Kelp Restoration in the Boulder Patch

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Abstract

This study explored the use of artificial reefs in the Stefansson Sound Boulder Patch, Beaufort Sea, for the enhancement of the epilithic community, especially the foundation kelps of the system. Artificial reefs consisting of natural rocks from the Brooks Range were deployed at four sites within the Boulder Patch in 2021, and five rocks per reef were re-sampled in 2022 and 2023. In addition, sediment traps were deployed at three of the sites next to the artificial reefs, and surveyed annually. A small artificial reef consisting of concrete pieces was deployed at one site to assess its substrate suitability. Recruitment occurred within one year, dominating in biomass mostly of the red alga *Phycodrys fimbriata*, the sponge *Halichondria panicea*, and the bivalve *Hiatella arctica*. Other common recruits were barnacles and spirorbid polychaetes. Individuals of the kelp *Laminaria solidungula* also were observed on one rock in each year. Recruitment occurred through a mixture of vegetative growth, fragment dispersal, mobile immigration, and new recruitment of larvae or spores. In both 2022 and 2023, episodic events of what appears to be mass recruitment of nudibranchs (*Onchidoris bilamellata*) occurred in 2022, and chitons (*Stenosemus albus*) in 2023. Such episodic events may be common and could exert significant grazing or predation pressure on new recruits and influence the development of the epilithic community. Sedimentation differed intensely among sites and between the two study years. Contrary to expectation, the site with the highest sedimentation rates in both years also was the site with the highest recruitment biomass, presenting the possibility of sedimentation-supported recruitment. Should artificial reefs be used for habitat enhancement, natural rocks from the Brooks Range appear to be a suitable substrate. Artificial reefs should be deployed as smaller reef patches throughout the Boulder Patch, compared to one large reef, to offset the highly variable environmental conditions across the Boulder Patch range and the seemingly localized nature of episodic recruitment events. Despite the early recruitment after one year, including kelp, the development of a mature epilithic community resembling that natural community will still take decades.

1   Introduction

Nearshore systems in the Arctic are undergoing tremendous changes due to climate variations and changes in the cryosphere. Unlithified coasts common along the Alaskan, Canadian, and Siberian coastlines are particularly affected by erosion from climate change-related melting permafrost and increased weather events (Irrgang et al. 2022). Changes in the seasonal timing of sea ice cover, thickness, and magnitude of bottom-fast ice (Barnhart et al. 2014) affect the physical integrity of the coasts, often resulting in dire consequences for human settlements and infrastructure, as well as for the shallow marine ecosystems along Arctic shores.

As opposed to the open ocean, one unique feature of many Arctic coasts is the presence of benthic primary producers; namely macroalgae fueled by the light penetrating to the seafloor. Macroalgae provide important habitat for associated taxa increasing overall diversity, and support coastal food webs to grazers or, with the provision of organic matter, to the detrital pool (Dunton and Schell 1987; Renaud et al. 2015; Paar et al. 2019). One of the main consequences of coastal erosion, permafrost melt, and increased river discharge on these macroalgae is the large quantity of sediment that is being transported into the Arctic coastal system (Syvitski 2002; Radosavljevic et al. 2022). While some of that sediment input increases nutrient and organic carbon delivery which enhances primary production (Terhaar et al. 2021), it can also present a severe disturbance to the coastal benthic system. Suspended and deposited sediments pose a risk for benthic primary producers (macroalgae) because of the attenuation of light (Bonsell and Dunton 2018; Singh et al. 2022), burial and abrasion of microscopic dispersal stages (Spurkland and Iken 2011; Traiger and Konar 2017; Phelps et al. *in revision*), and clogging of delicate feeding apparati of filter and suspension feeders associated with macroalgal stands (Miller et al. 1992; Hamann and Blanke 2022).

Another aspect of sediment input into the Arctic coastal system is the limitation of available light, which, in turn, can limit kelp production (Bonsell and Dunton 2018; Filbee-Dexter et al. 2019). Light in the winter is typically limited because of the low angle of the sun and sea ice, but in past decades high light availability during the ice-free summer has traditionally supplied these shade-adapted macroalgae with sufficient light to sustain annual production (Dunton 1990; Dunton and Dayton 1995; Aumack et al. 2007). Contrary to findings in the offshore shelf regions of the Chukchi and Beaufort seas where the decline of seasonal sea ice has been predicted to result in higher pelagic primary production (based on increased light availability (Arrigo and van Dijken 2015; Song et al. 2021) or macroalgal production along many rocky shores in other regions of the Arctic (Scherrer et al. 2019; Lebrun et al. 2022)), light availability for benthic primary production in the sedimentary coast regions of the of the Beaufort Sea has actually declined in recent years (Bonsell and Dunton 2018). This is due to an increase in light-absorbing suspended sediments in the summer based on resuspension from increased storm activities and increased river discharge with climate warming (Aumack et al. 2007; Bonsell and Dunton 2018; Singh et al. 2022). Kelp species occurring in the coastal Beaufort Sea areas are low-light adapted (Bartsch et al. 2008), with the most extreme adaptation in *Laminaria solidungula*, which has the lowest annual quantum yield budget on record (45 mol photons m^{-2} yr^{-1}; Dunton 1990). However, sedimentation can decrease local light conditions, making them insufficient to meet the kelps' carbon balance (Aumack et al. 2007), resulting in physiological stress for the plants (Dunton and Jodwalis 1988).

Disturbances such as from high sediment input can severely hinder the recruitment of new individuals and regrowth/recovery from surrounding organisms in the coastal Beaufort Sea (Dunton et al. 1982). Experimental clearings of natural rock substrates or settlement tiles suggest that full recovery of the sessile community may take a decade or longer (Konar 2007; Bonsell and Dunton 2021). Vegetative regrowth of encrusting species may assist in recovery, but recruitment of habitat-forming kelps on these available substrates was not observed in these experiments (Konar 2013; Bonsell and Dunton 2021). This leads to the assumption that dispersal and settlement of propagules may be the bottleneck in natural recovery. Among the most likely explanations for this bottleneck are the possible limitations of suitable settlement substrate or limited spore settlement due to high sedimentation. Spores are the main dispersal stage of kelps. Some kelp spores have the ability to disperse over the course of weeks (Reed et al. 1992), but many have spores that will settle close to where they are released. In many kelps, significant

dispersal is limited to a few meters (2–3 m) past the release location (Reed et al. 1988). If no suitable substrate is available in this close range, a large number of spores will not be viable. Under sediment disturbance, any new recruitment is likely to be drastically reduced.

The purpose of this project was to explore kelp and other epilithic organism recruitment limitation in an isolated kelp community in the Stefansson Sound Boulder Patch in the coastal Beaufort Sea. We established an artificial reef in the Boulder Patch to assess the role of substrate limitation for epilithic organisms and the possibility of artificial reefs aiding in the mitigation of habitat loss in the coastal Arctic in this highly suspended sediment-influenced environment.

2   Site Description

Alaska's Beaufort Sea shelf is typically characterized by silty sands and mud, with hard substrate for macroalgal beds and associated organisms mostly absent (Barnes and Reimnitz 1974). In 1971, a boulder area extending approximately 63 km^2 and harboring a diverse kelp and invertebrate community, was discovered near Prudhoe Bay in Stefansson Sound, Alaska (Figure 1). This area, named the Boulder Patch, has been subject to much research and monitoring due to the need to protect unique, diverse, and sensitive biologically productive systems. Kelps, specifically the Arctic endemic *Laminaria solidungula*, and secondarily the broad-range species *Saccharina latissima* and *Alaria marginata*, are the foundation species and main primary producers for this area (Dunton et al. 1982; Dunton 1990; Dunton and Schell 1987; Dunton and Jodwalis 1988; Dunton and Schonberg 2000). In addition to these kelps, a variety of other brown, green, and red algal species add to the system diversity and habitat structure (Wilce and Dunton 2014). Several hundred invertebrate species, mostly sessile taxa such as sponges and byrozoans, but also a large number of mesograzers (amphipods, isopods) and some larger gastropods and sea stars are found in the complex three-dimensional structure created by these macroalgae (Dunton and Schonberg 2000). Macroalgae also provide a food source for such Arctic rocky systems, either via direct grazing or through particulate organic matter (POM) (Dunton and Schell 1987; Buchholz and Wiencke 2016; Filbee-Dexter et al. 2019), adding to the ecological significance of the Boulder Patch as a diversity and productivity hotspot in the region.

3   Relevance to the Coastal Marine Institute

The Boulder Patch region is of interest to the Coastal Marine Institute (CMI) and the Bureau of Ocean Management (BOEM) as this highly diverse and sensitive ecosystem is located in the midst of ongoing oil and gas extraction activities of the Prudhoe Bay oil field. To the southwest of the Boulder Patch is the Endicott Production Island (operated by Hilcorp Alaska, LLC), an artificial island connected to the mainland by a causeway. Toward the northwest of the Boulder Patch is Northstar Island, a 20,000 m^2 artificial island supporting a production well to harvest the Northstar Oil Pool. The above-mentioned climatic stressors, in addition to potential anthropogenic influences from these extraction activities, require a better understanding of potential mitigation strategies to ensure the persistence of the high-diversity and highly productive Boulder Patch community.

This project addressed the CMI Framework Area requesting *"Information for a better understanding of marine environments affected by oil and gas exploration and extraction"* by providing information regarding kelp restoration to support management decisions. One of the key topical areas of interest in the CMI 2018–2019 Environmental Studies Program was *"Studies of impacts to kelps from environmental variability and disturbance."* The project also directly addressed BOEM Program Announcement M19AS00007 Selected Research Topic *5. Kelp Restoration in the Boulder Patch*. The work addressed these target topics by testing artificial reefs for the enhancement of kelp foundation species in the Boulder Patch to provide a better scientific understanding of how the potential impacts of OCS oil and gas activities on this sensitive environment could be mitigated.
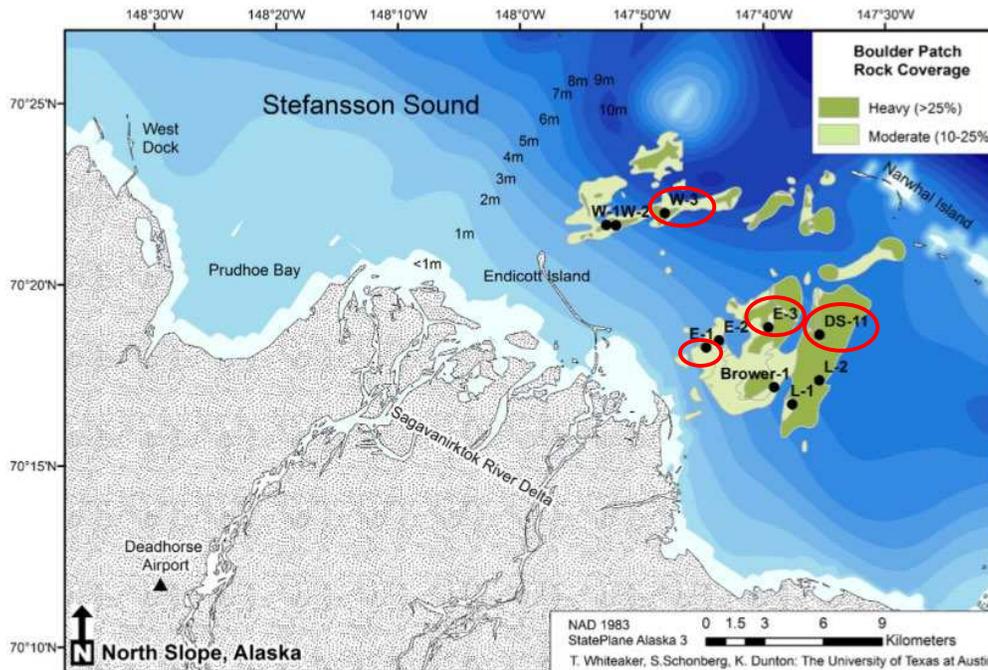
Figure 1:   Map of the Boulder Patch Region with Established Sites from Long-term Monitoring

Notes: The sites for the experimental artificial reefs are DS-11, E3, E1, and W3, and are shown in red circles. Map adapted from Bonsell and Dunton 2018.

4   Methods

Field work for the project started in summer 2021. During 12–21 July 2021, four main artificial reefs were deployed at study locations DS11, E3, E1, and W3 (Figure 1). These reefs were composed of 60 rocks each that originated from Atigun Pass in the Brooks Range and had been transported to Deadhorse for seawall construction around Endicott Island (Figure 2a, b). The cobble size of the rocks closely mimics the average size of those that occur naturally in the Boulder Patch. Much sediment of various sizes is transported from the Brooks Range into the nearshore system, creating a geological connection between the experimental rock origin location and the Beaufort Sea coastal system. In addition to these four main reefs, we also deployed a smaller reef (25 pieces) of broken interlocking concrete slabs at DS11. These interlocking concrete slabs are the main construction material for artificial island construction in the Prudhoe Bay region; there was also interest in investigating whether this material could support organism settlement. The reason only a small reef with this material was built, and only at DS11, was that the concrete tended to crumble when broken into smaller (cobble-sized for handling) pieces. The concrete pieces were deployed about 10 m distance from the rock reef at DS11. Reefs were deployed in areas of the study sites that were dominated by bare soft substrate, but surrounded by natural rocks carrying kelp (mostly *Laminaria solidungula*) as a source for new kelp recruitment. In addition, small rocks (pebble-sized so as not to be confused with rocks from the artificial reef) carrying adult *Laminaria solidungula* were placed in the midst of the artificial reefs to ensure proximity of adult kelp for spore release. Reef locations were marked with 50 m lengths of rope from a well-documented (via GPS coordinates) central site location so that the reefs could be found even during suboptimal visibility conditions by swimming search circles.

In 2023, three "control" natural rocks per site were marked under water and the natural epilithic community composition visually assessed as percent cover. This was to gain a better understanding of the community composition at each site and monitor natural changes of the community in comparison to the recruitment on experimental rocks. These control rocks were supposed to be marked during the initial

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year of artificial reef set-up and then annually assessed, but weather conditions did not allow this to occur until 2023 and then only for three control rocks per site.

Alongside the reefs at sites DS11, E1, and W3, we deployed sediment traps which remained for one year and were recovered and then re-deployed during the next summer's field season. (Figure 2c). Traps were constructed of two parallel PVC pipes (SCH40) with an inner diameter of 5 cm and a length of 12.5 cm. They were affixed with hose clamps to a rebar iron frame, which anchored the trap on the seafloor. The sediment composition of each site was also assessed in 2023 by visually determining percent cover of boulder, cobble, gravel, and sand/mud (following the standard Wentworth scale of sediment grain size; Wentworth 1922); this information was obtained from 10 replicate 0.25 m^2 quadrats placed haphazardly at each site in a larger area around the artificial reefs.

Figure 2: (a) Cobble-sized Rocks from Atigun Pass Used for Seawall Enforcement around Endicott Island; (b) Experimental Rocks Deployed at the E1 Study Site as a Dense Artificial Reef; and (c) Sediment Trap Design Deployed Next to Artificial Reefs at DS11, E1, and W3

Lastly, through a BOEM partner project (NSL AK-19-01; Contract number M19AC00012) as well as in partnership with the Beaufort Lagoon Long-Term Ecological Research (BLE-LTER) program (funded by the National Science Foundation; https://ble.lternet.edu/), we collected additional long-term environmental information from two of the artificial reef sites (DS11 and E1). At both of these sites, we deployed a LI-COR spherical quantum sensor just above the kelp bed (~0.5 m), connected to a LI-1400 datalogger (LI-COR Inc.) to record photosynthetically active radiation (PAR) hourly as $\mu mol\ m^{-1}\ s^{-1}$ for the entire year. We also measured temperature and salinity data from a similar height above the seabed from a combination of a StarOddi DST and an RBR Concerto CTD set to record every hour. These sensor arrays were recovered once a year at approximately the same time that rocks for the artificial reefs and sediment traps were sampled.

4.1 Annual Sampling

Artificial reefs, sediment traps, and environmental sensors were sampled once a year by SCUBA diving in late July (2022 and 2023). From each reef, five rocks were collected by individually placing them into fine-meshed bags and brought to the surface. Rocks were placed in coolers filled with seawater from the sampling sites to keep experimental rocks cold and wet while transported back to Endicott Island, where samples were processed.

Each rock was photographed to document cover, and then all associated macro-organisms were removed and preserved in 70 percent ethanol for further analysis. These organisms included attached taxa such as sponges, macroalgae, barnacles, and bryozoans as well as mobile taxa such as polychaetes, bivalves, and chitons. The taxa were sorted, identified as best as possible, and counted and weighed (0.0001 g accuracy) at the University of Alaska Fairbanks lab. Since associated taxa contained a

large number of colonial taxa (sponges, bryozoans, macroalgae) that cannot be enumerated, biomass was used as the community metric.

Sediment traps were recovered each year from every site by SCUBA and carefully brought to the surface, where each PVC tube was emptied into a large Ziploc bag. These sediments were then brought back to the lab at UAF, settled into 500 ml Nalgene jars, and overlying water layers removed once clear of sediments (after ~2 days of settlement). Remaining sediments were then dried for 7 days at 60°C, after which dried sediments were weighed (0.1 g accuracy) and reported as g sediment deposited yr^{-1}.

4.2   Data Analysis

Biomass-weighted composition of the recruitment community on experimental rocks and of the natural community composition was analyzed using multivariate statistical approaches (Primer-e V7). Community data were fourth-root transformed and a Bray-Curtis similarity matrix constructed. A permutational analysis of variance (PERMANOVA) with site as a fixed factor was used to compare the recruitment community among sites in 2022 and 2023 individually, and a two-factor PERMANOVA with year and site as fixed factors was used for a combined analysis. Non-metric multidimensional scaling plots (nMDS) were used to visualize community patterns. A two-factor ANOVA with year and site as fixed factors was used to test differences between years and sites of sediment deposition into traps as well as for comparison of total biomass of recruits among years and sites using R-studio.

5   Results

5.1   Artificial Reef Recruitment

Recruitment onto experimental rocks from artificial reefs was determined for 2022 and 2023. Organisms detected included various macroalgae (esp. *Phycodrys fimbriata*) and several sessile invertebrates (sponges, bryozoans, spirorbid polychaetes, hydroids) and mobile/temporarily attached invertebrates (the bivalve *Hiatella arctica*, spionid polychaetes, chitons, etc.). The recruitment assemblage at the four sites in 2022 was significantly different among sites (PERMANOVA, $F_{3,16}$ = 2.923, p = 0.001; Table 1). Similarly, the recruitment assemblage in 2023 was significantly different among sites (PERMANOVA, $F_{4,18}$ = 2.923, p = 0.001; Table 1). When combining the datasets for the two years, both year and site were significant, as well as the interaction of the two factors. (In Table 1, note that this analysis excluded the DS11 concrete reef to achieve a balanced design.)

Table 1:   PERMANOVA Results of the Recruitment Assemblage at Four Boulder Patch Sites in 2022 and 2023

2022							
Source	df	SS	MS	Pseudo-F	P(perm)	MV Dispersion	
Site	3	24924	8308.1	3.241	**0.001**	DS11	0.829
Res	16	41015	2563.4			W3	0.678
Total:	19	65939				E3	1.117
						E1	1.376

2023							
Source	df	SS	MS	Pseudo-F	P(perm)	MV Dispersion	
Site	4	21020	5254.9	2.923	**0.001**	DS11	0.305
Res	18	32365	1798.0			W3	0.923
Total:	22	53384				E3	1.336
						E1	1.445
						DS11c	0.97

Combined 2022 and 2023					
Source	df	SS	MS	Pseudo-F	P(perm)
Year	1	12638	12638.0	5.757	**0.001**
Site	3	26132	8710.5	3.968	**0.001**
YearxSite	3	15059	5019.6	2.286	**0.001**
Res	32	70252	2195.4		
Total:	39	124080			

Notes: MV dispersion indicates the dispersion of the recruitment assemblage of the five rocks per site (but n = 3 for the concrete blocks at DS11 = DS11c). Significant results in bold.

In 2022, recruitment assemblages at the five replicate rocks per site were most similar at W3, followed by DS11 and E3, and most dissimilar at E1, measured as multivariate dispersion (Figure 3a, Table 1). On average, the recruitment assemblages at each site were dominated in relative biomass by one or two taxa (Figure 3b): DS11 was dominated by the red alga *Phycodrys fimbriata* (Figure 4c), W3 was dominated by *Halichondria panicea* (Figure 4d) and the bivalve *Hiatella arctica* (Figure 4b), E3 was dominated by the sponge *Halichondria panicea* and Hydrozoa, and E1 was vastly dominated by *Hiatella arctica*. There was a single recruit of a juvenile *Laminaria solidungula*, clearly identifiable by the discoid holdfast, on one rock at site W3 (Figure 4a). Barnacles (Figure 4e) were a common feature at most rocks and sites, except for E1, but did not amount to a large proportion of biomass of the recruitment assemblage. Notably, calcareous crustose algae (CCA, Figure 4f) were also detected on one rock at DS11, but could not be enumerated for biomass.
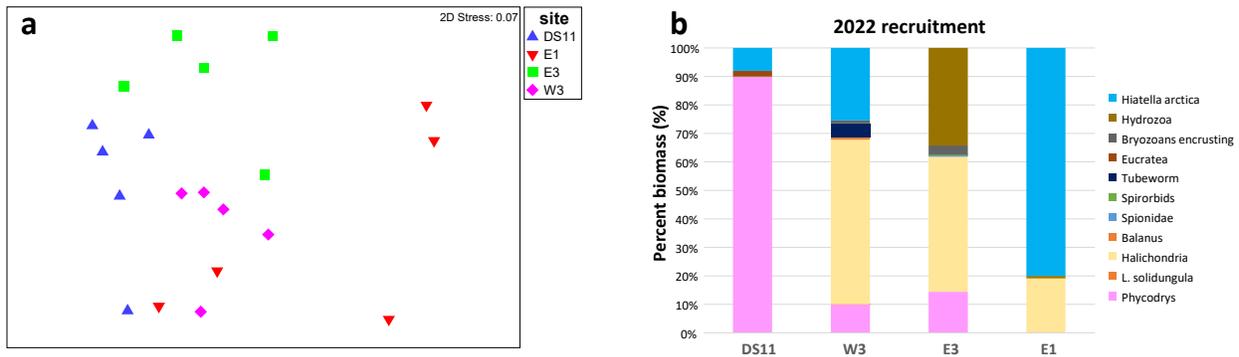
**Figure 3:   (a) Non-metric Multi-dimensional Scaling (nMDS) Plot of Recruitment Assemblages on Experimental Rocks at Four Sites in the Boulder Patch;
(b) Proportional Biomass Contribution of Taxa toward the Average Recruitment Assemblage at the Four Sites Sampled in 2022**
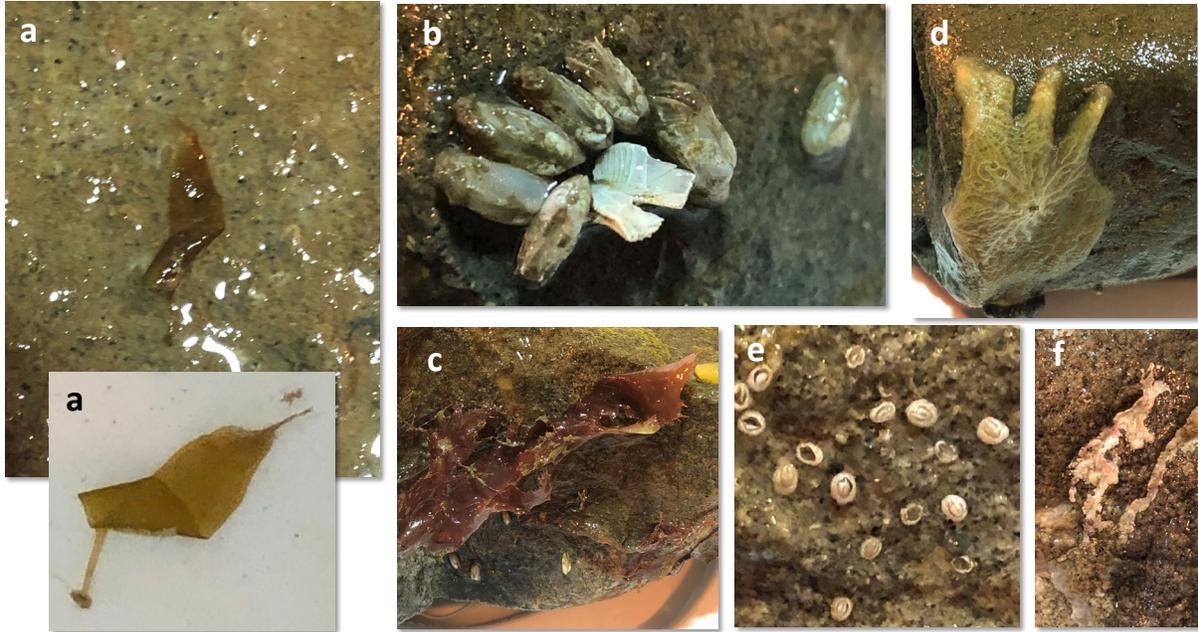
Figure 4:   (a) *Laminaria solidungula* Recruit on a Rock at W3—Note the Discoid Holdfast;
(b) The Bivalve *Hiatella arctica*;
(c) The Red Alga *Phycodrys fimbriata*;
(d) The Sponge *Halichondria panicea*;
(e) Barnacle Recruits;
(f) Crustose Coralline Algae (CCA) on an Experimental Rock at DS11

Unlike 2022, dispersion in the recruitment assemblages in 2023 was by far the lowest at DS11, indicating fairly consistent assemblage structure among the five replicate rocks at that site (Figure 5a, Table 1). However, the assemblage at site E1 had again the highest dispersion, showing that most rocks had some taxa recruited that did not occur on the other rocks at that site (Table 1). The assemblage in 2023 at DS11 was mostly dominated in biomass by the chiton *Stenosemus albus* and the red alga *Phycrodrys fimbriata*, while the assemblages at E1, E3, and W3 were dominated by the sponge *Halichondria panicea* (Figure 5b). In 2023, three concrete pieces were collected in addition to the five rocks from the reefs at DS11. The assemblage on the concrete pieces was very different from the assemblage on the rocks at the same site, with mostly *Phycodrys fimbriata*, *Coccotylus truncatus*, and one *Laminaria solidungula* recruit but no *Halichondria panicea*, which was very common on the rocks (Figure 5b). *Stenosemus albus* was abundant at DS11 in 2023 and occurred on every rock, but not on the concrete pieces at the same site, and were not detected in 2022 on either substrate at DS11.
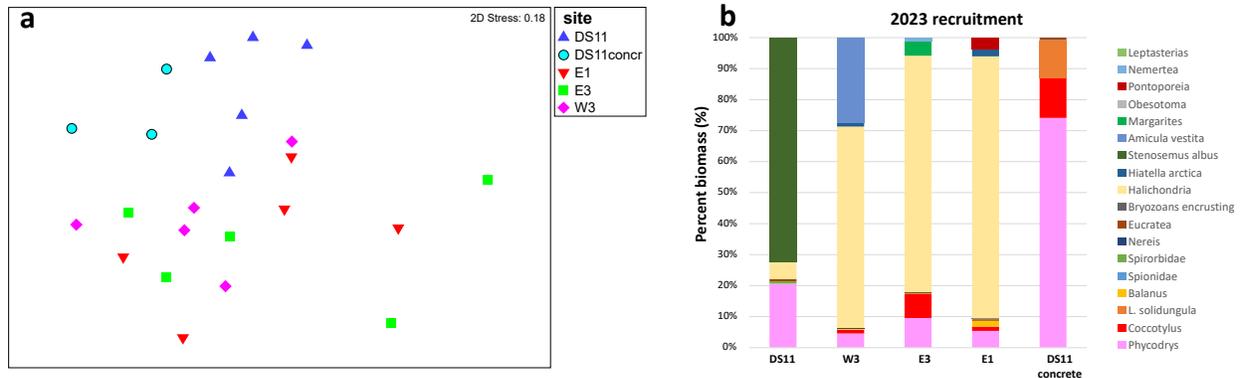
Figure 5: (a) Non-metric Multi-dimensional Scaling (nMDS) Plot of Recruitment Assemblages on Experimental Rocks at Four Sites and Concrete Pieces at DS11 in the Boulder Patch; (b) Proportional Biomass Contribution of Taxa toward the Average Recruitment Assemblage at the Five Sites Sampled in 2023
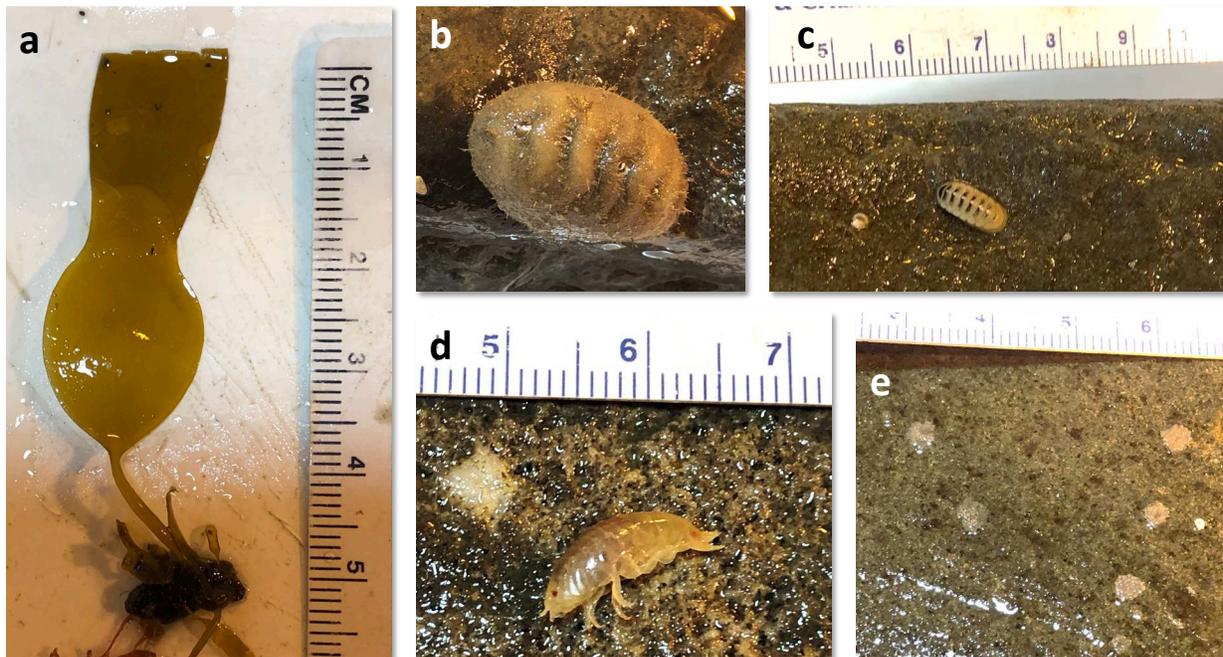

Figure 6: (a) *Laminaria solidungula* Recruit on a Concrete Piece at DS11; (b) The Chiton *Amicula vestita*; (c) The Chiton *Stenosemus albus*; (d) The Amphipod *Pontoporeia femorata*; and (e) Encrusting Bryozoan Recruits

Total biomass of recruits did not differ by year but did differ among the two years (Table 2); however, if only sessile or attached (e.g., *Hiatella arctica*) were considered by excluding all mobile recruits, no significant differences were observed among years or sites. There was a trend of higher biomass at site W3 in both years, but high variability likely prevented this trend to be of statistical significance (Figure 7).

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Table 2: **Two-way ANOVA Results of Biomass of Recruits**

All Recruits					
Source	**DF**	**SS**	**MS**	**F Statistic**	**P-value**
Year	1	3.609	3.609	2.687	0.1110
Site	3	12.139	4.046	3.013	**0.0444**
Interaction AB	3	4.835	1.612	1.200	0.3255
Error	32	42.978	1.343		
Total:	39	63.561	1.630		

Sessile Recruits					
Source	**DF**	**SS**	**MS**	**F Statistic**	**P-value**
Year	1	1.593	1.593	1.180	0.2856
Site	3	7.311	2.437	1.804	0.1663
Interaction AB	3	2.046	0.682	0.404	0.6816
Error	32	43.222	1.351		
Total:	39	54.171	1.389		

Notes: All recruits and only sessile/attached recruits at four Boulder Patch sites in 2022 and 2023. Only site was significant when all recruits were considered. Significant results in bold.
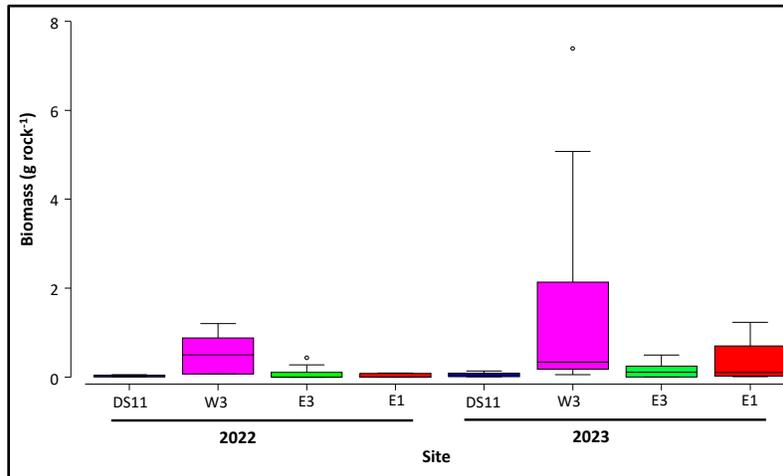
Figure 7:   **Box Plots of Total Biomass per Rock of Sessile Recruits at the Four Study Sites in 2022 and 2023**

Notes: All mobile recruits excluded.

5.2   Sediment Traps

Sediments retrieved from traps at three sites (DS11, W3, E1) in 2022 and 2023 differed both by site and year (Table 3). Sediment deposition was highest in both years at site W3 and lowest at DS11, with intermediate values at E1 (Figure 8). Also, sediment deposition in general was much larger (about double) in 2023 than 2022.

Table 3:   **Two-way ANOVA Results of Sedimentation at Four Boulder Patch Sites in 2022 and 2023**

Source	**DF**	**SS**	**MS**	**F Statistic**	**P-value**
Year	1	80196.8	80196.8	160.18	**<0.0001**
Site	2	68747.6	34373.8	68.66	**<0.0001**
Interaction YxS	2	18007.8	9003.9	17.98	**0.0029**
Error	6	3004.0	500.7		
Total:	11	169956.1	15450.6		

Notes: Both year and site were significant effects, as well as the interaction effect of the two (in bold).
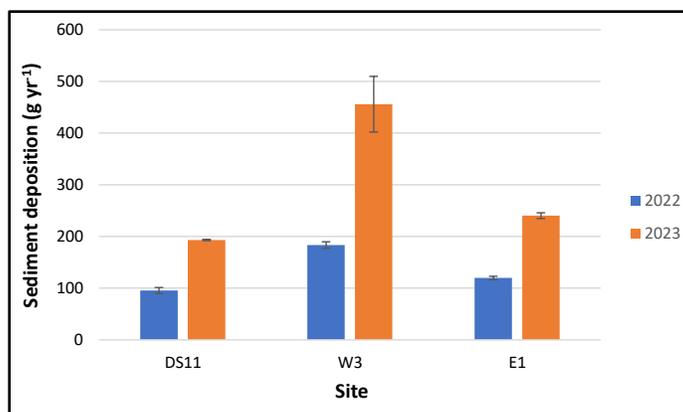
Figure 8: **Sediment Deposition at Three Sites over the Course of a Year into Sediment Traps in 2022 and 2023**

Notes: Values indicate mean ± SD (n = 2 per trap).

5.3   Natural Environment and Community Structure

The four study sites differed in their natural bottom sediment composition; DS11 had the largest proportion of large grain sizes (boulders and cobble). Site E1 was very distinct from the other sites by having very few larger grain sizes and about 90 percent of sand/mud, while that proportion was similar among the other three sites (Figure 9).

Natural rock epilithic community composition on the three control rocks in 2023 differed by site (Table 3). Community similarity among the three replicate rocks at DS11, E3, and E1 was equal (MV Dispersion, Table 4) while community composition was very different among the rocks at W3 (Figure 10a). One distinct site difference was due to the amount of CCA covering rocks, which was high at DS11 and E3, but low at W3, and nonexistent at E1 (Figure 10b). One of the reasons for the high dispersion of community composition at W3 was one of the rocks not having any CCA and having a much larger proportion of bare rock than the other two rocks. It should be noted that only three rocks per site could be surveyed due to weather conditions, so results should be considered with care based on low replication.
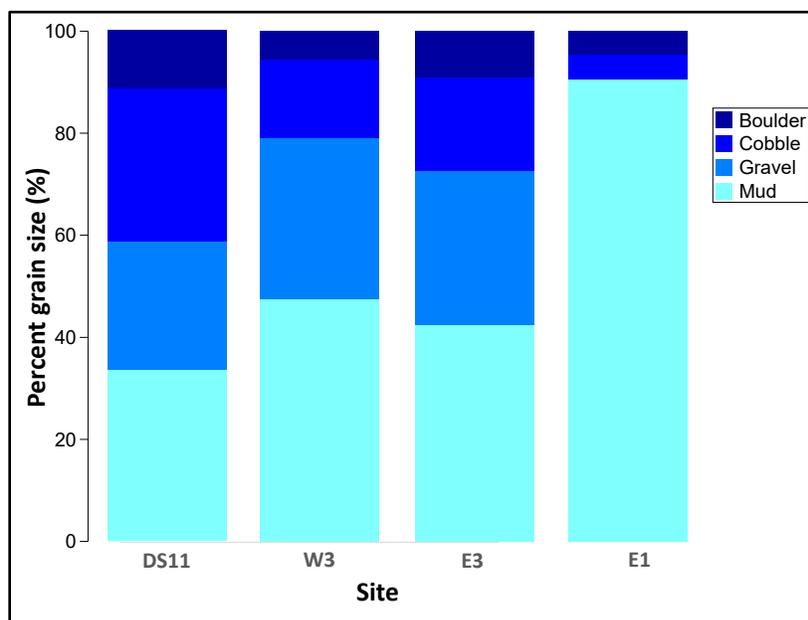
Figure 9: **Natural Sediment Grain Size Composition Visually Assessed at all Sites**

Table 4: **PERMANOVA Results of Control Rock Composition at Four Boulder Patch Sites in 2023**

Source	DF	SS	MS	Pseudo-F	P(perm)
Site	3	10191.0	3396.9	3.563	**0.022**
Res	8	7627.7	953.5		
Total:	11	17818.0			

MV Dispersion	
DS11	0.872
W3	1.436
E3	0.821
E1	0.872
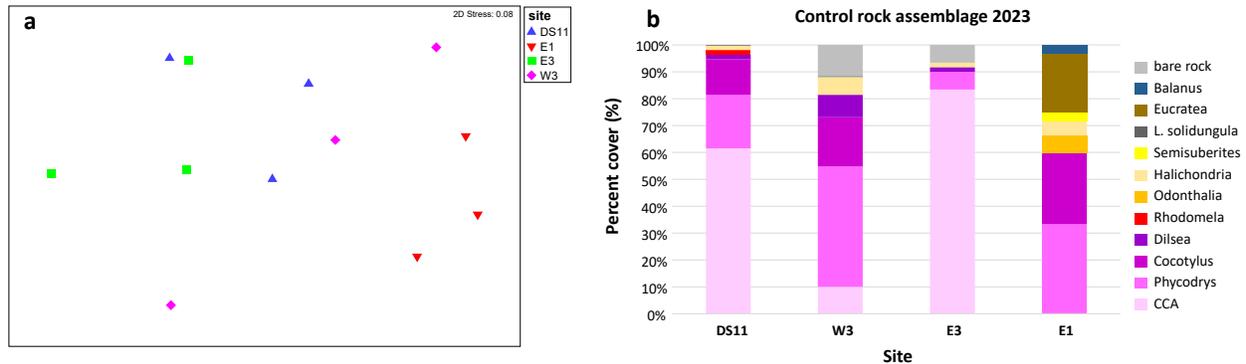
Figure 10: **(a) nMDS Plot of Natural Epilithic Community Composition at Control Rocks; (b) Percent Cover of Taxa on Control Rocks**

Long-term sensors deployed at sites DS11 and E1 provided environmental context for at least two of the sites in terms of temperature, salinity, and PAR (Figure 11). Long-term trends in temperature and salinity were as expected at both sites, with below zero-degree bottom temperatures for most of the year, except for a short summer period between mid-July and early October. Summer peak temperatures were warmer at E1 than DS11 by 1–2°C. Early temperature increases coincided with a salinity drop from the onset of river discharge. This salinity drop is several units larger at E1 compared to DS11, based on the greater proximity of E1 to the coast and the mouth of the Sag River. Lastly, PAR increases coincide with the open water (warmer and less saline) period and were similar between the two sites in 2022, but much higher PAR levels (more than double) occurred in 2023 at DS11 compared with E1.
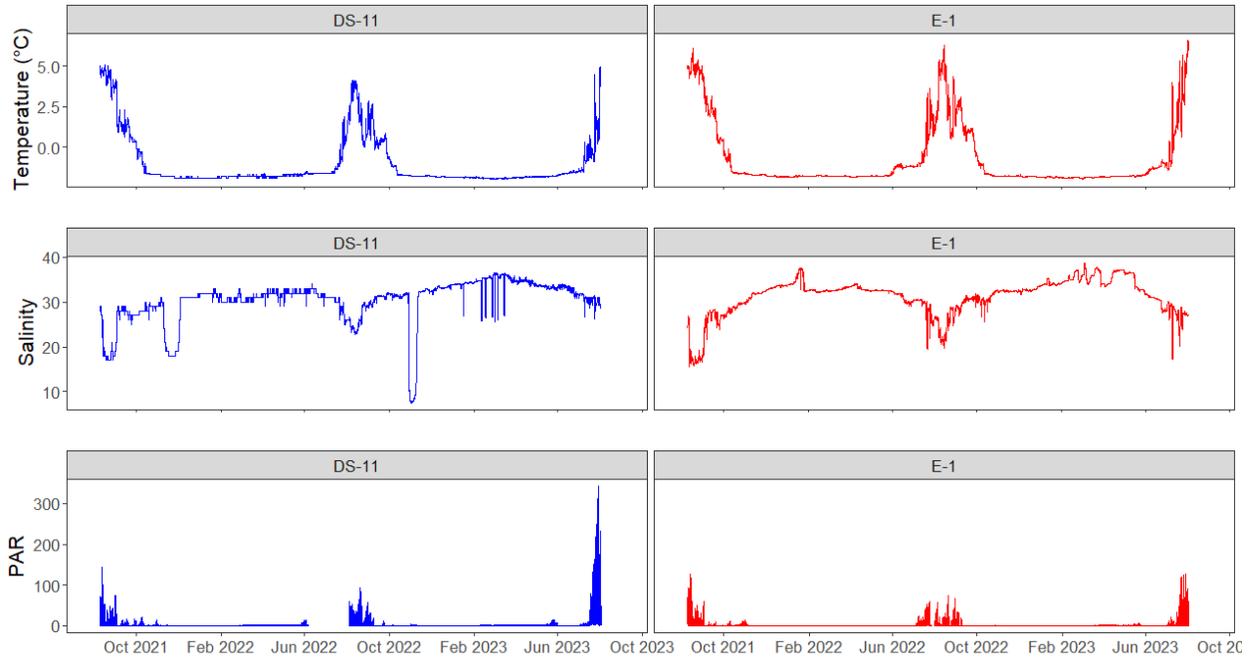
Figure 11: **Long-term Records of Bottom Temperature, Bottom Salinity, and Photosynthetically Active Radiation (PAR) at Study Sites DS11 and E1**

Notes: The large "icicles" in the temperature record at DS11 are likely a sensor artifact.

6   Discussion

We detected recruitment onto the experimental rocks within one year at all sites. Out of all experimental rocks retrieved, only two rocks from E1 in 2022 did not have any recruitment. Recruitment in the Boulder Patch region has previously been reported as very slow (Konar 2007, 2013; Bonsell and Dunton 2021), with estimates that it would take decades for bare space in the Boulder Patch community to fully recolonize. These prior studies have suggested that low recruitment, lack of suitable substrate, and strong physical disturbance are major drivers of slow community recruitment and recovery. Therefore, the present study assessed community recruitment to abundant new space (artificial reefs) in the presence of adult kelp (placed near artificial reefs) and in conjunction with measurements of sedimentation as one of the suspected main drivers of community disturbance. The deployment of artificial reefs has been a successful mitigation strategy in other subtidal, rocky reef systems in the world (Terawaki et al. 2001; Campos et al. 2020); one purpose of this study was to investigate if such mitigation strategies could also be applicable to the coastal Beaufort Sea.

6.1   Artificial Reef Substrate

One of the main concerns with the establishment of artificial reefs is the substrate being used. Reef substrate can significantly influence both the type of taxa recruiting as well as their abundance and timing (Spieler et al. 2001; Spagnolo et al. 2014; Siddik and Satheesh 2021). Previous work in the Boulder Patch used natural rocks from the study region that were scrubbed free of epilithic organisms (Konar 2007, 2013) as well as artificial tiles (Bonsell and Dunton 2021). One of the advantages of small, flat tiles is that they have a standardized surface area where recruitment can be relatively easily quantified. The problem is that many propagules may not be amenable to settling on artificial surfaces so that extrapolation of results for natural recruitment and succession patterns can be difficult. Natural substrates are preferred if investigating reefs for mitigation purposes as they provide a more "realistic" substrate for propagules, and should reefs be constructed for actual mitigation, then such natural substrates are more likely to be used than artificial tiles. Conversely, natural substrates are difficult to standardize based on

surface area covered by settling organisms because of their irregular shape and the fluid distinction between top surface, side surfaces, and which part was touching the bottom. In this study, we used a natural substrate (cobble-sized rocks from the Brooks Range), as the purpose was to determine the feasibility of habitat restoration using artificial reefs. Previous work elsewhere has determined that artificial reefs that are most similar to the natural reef in rugosity, relief, and substrate size do best to attract a similar community as the natural reef (Granneman and Steele 2015). This approach was different from a previous study using natural rocks from the Boulder Patch scrubbed free of epilithic organisms (Konar 2007, 2013); we used natural rocks from the greater region that had never been submerged. On occasion, even small remnants of natural cover organisms (e.g., CCA) can influence new recruitment (Breitburg 1984; Johnson and Mann 1986; Price 2010). Yet, if indeed the Boulder Patch area were to be enhanced with increased rocky substrate through artificial reefs, it would have to be from newly deposited, additional rocks, not rocks that are already in place in the system. We also tested the suitability of concrete slabs that have been used for production island and causeway construction in the Prudhoe Bay Oil Field as this could show if these constructions themselves can enhance epilithic settlement. It must be noted that the intact concrete slabs used for construction have a smooth surface but they are impossible to handle without major construction equipment, so we had to use broken pieces. While we did find recruitment on these concrete pieces in 2023 (weather conditions in 2022 did not allow the collection of concrete pieces in that year), the assemblage was very different from that on the rocks. One possibility is that the rough and at times jagged surface of the broken concrete provides a surface structure that is suitable for recruitment, but it is possible that different propagules have different preferences for surface structures between rocks and concrete. Other, biological possibilities for the differences in recruitment between substrate types at DS11 are discussed below.

6.2 Recruitment Patterns

All recruitment and settlement studies in the Boulder Patch had one common result: recruitment of the epithithic community is extremely slow (Konar 2007, 2013; Bonsell and Dunton 2021; this study). Settlement on natural Boulder Patch rocks where the epilithic community was removed only had recruitment after four years, mostly of barnacles (Konar 2007). Recruitment on tiles (Bonsell and Dunton 2021) and on rocks from the Brooks Range Atigun Pass (this study) were similar to each other in that first recruitment was observed after one year. Slow benthic recruitment is a typical feature of Arctic benthic communities (Beuchel and Gulliksen 2008), and even of high polar systems in general (Dayton et al. 2016). This is likely even more so in isolated habitats like the Boulder Patch than in other Arctic, shallow-water, continuous hard-bottom habitats (Meyer et al. 2017) where a wide-spread surrounding community can provide large quantities of propagules. The slow recruitment is mostly related to highly peaked, seasonal larval abundance in Arctic systems, which requires suitable conditions of substrate, food, light, nutrients, etc., for successful recruitment and post-settlement development (Kuklinski et al. 2013; Stübner et al. 2016).

The recruitment in the first years after substrate deployment was mostly dominated in biomass by the red alga *Phycodrys fimbriata*, the sponge *Halichondria panicea,* and the bivalve *Hiatella arctica*. It should be noted that all these species have the ability to move (*Hiatella arctica*), disperse as fragments (*Phycodrys fimbriata*), or colonize rocks via vegetative growth (*Halichondria panicea*). This means that new recruitment through spores (macroalgae) or meroplankton stages (invertebrates) is not the only, and maybe not even the primary, mode of new surface colonization. Vegetative growth as a colonizing mechanism is well-documented for marine systems (Valiela 1995). It is not always possible to distinguish whether a taxon recruited from a fragment, immigration movement, or vegetative growth when surveying the experimental rocks, but we did find strong indications for all these processes as well as for colonization from propagule settlement on the Boulder Patch artificial reefs. Some *Phycodrys fimbriata* were clearly fragments or even small plants that had drifted into the reef and were able to attach to the new surface with lateral rhizoids, a common vegetative growth mode in *Phycodrys* (Schoschina 1996). In other cases, small *Phycodrys fimbriata* plants were clearly attached to the experimental rocks with a holdfast, indicating new, tetraspore-based recruitment. Similarly, some growth of the sponge *Halichondria panicea* was clearly from vegetative growth from surrounding rocks, indicated by broken edges of the sponge on a rock from when it was removed from the bottom. It should be noted, though, that experimental rocks in the artificial reefs are not directly touching natural rocks, although they are in close

vicinity at some sites. This could mean that sponge larval recruitment occurred on a neighboring experimental rock and then began overgrowing the rock that was randomly selected for analysis. In many cases, these sponge portions covered a considerable amount of the rock surface, explaining the high contribution of the sponge to early recruitment and also supporting the notion that vegetative growth in this sponge can be very efficient (Thomassen and Riisgård 1995; Bell 2008; Konar 2013). In other cases, complete sponges with intact edges were observed, suggesting recruitment from larval stages. In most observations, sponges occurred along the sides of the rocks, a microhabitat that has been suggested as preferred for this species, possibly due to sensitivity to high sedimentation (Konar and Iken 2005; Tillin and Stamp 2016). Lastly, *Hiatella arctica* is a common bivalve on hard substrates in Arctic waters that can attach reversibly to the substrate with byssal threads (Oberlechner 2008). This means that adults from the surrounding community can disperse and reattach to the new substrate. The size of some of the individuals with multiple shell surface ridges (possibly an indication of age) suggests that this adult immigration occurred in several of the observations of this species. The fact that the body size of some *Hiatella arctica* clusters on the experimental rocks was small and all individuals were of the same size, might suggest that in other cases new recruitment may also have occurred.

In other taxa, recruitment can only occur through larval or spore settlement. This includes some macroalgae, particularly kelp, as well as several of the invertebrate species observed such as barnacles, spirorbid polychaetes, and bryozoans. A particularly exciting and noteworthy result of the present study was the observation of juvenile kelp on experimental rocks in both study years. In fact, understanding whether kelp recruitment can be enhanced through artificial reefs was one of the main motivators of this study. No kelp has been reported in any of the previous recruitment studies, which occurred over much longer time periods (Konar 2007, 2013; Bonsell and Dunton 2021). Kelp are considered a foundation species in the system and the potential loss of kelp is expected to lead to the loss of associated taxa, overall diversity, and important carbon inputs into the coastal food web (Dunton and Schell 1987; Renaud et al. 2015; Paar et al. 2019). Therefore, while they may not be the most abundant taxon in the natural epilithic communities at all sites in the Boulder Patch, they provide essential ecosystem functions for the Boulder Patch and their restoration is of utmost importance. While the observation of juvenile kelp was exciting, we only observed one plant each year, and not at the same sites or substrate. The kelp in 2022 was on a rock at W3, and in 2023, it was on a concrete piece at DS11 (note that this was a 2-year individual, noticeable by the development of a second blade lobe, meaning it recruited in 2021). It is possible, of course, that there were more recruits, but a larger number of rocks would need to be surveyed annually. Regardless, this finding suggests that additional reef structure in the Boulder Patch could be a way to combat habitat loss, although substrate is likely not the only limiting factor for epilithic community recovery and persistence (see Section 6.3 on environmental factors).

Among the invertebrates that recruit through larval stages, barnacles and spirorbids have been reported as the main colonizers in the Boulder Patch on cleared rocks, but only occurring after several years of exposure and at extremely low percent cover of the rocks (Konar 2007). Both these taxa in this study occurred regularly at most sites after one year, indicating much faster recruitment than in the Konar (2007) study. It is unclear, however, if individuals encountered in the second year had recruited during the first or second year of exposure in our study. While body size was not specifically quantified, individuals seemed of similar size in both years. This could mean that they grow very slowly once settled, or that they settled in year 1 but were removed due to some disturbance and those observed in year 2 were new recruits. The difference in recruitment timing to the earlier study (after one instead of multiple years, Konar 2007) could either be due to the substrate differences of the studies (see Section 6.1 on artificial reef substrates) or due to interannual differences in reproductive output and meroplankton availability during both studies (see Michelsen et al. 2017; Lalande et al. 2021 on meroplankton variability). Potential loss of individuals settled in the first year could be from physical disturbances such as sedimentation (Airoldi 2003; also see Section 6.3 on environmental factors) or from biological disturbance such as from grazing organisms. The influence of grazing has been deemed minimal for the Boulder Patch community (Konar 2013), perhaps due to the lack of large, voracious grazers such as sea urchins that are known to decimate kelp systems in other cold-temperate systems (Feehan et al. 2012; Filbee-Dexter and Scheibling 2014, Filbee-Dexter et al. 2019). In the second year of study, we observed large numbers of chitons (*Stenosemus albus*) at the DS11 site; while this species occurs regularly in the Boulder Patch (Dunton et al. 1982), the fact that we found multiple individuals on every rock at DS11 was unusual.

Chitons are indiscriminate grazers, meaning they bulldoze the rock surface and can remove new invertebrate recruits in addition to algae and strongly influence overall community composition (Aguilera and Navarrete 2007; Aguilera et al. 2015). Such episodic mass recruitment of a grazer into the artificial reef could cause the loss of new recruits or even small individuals that recruited in previous years. A similar mass event was observed at W3 in 2022, when large numbers of the barnacle-eating nudibranch *Onchidoris bilamellata* was observed. While none of them occurred on the rocks sampled for recruitment that year, one rock was nearly entirely covered in egg casings (removed from analysis). There were no nudibranchs observed at W3 in 2023, another indication that episodic events in the form of large recruitment of some species may be common in the Boulder Patch, as also described for some other polar systems (Dayton et al. 2016, 2019; Reed et al. 2021). The fact that there was not an increase in recruited biomass between the first two years could support this idea of biological disturbance, indicating that recruitment and loss were relatively even.

We also observed a large number of mobile taxa on the experimental rocks, specifically spionid polychaetes, chitons, amphipods, etc. Mobile species arguably are not part of a "recruitment" community as they may just migrate in and out of the artificial reef. While that is true, they are still part of the biological assemblage and can engage in predatory/grazing (see above), competitive, or facilitating interactions. It also stands to reason that some of the mobile species' presence on the experimental rocks is not by chance, but that they recruit or migrate there for the specific conditions. For example, spionid polychaetes were common in both years on these rocks, possibly because the thin sediment layer on the rocks provided these surface deposit feeders with nutritious food particles trapped between sediment grains (Dauer et al. 1981, Ferner and Jumars 1999). As mentioned above, large accumulations of some mobile species like chitons or nudibranchs can influence the community, and it is possible that the mostly unvegetated substrate of the experimental rocks provide these taxa an easy foraging ground. It must be noted, however, that the quantification of mobile species on experimental rocks may be flawed by the escape of some individuals during the collection process. While rocks were placed into fine mesh bags underwater before moving them to the surface, it cannot be excluded that some may escape during the handling of the rock underwater.

The recruitment community on experimental rocks differed by both site and year, indicating that the sum of factors that influences the development of a newly recruited community is at least in part driven by stochastic events. This includes the variability and unpredictability of propagule supplies, variability in the strength of environmental factors, as well as post-recruitment processes shaping the settlement community (e.g., grazing). Propagule density may differ among the sites, as less abundance of adults at some sites (e.g., E1) will likely lead to less larval or spore supply at that site compared to a site with much higher adult community cover. It would then depend on the dispersal distances and directions whether low reproductive output at a site could be compensated. Our current state of knowledge tells us this may be the case: total biomass at site W3 was the highest in both years despite lower overall adult epilithic community cover than at other sites, such as DS11. If much flow during the time of propagule availability is westward, W3 might receive propagules from the central, more densely populated Boulder Patch region. It also seems that what we assume are episodic events, such as the mass recruitment of chitons at DS11 in 2023 or the massive amounts of nudibranchs observed at W3 in 2022, could play an important role in the recolonization of the epilithic community. The spatial scale of these episodic events is uncertain, but it is notable that no chitons were observed on the concrete pieces at DS11 in 2023 when they were on every rock from the rock reef at DS11; these two reefs are only about 10 m apart. It seems that substrate colonization in the Boulder Patch is strongly influenced by such episodic events, more so than by a predictable succession taking place, at least over the short term. These patterns may be different when colonization of these bare substrates is observed over long time periods (decades), the timeframe that has been suggested for Boulder Patch and other Arctic systems (Konar 2007, 2013; Beuchel and Gulliksen 2008; Meyer-Kaiser et al. 2019; Bonsell and Dunton 2021), over which the resulting community may "average" out at each site.

6.3   Environmental Influences

Environmental conditions at various locations within the Boulder Patch are known to differ (Dunton et al. 1982; Aumack et al. 2007; Bonsell and Dunton 2018, 2021). Here, we only observed a few environmental drivers at the study sites, namely substrate cover and sedimentation, with temperature, salinity and PAR also recorded continuously at two sites. Substrate cover is important as larger-sized sediments (boulder and cobble, in particular) are essential for the epilithic community. Therefore, the greater abundance of large-sized substrate at site DS11 is likely a major driver of the rich natural epilithic community known for that site (Bonsell and Dunton 2021), especially compared to sites that are mostly dominated by fine sediments (e.g., E1). Sedimentation was measured at three of the sites, and relative patterns in sedimentation load were similar between the two years with the highest sedimentation at W3 and lowest at DS11. This result was surprising as the W3 site seemed visually less sediment-influenced than the high soft-sediment and low visibility E1 site, which is also closest to shore and the Sag River outflow. Noteworthy also is that sedimentation rates between the two years were vastly different, with much higher (about double) rates in 2023 than 2022. Annual weather conditions can play a role in this as sedimentation in the region is driven both by discharge of sediments from the Sag River, which will be higher during warmer years, and coastal erosion inputs and resuspension of sediments at the sites that are driven by storm events (Bonsell and Dunton 2018). High sediment load also influences summer light availability at the sites. Our continuous PAR measurements at two sites, DS11 and E1, showed differences in PAR availability especially in summer 2023, where the DS11 benthos received nearly three times the light levels than at E1. It may be that the very high sedimentation rates in the last year of the study at E1 was related to the low light availability that year.

Sediments, salinity and light can impact the benthic and recruiting communities. Sediments smother sessile organisms, inhibit filter feeding, and limit successful reproduction in organisms that rely on propagule or dispersal for recruitment (Airoldi 2003). *Laminaria solidungula* in the Boulder Patch are known to be positively related to higher salinity (e.g., away from river inflow; Bonsell and Dunton 2021, Muth et al. 2021), and the microscopic life phases can be affected by sedimentation (Phelps et al. *in revision*). *Laminaria solidungula* is well adapted to the generally low-light environment of long Arctic winters and low light even in the summer (Dunton and Jodwallis 1988), but its life strategy of alternating photosynthesizing periods during summer and biomass production periods during nutrient-replete winter (Chapman and Lindley 1980; Dunton and Schell 1986) requires sufficient light in summer to produce blade biomass (Dunton et al. 1982; Bonsell and Dunton 2018). Contrary to expectation, high colonization was observed on rocks at site W3, which had the highest sedimentation rates in both years. While suspended and settling sediments are generally considered detrimental to benthic taxa, it may be that sediments enhance settlement by "scavenging" propagules from the water column and increasing their sinking to the seafloor. Alternatively, conditions in which sediments settle more easily from the water column may also foster the settlement of larvae or other propagules, overcoming hydrodynamic constraints (Butman 1987), explaining both high sedimentation and high recruitment. In summary, the environmental conditions at the various Boulder Patch sites are complex and likely play an important role in the success of the recruitment and colonization of any available substrate.

7   Conclusions

This project aimed to assess the suitability of artificial reefs for the enhancement of subtidal rocky reefs in the Arctic Boulder Patch. Natural rocks originating from Atigun Pass in the Brooks Range were used to build reefs in four locations in the Boulder Patch, which were surveyed after one (2022) and two (2023) years. Recruitment of both macroalgae, including kelp, and invertebrates was observed, indicating that this rock type is a suitable option for artificial reef enhancement in the Boulder Patch. Other substrates such as concrete blocks typically used for production island construction in the region, also seems a suitable substrate, if needed, but are logistically more difficult to achieve. Recruitment was slow, as typical for Arctic benthic communities, but recruitment of a variety of benthic invertebrates and macroalgae was observed within a year. Episodic recruitment events may play a large role in shaping the early colonizing community; for example, through grazing, suggesting that artificial reefs will need to be deployed a number of years to achieve what may be considered a "typical" epilithic community. Different locations in

the Boulder Patch differ in their prevalent environmental conditions, which may be more or less challenging for main epilithic taxa. If the impact of natural climate drivers and anthropogenic activities, which challenge epilithic organisms especially at the fringes of the current Boulder Patch region, cannot be easily mitigated, then reef enhancements would be most impactful in central regions or regions away from land-derived influences such as river discharge or coastal erosion. One consideration for artificial reefs could also be the spacing of rocks in an artificial reef. For practicality of finding and resampling the rocks, our reefs were deployed with the rocks in close proximity to each other, although not covering each other. The space between rocks in a reef is known to influence the small-scale hydrography, which can influence the deposition versus resuspension of finer substrates (Papanicolaou et al. 2018). This has unknown effects on the community development in the Boulder Patch, but suggests that multiple smaller reefs dispersed across the larger Boulder Patch region would be the most impactful design, as it would dampen, on a system-wide scale, localized episodic recruitment and environmental disturbance events.

Acknowledgments

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