2025.

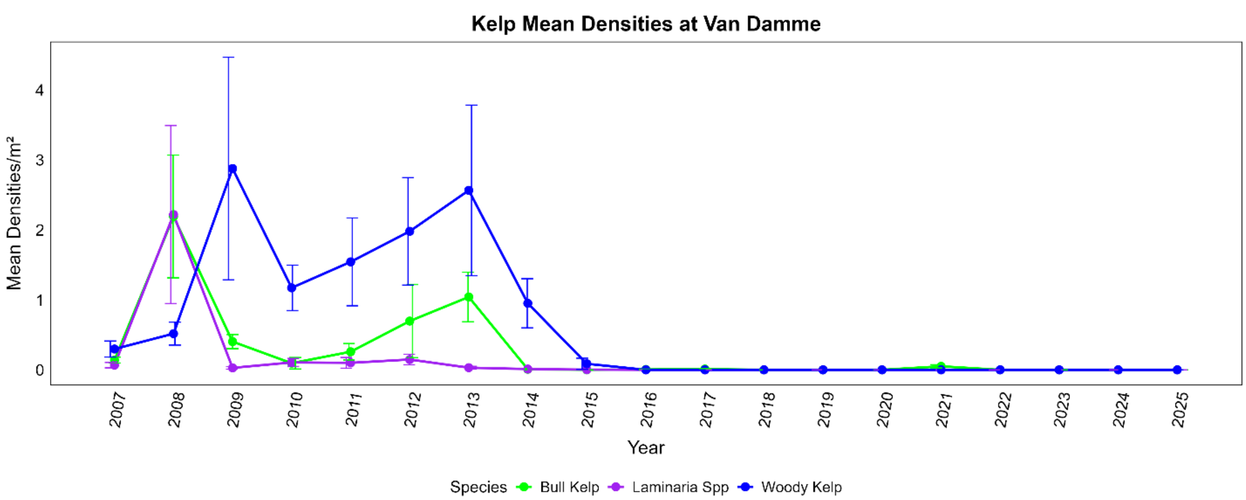

Figure 35. Mean kelp densities per square meter with standard error for canopy and subcanopy species at reference site, Van Damme from 2007-2025.

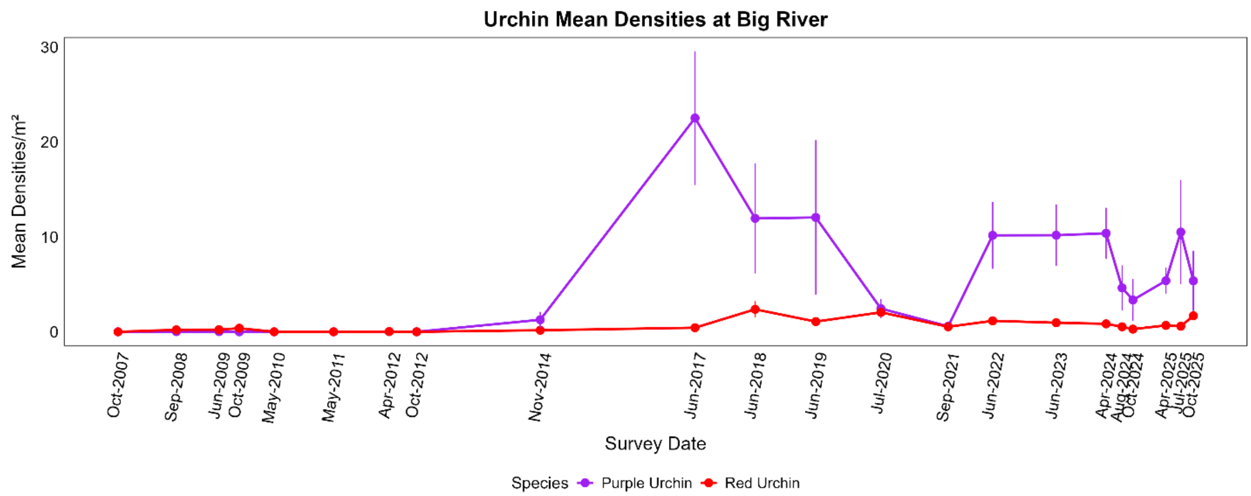

Figure 36. Mean sea urchin densities (>2.5cm in size) for both red and purple sea urchins per square meter with standard error at Big River from 2007-2025.

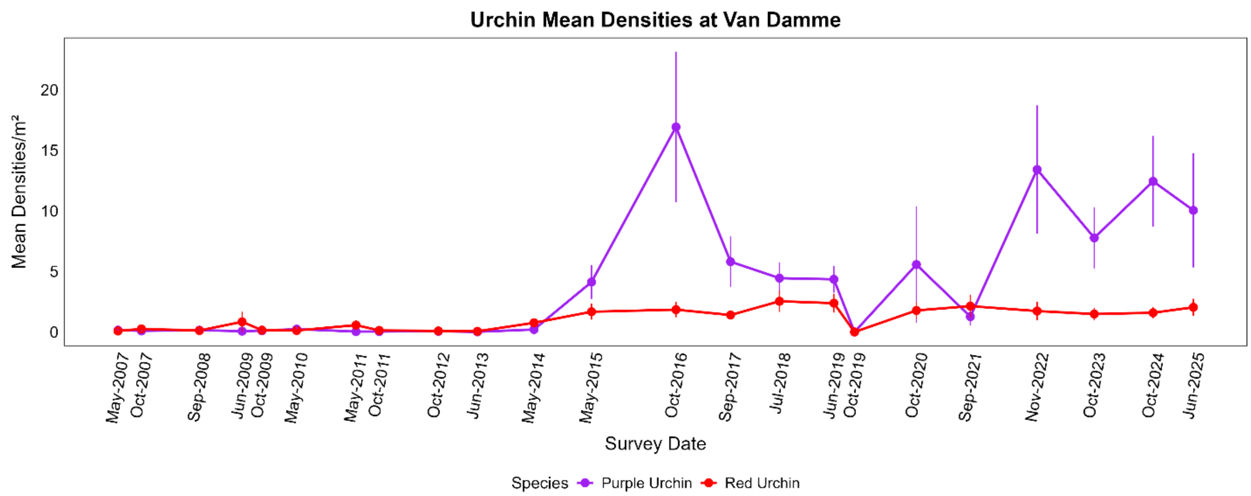

Figure 37. Mean sea urchin densities (>2.5cm in size) for both red and purple sea urchins per square meter with standard error at reference site, Van Damme from 2007-2025.

Objective 2

2. Investigate sea urchin fishery adaptation to effectively direct kelp restoration efforts and to evaluate blue economy opportunities in purple sea urchin removal
    a. Understand kelp forest and red sea urchin fishery feedbacks to guide sea urchin harvest for guarding remnant forests
    b. Assess historical and future capacity for red sea urchin diver adaptation in response to the collapse of the red sea urchin fishery
    c. Create a framework to assess downstream economic opportunity for various market uses of purple sea urchins

Objective 2a-b

Sea urchin fishery adaptation

This component of OPC HCE 45 is led by UC Davis and aims to evaluate how red sea urchin divers have adapted—and may continue to adapt—to the collapse of the red sea urchin fishery. The analysis is structured in two stages.

- Stage 1 establishes baseline participation patterns (2005–2014) using historical licensing, logbook, and landings data.
- Stage 2 examines post-decline adaptation (2015–present), assessing whether divers shifted to other dive fisheries, other regions, or out of fishing altogether.

Progress on the OPC HCE 45 diver-adaptation study advanced through several key milestones in 2025, though unexpected delays have extended the project timeline. In July, the team finalized the data security plan, built the secure computing environment, and received the confidential CDFW dataset. Data analysis began in August. In October, a flood in the secure server room damaged the firewall, cutting off access to the protected machine that stores the data. Although the device itself was unharmed, access was not restored until mid-November. Because of delays in receiving the dataset and the subsequent access interruption, the analysis will extend beyond the approved project period, and a no-cost extension is being requested.

Stage 1 is underway using MLDS landings data for major dive fisheries (abalone, sea urchin, sea cucumber). Early results confirm that the red sea urchin fishery dominated diver activity prior to 2015 and that only a minority of sea urchin divers participated in multiple fisheries. Ongoing analysis is assessing whether cross-fishery or cross-region involvement influenced divers' ability to adapt after the decline, and how participation changed in the early (2015–2019) and prolonged (2020–2024) phases of the collapse.

Several challenges are being addressed, including incomplete license identifiers in MLDS records and the lack of visibility into non-fishery employment or fishing activity outside California. To partially fill these gaps, CDFW data is being augmented with PacFIN records.

This work will provide a clearer picture of diver resilience and mobility within and beyond California's commercial fishing sector, information that will directly inform KRMP implementation and broader workforce adaptation planning.

Objective 2c

Dockside monitoring

Of sea urchins landed for restoration in 2024-2025, nearly 5,000 sea urchins were analyzed to characterize sea urchin size frequency, morphometrics, disease presence, and gut content. After the 2024 field season, a preliminary analysis of sea urchin morphometrics generally showed that sea urchins had a higher gonad weight and test diameter relationship when kelp was present than in those collected from areas devoid of kelp canopies. To build on this preliminary analysis, in 2025, we designed a study to measure sea urchin morphometrics in relation to sea urchin proximity to bull kelp at the Big River restoration site. Using aerial kelp canopy data (Figure 38) collected at 3cm resolution scale, we were able to calculate mean distance between urchins collected within a block and the nearest kelp patch (i.e., food source). The preliminary results clearly reveal that with increased proximity to a kelp patch, there is increased sea urchin gonadal condition (Figure 39). As this data is shared with commercial sea urchin divers, we anticipate it will be especially useful to inform adaptive management of the project and further identify opportunities for strategic harvest for food and non-food uses of sea urchins.

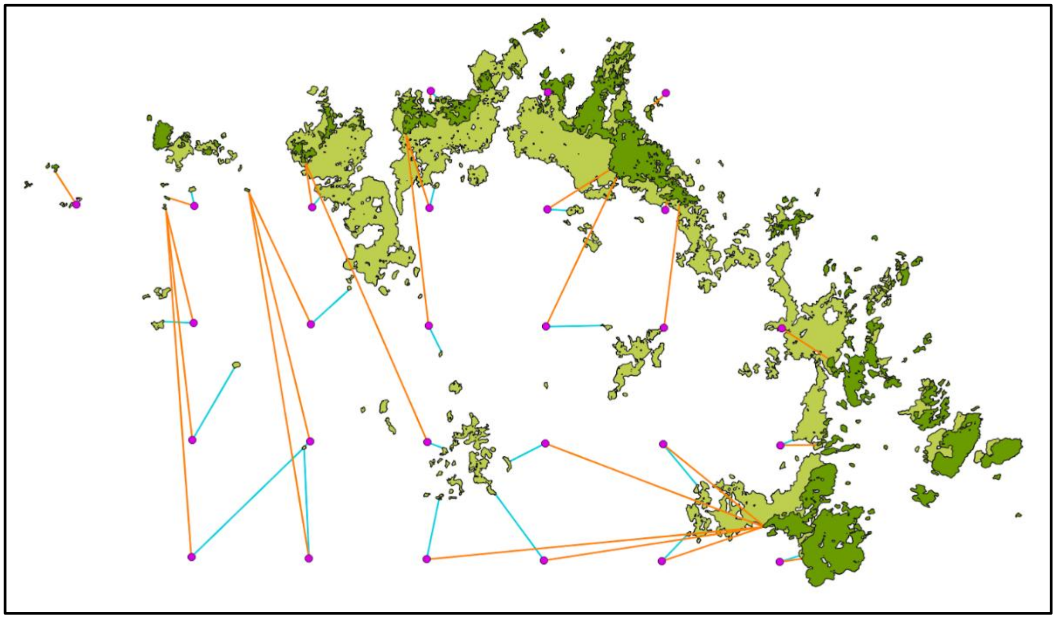

Figure 38. Distances from sea urchin harvest block centroids (pink points) to nearest kelp patch > 4m2 in 2024 (orange lines), and 2025 (blue lines). Dark green represents kelp canopy cover in 2024, and light green represents kelp canopy cover in 2025.

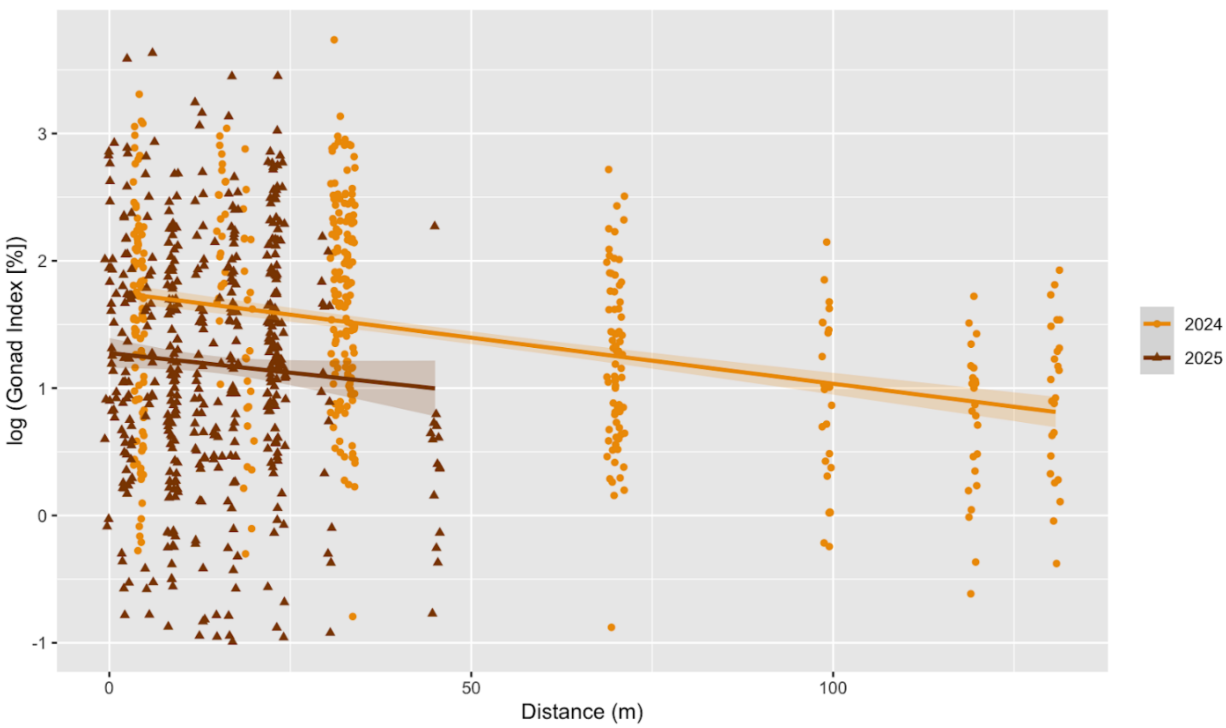

Figure 39. Log-transformed gonad indices of purple sea urchins as a function of distance (m) to nearest kelp patch in 2024 and 2025. Points represent individual gonad index data. Points were jittered vertically and horizontally to better visualize data density. Lines represent linear regression model predictions shaded with 95% confidence intervals. Predictive model coefficients can be found in Table 1.

Non-food market development/opportunities

For the last several years, TNC has been advancing ambitious work to identify market-based solutions that will dramatically reduce the cost of urchin removals for kelp restoration in California and incentivize harvest of this overabundant species. Over the next five years, as part of California Ocean Protection Council's 2026-2030 strategic plan to restore at least 2,000 acres of degraded kelp forests, approximately 26 million pounds of purple sea urchins could be harvested from degraded kelp forests to achieve this target. This represents a blue economy opportunity with a value of $39 million in purple urchin harvest. A framework was developed to assess downstream economic opportunities for various market uses of purple urchins, along with its implication for sea urchin removal and blue economy opportunities.

While purple sea urchins have not conventionally been widely utilized for seafood in comparison to red sea urchins due to smaller gonads and more intensive processing requirements, sea urchin ranching has distinct advantages that can increase the quality and value of purple sea urchins. With modest startup costs, relative stability especially in winter seasons, and recent advances in feed and aquaculture systems – sea urchin ranching provides an avenue for increasing the value of purple sea urchins for food uses, when harvested from targeted restoration sites.

However, not all sea urchins at a given restoration site can meet the minimum size requirements for sea urchin ranching and seafood. As a supplementary approach, non-food uses for purple sea urchins can offer an additional market-driver for commercial sea urchin divers, while providing a more comprehensive, profitable harvest to facilitate kelp forest recovery. Since 2021, TNC has been working with Primitives Biodesign to develop new non-food uses and product applications for purple sea urchins. Primitives is a public benefit corporation founded by MIT engineers and designers that develop advanced materials and products from a range of biomass to address environmental and ecological challenges. As a result of this collaboration, Primitives has developed a series of use cases and product applications for purple sea urchins, that has the potential to incentivize harvest of these animals to drive kelp forest recovery, support blue economy with purple sea urchin harvest, while providing an eco-friendly alternative to conventional manufactured goods.

With dockside data and sea urchin demographic information acquired from sea urchins landed for restoration, we have been working to create a framework to assess downstream economic opportunity for various market uses of purple sea urchins. With these data, we hope to visualize economic opportunity as we categorize sea urchin by size: < 5.72 cm (2.25 in.) diameter as non-food and > 5.72 cm (2.25 in.) diameter as food. For example, using the size criteria above and the sea urchin demographic data from dockside monitoring, this allows us to understand X% is of viable size for food markets and Y% for non-food markets at a given restoration site.

Primitives has developed applications and use cases for non-food applications for purple sea urchins. These include four patent-pending product applications that could potentially drive large-scale purple sea urchin removal, as shown in Figure 40, which include: pigments, leather, engineered stone, and 3d printing filament. A unique class of natural pigments called spinochromes was isolated and stabilized from purple sea urchins, giving rise to three unique colors - purple, red, and orange. A leather made from sea urchin is compostable and marine biodegradable with enhanced mechanical and moisture barrier properties. A 3d-printing filament was produced, and tests show they are compatible with standard, off-the-shelf 3d printers containing 1.75mm nozzles. A *biomarble* stone, termed Urchinite™ which has been engineered with competitive mechanical performance compared with commercial natural and engineered stone.

Of the four materials products, Urchinite engineered stone was selected for further research, development, and subsequent launch as the first debut sea urchin derived product under the brand MARBLIS. Due to Urchinite's high technology-readiness level, flexibility with sea urchin composition, alignment with restoration targets, market opportunity, and demand, it offers a promising product that bridges California's green building initiatives, as well as kelp restoration and blue economy initiatives. Studies have been conducted to examine preliminary technical, economic, and environmental viability of MARBLIS Urchinite, with a promising go to market path to commercial adoption by architects and designers as interior surfaces in the green building materials market for the construction industry. Until this time, no such uses have existed for non-food applications of purple sea urchins.

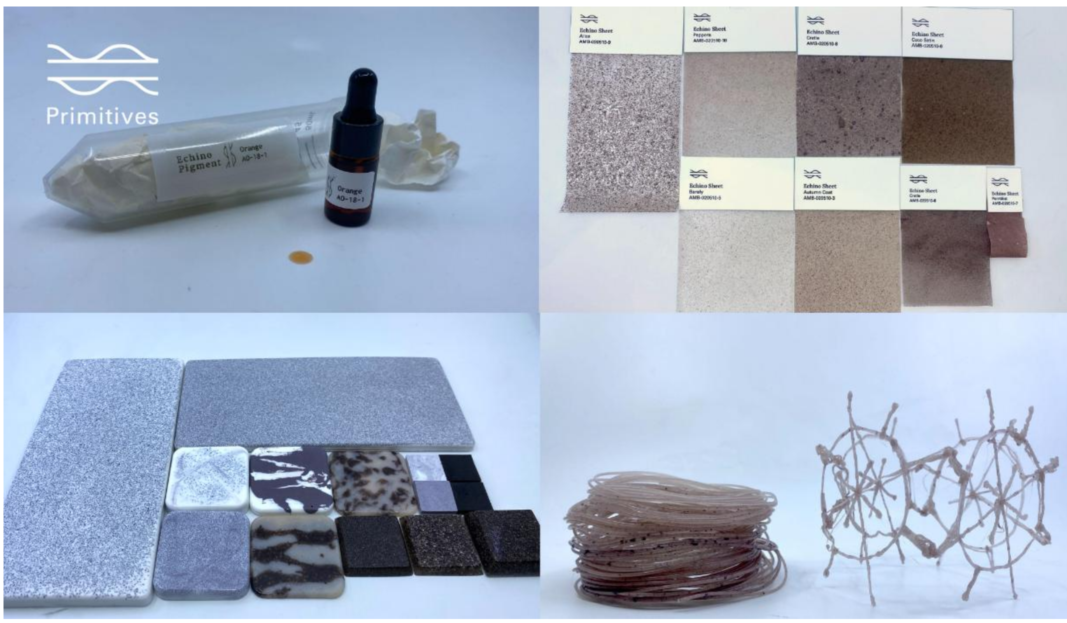

Figure 40. Engineered urchin materials and products developed by Primitives from 2021 - 2023: (top left clockwise) natural pigments, leather, marble, 3D printing filament

Over the last year, Primitives Biodesign has advanced prototypes to demonstrate the marketability of sea urchin-derived biomaterials, specifically with Urchinite engineered stone for the architectural surfaces market. At the same time, they have calculated the volume of sea urchin that could be absorbed by their product production, their target market capture, and the resulting impact on the sea urchin population control. To date, Primitives has processed a total of 1,563 pounds of fresh purple sea urchin for research and development since 2021, as shown in Figure 41. Primitives team has transitioned from phase 1 exploratory research in 2021-2023 to phase 2 targeted engineered stone product development beginning in 2023 onwards. In May 2025, Primitives launched MARBLIS architectural surfaces brand to bring its debut product, Urchinite to the market (Figure 42). Its successful launch led to recognition from leading press outlets including SF Chronicle, The New York Times, and Sunset Magazine. This has attracted over 100 architects, designers, and homeowners who have placed pre-orders and joined the waitlist to be the first to install Urchinite. This suggests promising customer interest and demand for Urchinite engineered stone, demonstrating viability as market-driven solution for purple sea urchin removal and kelp restoration.

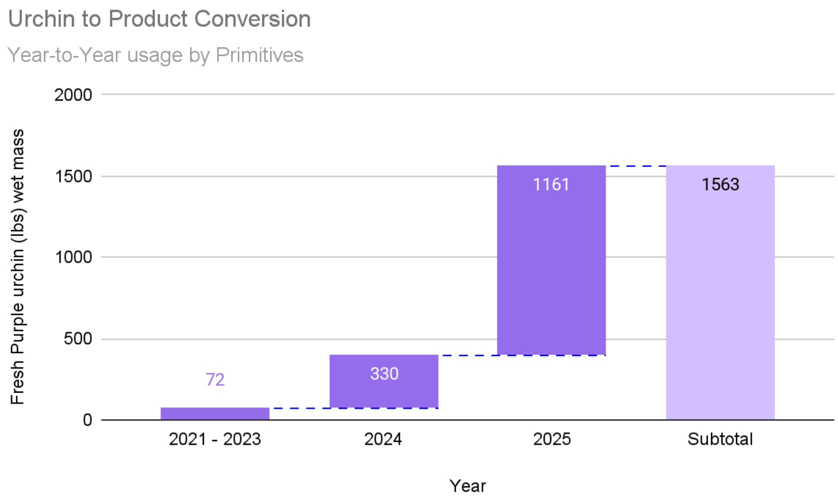

Figure 41. Primitives year-to-year purple sea urchin processing and product conversion from 2021 to 2025 in wet mass

In response to this initial customer traction, the Primitives MARBLIS team has begun to optimize material performance and conduct manufacturing trials, in preparation for its first pilot product installations that are planned for summer 2026. A suite of baseline material performance tests were conducted to understand how Urchinite compares with standard commercially available natural and engineered stones in use today. In our baseline study, Urchinite was found to have very strong compressive strength, with the ability to withstand loads of up to 16,700 psi following ASTM C170. Urchinite surpasses requirements for our target applications. For reference, required compressive strength for countertop applications is 6,000 psi, and flooring is 4,500 psi. When compared to natural and engineered stone in compressive strength, Urchinite exceeds the performance of natural marble (avg. 16,242 psi), engineered terrazzo (which averages 9,979 psi), and concrete (avg. 3,250 psi). Urchinite is exceptionally lightweight, weighing only 12 lbs/sqft at 1.25" thickness. It is 21% lighter than the average engineered quartz, and 31% lighter than the average natural marble. Due to Urchinite being both strong and lightweight, it has exceptional compression strength to weight ratios and sits on the higher end of both natural and engineered stone, as shown in Figure 43.

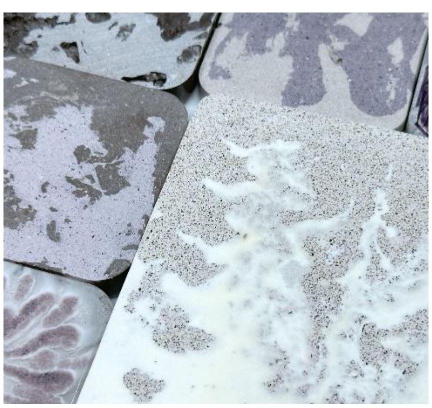

Figure 42. Close up of Urchinite surface

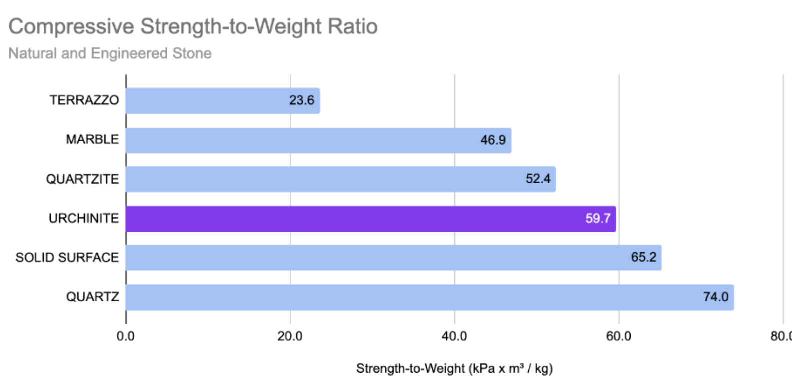

Figure 43. Compressive strength to weight ratios of Urchinite, compared to other widely used surfaces on the market

In fall 2025, Primitives successfully completed manufacturing trials and converted ~700 lbs of fresh purple sea urchin into raw materials. Raw materials were then manufactured into several large Urchinite stone panels totalling 14.28 squarefoot, each measuring 3 foot by 1.6 foot at ⅜" thick and 2 foot by 1 foot at ¾" thick. Figure 44 shows example images from Primitives and partner plants in the course of the trial. These successful manufacturing trials demonstrate proof of concept viability and feasibility of commercial scale sea urchin processing and Urchinite stone manufacturing.

This paves the way for upcoming pilot production runs in 2026, where an estimated 32,085 lbs of fresh sea urchins will be processed into Urchinite units to be utilized and installed by pilot customers. Dockside data collected on sea urchin demographics, size, and frequency provides an understanding of how urchin size might impact material performance, visual characteristics, and batch-to-batch consistency of Urchinite as product is manufactured from a given restoration site over time. In recent landings, we've observed that harvest sites with higher densities of small sea urchins have contributed significantly to rock contamination - posing issues to equipment, increasing processing time and cost. Additionally, sea urchin landings with high rock contamination are more likely to be rejected by manufacturing partners and customers, as they damage machinery and mislead customers due to limited sea urchin content. While Urchinite can utilize any size, health, and state of sea urchin with minimal selective harvest required, sea urchin characteristics such as demographics, harvest location, size, and frequency impact ultimate material performance, chemical composition, and season-to-season consistency is still largely unknown. In the upcoming season, we aim to evaluate how sea urchin diameters and densities harvested by blocks impact material performance such as compressive strength, tensile strength, and flexural strength. Rigorous collection of sea urchin dockside data as it relates to specific restoration sites (and blocks) over time, will enable us to understand how such variations may impact product quality, performance, aesthetics, processing requirements, and production schedules to ensure product scalability and customer satisfaction.

Figure 44. Primitives MARBLIS manufacturing trial successfully converted raw dried sea urchin into large proof of concept Urchinite slabs at manufacturing plant.

The countertop market alone exceeds $11 billion in California, supported by more than 10,000 architectural design firms, new statewide housing mandates, wildfire rebuilding initiatives and 2028 LA Olympics, which would drive construction and remodeling activities. Across the U.S., the interior building materials opportunity spans $143 billion, while the global green building materials industry is valued at $423 billion and growing 12% annually. Additionally, recent US tariffs and global epidemic of silicosis have impacted the cost of overseas engineered stone materials, presenting a favorable market condition for US manufactured innovations like MARBLIS Urchinite to enter the market by offering a safe, durable, eco-friendly, and cost competitive alternative. Figure 45 shows the annual projected sea urchin usage based on MARBLIS Urchinite sales targets and available manufacturing capacity of our partner plant in California. A projected amount of up to 73,040 lbs of fresh sea urchin will need to be processed into Urchinite slabs in 2027 in order to fulfill planned sales targets. The MARBLIS partner manufacturing plant located in the Bay Area, California has a production capacity which can absorb up to 7,498,400 lbs of fresh sea urchin annually - converting fresh sea urchin into MARBLIS Urchinite stone slabs.

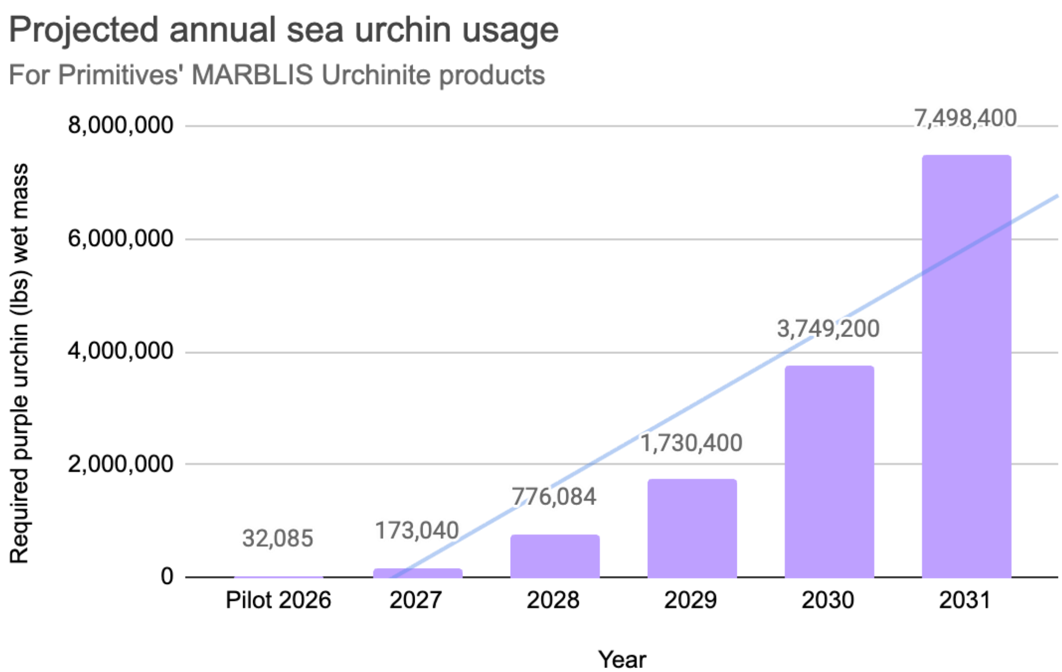

Figure 45. Primitives future 2025-2027 projections for purple urchin processing and product conversion.

Further development of MARBLIS Urchinite products, applications, and performance could unlock the key to deploying market-based solutions for sea urchin harvest and kelp restoration. These demonstrate greater promise even than their seafood counterparts. Opportunities in the blue economy within these market-based solutions support regional workforce development. Additionally, MARBLIS Urchinite architectural products are regionally manufactured and offer strategic supply chain security for US manufactured materials, while providing high performance, low-carbon, VOC-free, and silica-free products in support of California's strategic green building initiatives.

Objective 3

3. Ensure long-term kelp restoration success and stewardship by providing opportunities for the local community through experience and art

a. Provide internships for local divers to build diver workforce capacity and engage previously underrepresented groups in monitoring and restoration

b. Develop a series of tangible and replicable art/science products and events to engage and communicate project goals and outcomes

Objective 3a

Internships

The Kelp Restoration Internship, hosted by Reef Check, offered a unique opportunity for early-career marine scientists to gain hands-on experience in marine science and conservation while building meaningful connections in the field. Interns had the opportunity to participate in restoration planning meetings alongside leading kelp forest restoration experts from NGOs, academia, government agencies, tribes, and recreational and commercial fisheries.

Reef Check (RC) provided internships for a total of six interns, local to northern California, over the two-year funding period. A summary of interns, backgrounds and learning experiences can be found in Table 3. RC Staff also supported four additional interns from The Nature Conservancy (TNC) through the COAST internship program to maximize research impact for project and learning opportunities. All six interns participated in a range of activities, including ecosystem monitoring, attending weekly field meetings with project partners, and community outreach.

Non-divers contributed to sea urchin dissection studies, assisted with data entry and report writing, supported field operations through data management and top-side data collection, and supported outreach activities as part of the HCE OPC-45 award. Those with RC dive training assisted with subtidal surveys at Reef Check long-term monitoring and restoration sites. Those with AAUS training assisted with Objective 1 activities led by Moss Landing Marine Laboratory, Sonoma State University and The Nature Conservancy in conducting research activities.

RC supported individual interests to expand their career and experiences. For example, interns were offered the ability to obtain an open water dive certification to expand upon their skillsets (Table 3). Others attended and presented at the Western Society of Naturalists conference. At the end of the internship, many of the interns reflected on their experience in individual reports available by request. Overall, we are happy with the internships and their feedback. We believe the interns had a meaningful experience and expanded their knowledge of restoration science.

Ecosystem Monitoring

In the spirit of leveraging long-term datasets and communicating site-wide responses to restoration, through the OPC HCE 45 award, RC led in conducting seasonal ecosystem monitoring of kelp, invertebrates, fish and habitat via their long-term monitoring program protocols. Data collected was reported in Objective 1 and was a highly valuable dataset to inform sea urchin harvest (e.g. tracking sea urchin densities across site) and overall project progress (e.g. kelp recovery and other ecologically, economically, and culturally valuable species such as rockfish, abalone, kelp and red sea urchin).

During the course of the award, RC long-term monitoring data has been used in presentations to legislative staff and state agencies, such as the Ocean Protection Council, and California Department of Fish and Wildlife through the Accelerating Kelp Research and Restoration (AKRP) and Kelp Restoration Management Plan (KRMP) meetings. Restoration data has also been used to communicate project results, such as the Western Society of Naturalists conference in 2024 and 2025.

Over the two years, Reef Check staff, volunteers, and interns successfully conducted six subtidal monitoring surveys at the restoration site, Big River and two subtidal monitoring surveys at the control site, Van Damme. Big River surveys were conducted seasonally in April, August, and October, while the control surveys were conducted annually. The number of divers, dives and time to complete this work is summarized in Table 2.

Table 2. Summary table of Reef Check staff, volunteers, and interns participating in subtidal monitoring surveys at the Big River restoration and Van Damme control sites.

Year	Site	Total Number of Divers	Days to Complete
2024	Big River	5	3
2024	Van Damme	2	1
2025	Big River	12	4
2025	Van Damme	14	1
Total		**33**	**9**

Overall, Reef Check successfully met its goals with respect to both Objectives 3a and 3b. There have been no cost overruns. Qualitative outcomes are best described by the attached reports from the six interns available by request. All monitoring data has been provided to The Nature Conservancy in excel spreadsheets at the end of each calendar year.

Table 3. Summary of summer interns, residency, skill set, and opportunities to build a resume in restoration science beyond scope of internship. In the Focal Area of Interest column, we summarized language from each intern's application, and verbal responses as to what they were hoping to achieve.

	Name	Home Institution/College	Degree & Graduating Year	Residency	Skill set	Focal Area of Interest	Additional Internship Benefits
2024	Kyla Marcello	University of California, Los Angeles	BSc 2026	Fort Bragg	Non-diver	Receiving dive training, becoming a Reef Check diver, expanding knowledge on restoration activities in hometown	Obtained Open Water Certification
	Cassidy Daniels	University of Idaho (online courses)	MSc 2025	Fort Bragg	Non-diver	Expanding knowledge on restoration activities and marine conservation in hometown	Attended WSN
	Kylee Michaud	Cal Poly Humboldt	BSc 2025	Humboldt County	Diver-AAUS	Contribute to conservation and restoration, and further experience in research diving	Participated in other Restoration Projects ecosystem monitoring, such as Big Sur and Tankers Reef
2025	Dylan Hutchinson	Pitzer College	BA 2026	Fort Bragg	Diver-AAUS	Pursuing a graduate degree in marine biology, marine conservation research, expand on diving experience, assist with restoration in hometown	Presented poster on Sea Urchin Morphometrics in Big River at WSN
	Sofia Orelind	University of California, Santa Cruz	BSc 2025	Humboldt County	Diver-AAUS	Contribute to conservation and restoration, and further experience in research diving	Participated in other Reef Check long term monitoring camp outs and events
	Joanie Hardcastle	Cal Poly Humboldt	BSc 2025	Humboldt County	Diver-AAUS	Contribute to conservation and restoration, and further experience in research diving	Participated in other Reef Check long term monitoring camp outs and events

Objective 3b

Community engagement and public outreach continued to expand significantly across 2024 and 2025, driven by the growing success of KelpFest! and the strong performance of the Bull Kelp Webstory. Together, these efforts have strengthened public awareness of kelp forest decline, restoration science, and the collaborative work underway along the North Coast.

KelpFest! launched its inaugural season in 2024 with 16 events spread over five weekends, drawing 1,590 registered participants and generating substantial online interest, including 11,394 website hits and 8,900 unique visitors. The festival was guided by a 10-member Steering Committee and received an enthusiastic response from the community, establishing a strong foundation for future growth.

Building on this momentum, KelpFest! 2025 expanded its reach and visibility. The second year featured another 16 events, condensed into a dynamic five-day program that attracted 2,462 participants—an increase of more than 50% from the previous year. Digital engagement also grew, with 12,000 website hits, 25,000 page views, and 8,200 unique visitors. Organizational capacity strengthened as well, with the Steering Committee expanding to 14 members and the addition of three new promotional reels. Notably, the festival received national attention through a feature article in *The New York Times*, further elevating its profile and reinforcing community enthusiasm for establishing KelpFest! as an annual signature event.

Across both years, KelpFest! delivered a combined total of 32 events and engaged 4,052 participants, supported by 23,394 website hits and 17,100 unique visitors. The festival's rapid growth reflects both rising public interest in kelp forest recovery and the effectiveness of coordinated outreach strategies. Plans are underway for KelpFest! 2026 to further integrate the program into the community and explore ways to further benefit the local economy as well as this essential coastal ecosystem.

Complementing these in-person and digital engagement efforts, the Bull Kelp Webstory (bullkelp.info)—launched in November 2023—continued to serve as a major educational platform. To date, it has attracted 40,000 visitors and generated 309,000 page views. The addition of 11 new pages, along with updates to the resources list, the integration of a new restoration database and a new webpage for the Eastern Pacific Kelp Congress (EPaK) has expanded its value as a comprehensive, accessible resource for the public, practitioners, and policymakers across the Eastern Pacific

Together, KelpFest! and the Bull Kelp Webstory demonstrate the growing reach and impact of community-centered communication strategies. These platforms are helping to build broad public support for kelp restoration, strengthen local stewardship, and elevate the visibility of science-based recovery efforts across the region.