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Mapping and Characterizing Benthic Habitats in Northern Labrador: Insights for Marine Conservation and Indigenous Resource Management

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ABSTRACT. In the face of rapid climate change impacting Canada's northern coastlines, northern fish, benthic ecosystems, and ecosystem services are being heavily impacted. The ongoing environmental pressures continue to influence the social, cultural, and physiological well-being of Labrador Inuit who are intrinsically linked with the marine environment. Collaborating closely with the Nunatsiavut Government, this research presents a detailed map of benthic faunal assemblages in an understudied northern inshore system, providing essential information on benthic habitats and incorporating community-identified fishing locations for ogak (Greenland cod). A total of 75 drop-camera transects unveiled 44,809 organisms belonging to 50 morphotaxa, clustered into three distinct faunal assemblages. Fishing locations were represented in two of three assemblages which were heterogeneous and composed mainly of pebbles, boulders, and rhodolith beds. The unrepresented assemblage was homogeneous and composed entirely of fine sediments. Numerous benthic taxa, potentially sensitive to environmental disturbances, were identified, including tube-dwelling anemones, large sea squirts, erect bryozoans, and extensive rhodolith beds. Insufficient data on benthic species and their associated habitats limit our comprehension of species distributions, abundances, and functional roles in northern waters, creating obstacles for effective self-governance. This research identifies the distribution and structure of benthic habitats in a culturally and economically important region of the Labrador coast, feeding directly into conservation and management strategies of marine habitats under the pressures of climate change in Nunatsiavut.

Keywords: species assemblages; habitat; seafloor mapping; Indigenous conservation; Arctic; video surveys; benthic ecology; climate change; Greenland cod

INTRODUCTION

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Benthic habitats, comprising the ecological communities and physical structures on the seafloor, are vital for supporting marine ecosystems and organisms, offering significant economic, cultural, and ecological benefits (Kritzer et al., 2016; Griffiths et al., 2017; Flávio et al., 2023). Yet, the collection of benthic habitat data across vast stretches of the seabed remains highly constrained globally (Mayer et al., 2018), particularly in northern regions characterized by challenging environments, high operating costs, and seasonal ice cover (Wynja et al., 2015; Coad and Reist, 2017). In the Canadian context, northern regions—spanning the Arctic, subarctic, and parts of the boreal zone—are home to many Indigenous peoples, including Inuit, who have historically depended on marine ecosystems for subsistence and cultural continuity. These areas, however, have been underrepresented in benthic data collection, which has been primarily concentrated in temperate and southern regions, where accessibility and infrastructure make exploration more feasible. Moreover, the scarcity of specialized surveying equipment, such as multibeam sonar and remotely operated vehicles (ROVs), further exacerbates the data gap in the north, limiting our understanding of these ecosystems. This disparity suggests a lower priority in Arctic and subarctic areas, despite the reliance of Indigenous communities in these regions on marine resources for food security, cultural practices, and economic well-being.

The lack of baseline data in these northern marine ecosystems restricts our ability to detect ecological changes, predict species distributions, and inform sustainable management strategies. This issue is particularly urgent as the Circumpolar North is experiencing the most rapid and pronounced impacts of climate change relative to the rest of the world (Bush and Lemmen, 2019). However, Traditional Ecological Knowledge (TEK) and Local Ecological Knowledge (LEK), offer long-term insights into species distributions, ecosystem changes, and habitat variability. These knowledge systems have guided sustainable harvesting practices for generations and provide a historical baseline that can significantly improve the efficiency and scope of scientific surveys (Rangeley et al., 2022; Cote et al., 2023). In northern ecosystems, where rapid and broad-scale changes are occurring, the implementation of multiple knowledge systems becomes increasingly necessary to support marine resource management.

In this context, Nunatsiavut, a region in Labrador home to Labrador Inuit, serves as a vital example of how the health and well-being of Indigenous communities are intricately tied to the coastal marine environment. Throughout the region, communities have expressed a range of priorities and concerns related to their local marine waters, including issues like navigation and over-harvesting, all within the broader challenge of adapting to a changing climate (Felt et al., 2012; Durkalec et al., 2015; MacDonald et al., 2015; Rangeley et al., 2022). The ongoing effects of climate change continue to impact subsistence activities, food security, and the physical and mental health of northern communities (Ford et al., 2012; Cunsolo Willox et al., 2013; Middleton, 2020; Bishop et al., 2022). In response to these pressing needs, the Nunatsiavut Government (NG) established the Imappivut – 'Our Oceans' Marine Planning Initiative. This initiative is dedicated to understanding and managing the region's diverse marine environments through a marine spatial planning process that reflects both the ecological and cultural priorities of Labrador Inuit. Among its objectives is to uncover and map the spatial extent of important benthic habitats and species to support resource management strategies and decisions regarding protected areas in the region.

Benthic habitat mapping, recently redefined as "spatially continuous prediction of biological patterns on the seafloor" (Misiuk and Brown, 2024), is an important step in understanding and managing species, habitat, and harvesting interactions (Brown et al., 2012; Buhl-Mortensen et al., 2015; Baker and Harris, 2020). This process involves the utilization of full-coverage acoustic data (e.g., bathymetry – depth, backscatter – reflectivity) acquired through sonar systems, along with biological samples obtained through ground-truthing techniques (e.g., underwater videos, sediment grabs, dive surveys) (Brown et al., 2011). To characterize the seafloor physical morphology and composition, additional features (e.g., slope, roughness) can be derived from the acoustic layers (Wilson et al., 2007). These physical characteristics act as measurable proxies of drivers behind species-environment relationships (Wilson et al., 2007; Lecours et al., 2015). Through the integration of these data via a variety of modeling techniques, a comprehensive map of seafloor habitats can be produced, aiding in the understanding of marine ecosystems and their drivers (Brown et al., 2011). This approach allows scientists to pinpoint the habitat distribution for species at risk (Novaczek et al., 2017a), identify rare habitats, determine habitat vulnerability, and inform marine protected area planning and monitoring (Novaczek et al., 2017b; Proudfoot et al., 2020). The application of LEK and TEK systems can enhance this process by combining information about species presence in specific locations over longer periods compared to the limited perspective provided by single snapshots from ground-truthing techniques. The collaboration, application and engagement of knowledge systems can contribute to identifying distributional patterns of ecologically significant habitats and species, as demonstrated by the work of Misiuk et al. (2019), Rangeley et al. (2022), and Cote et al. (2023).

This research presents a detailed map and description of benthic faunal assemblages in an understudied northern inshore system, providing essential information on the distribution and structure of biological communities and their environmental drivers. In alignment with the Imappivut initiative's priorities, this study also recognizes the cultural and subsistence importance of Greenland cod (*Gadus ogac*) (Richardson, 1836), locally known as ogak.

To include local perspectives, community-identified ogak fishing locations were applied as survey sites, providing additional context on the habitats frequented by this species. Although the primary focus is on mapping and describing benthic habitats, these fishing sites offer valuable insights into the habitats that may be frequented by ogak, thereby enhancing our broader understanding of this culturally iconic species. In this collaboration with the Nunatsiavut Government, this study aims to empower Labrador Inuit with knowledge that can enhance effective self-governance and resource management, ultimately supporting the sustainability of marine resources in the face of climate change.

METHODS

Study Area

This research was conducted within the inshore marine waters of Nain, Nunatsiavut (56°N, 61°W; Fig. 1), a region at the border between a subarctic and polar climate (Roy et al., 2021). Situated as the northernmost and largest community in Nunatsiavut, Nain has a distinct landscape including an archipelago that has played an integral role in the region's history, boasting a legacy of abundant hunting and fishing grounds. Open to the Labrador Sea, Nain's coastline encompasses extensive and seasonally persistent land-fast ice, small and episodic areas of open water surrounded by sea ice (i.e., polynyas), and is composed of several islands, exposed headlands, extensive fjords, and protected inlets. Much of Nain's inshore is unmapped which limits present understanding of the spatial distributions and roles of benthic habitats.

Bathymetry

A consolidation of digital non-navigational bathymetric sources (*NONNA 100* dataset) managed by the Canadian Hydrographic Service was downloaded surrounding Nain's inshore and coastal marine ecosystem at a spatial resolution of 100 meters (Government of Canada 2025). These data were collected by echo-sounders, including both single beam and multibeam projects. The bathymetric data were patchy and contained multiple gaps in coverage (Fig. 2a). To fill these gaps, the interpolation of these data was performed using Empirical Bayesian Kriging (EBK) in ArcGIS Pro 2.8 (Fig. 2b). Classical kriging methods are limited in accounting for errors introduced by estimating a singular semivariogram model, EBK achieves this by estimating the spatial relationship of the input data through multiple simulated semivariogram models (Krivorouchko, 2012; Zou et al., 2015; Novaczek et al., 2019).

A 20 m resolution digital elevation model (DEM) from Natural Resources Canada was used alongside the bathymetric data to define land areas, minimize artifacts, and improve the accuracy of the interpolation process by reducing false bathymetric predictions. The bathymetric and DEM data were resampled to a 50-meter resolution to capture a similar scale as obtained from the ground truthing transects (described below) and reduce interpolation artefacts in areas of low data density (Novaczek et al. 2019). Using 100 iterative semivariogram models, EBK simulated new data for each known depth value. Bayes' Rule was used in this process, where a weight is assigned to each semivariogram, demonstrating how well the observed data can be generated from the respective semivariogram (Krivorouchko, 2012; Novazcek et al., 2019). The weighted distribution of the 100 semivariograms was then used to interpolate unknown depth values within the neighbourhood of each local model. Neighbouring models were assigned high overlap (overlap factor = 5) which requires more processing time, but produces a smoother output surface. The bathymetric raster was then clipped to remove all land data points (> 0m).

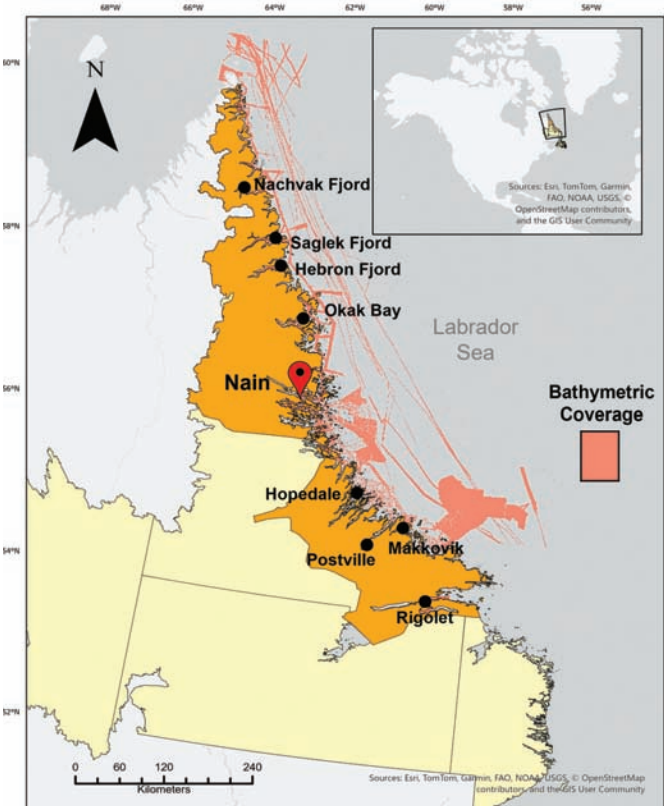

FIG. 1. Communities within Nunatsiavut's territory (orange). The study location is Nain, Nunatsiavut. Available bathymetric coverage in Labrador Sea from the Canadian Hydrographic Service's Non-Navigational Bathymetry data (NONNA) is also presented in red. Important bays and fjords in northern Nunatsiavut are listed.

Site Selection and Ground-Truthing

Residents of Nain who fish for ogak year-round in a subsistence fishery disclosed five important locations near the community as part of the Imappivut initiative. These locations were provided for this study by the NG under a collaborative agreement that respects Indigenous

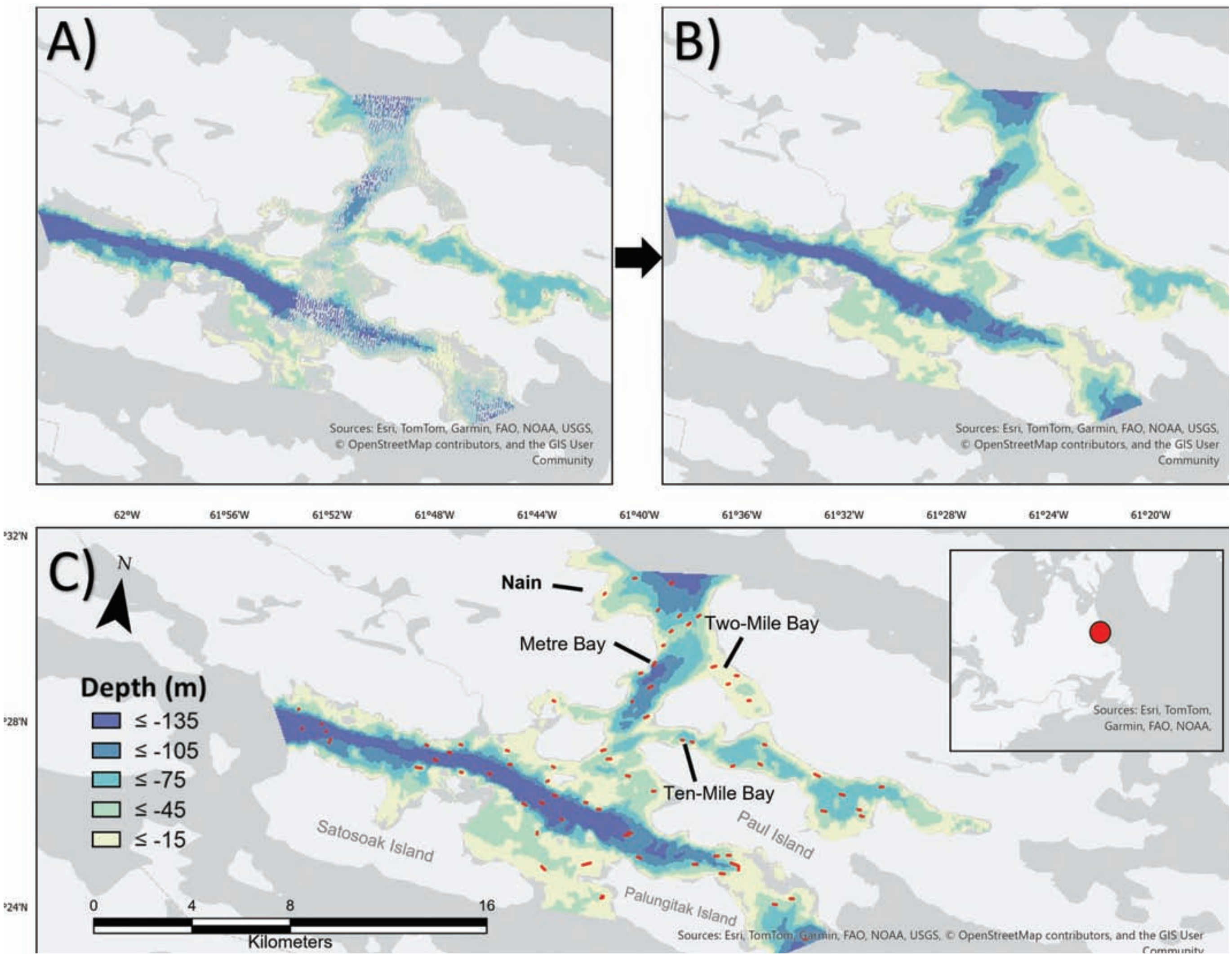

FIG. 2. Empirical Bayesian Kriging performed on non-navigational bathymetric data compiled by the Canadian Hydrographic Service. Original bathymetry (A) interpolated after kriging (B). Drop-camera video transect lines (n = 75) from GRTS design (C). Harvester-identified fishing locations are present but remain undisclosed and grouped with additional sites in red. Depth classifications from deep to shallow are coloured from dark to light, respectively. Insert represents study extent on Labrador coast.

data sovereignty principles, ensuring that the collection, use, and dissemination of cultural knowledge align with the priorities and governance frameworks of Labrador Inuit. Approval for this research was obtained through the Nunatsiavut Government Research Advisory Committee (NGRAC-16469991). Based on their expertise, ogak are commonly caught within Metre Bay (sometimes referred to as Meta Bay) and in proximity to Two-Mile Bay (M. Denniston, pers. comm.). Some ogak have been observed venturing off into Nain Bay and Paul Island (Fig. 2c) based on a developing telemetry study (B. King, pers. comm.). The residents report the most successful ogak fishing endeavors in proximity to the shoreline, where these fish are sought out among cobbles and boulders eroded from cliffsides (Mary Denniston and Liz Pijogge, pers. comm.). These reliable fishing sites, handed down through generations, hold immense significance and have been vital for community members.

Using the newly derived bathymetric surface, a Generalized Random Tessellation Stratified (GRTS) survey design (Stevens & Olsen 2004) was employed in *R* to select ground-truthing locations. This approach ensures that all significant bathymetric zones (e.g., shallow, mid-depth, and deep areas) are proportionally sampled, rather than relying on a simple random selection, which might over- or under-represent certain areas. From October 3 – 12, 2022, on board the *MV Inuttatik*, a total of 75 ground-truthing points, including the five community-identified fishing locations, were sampled using drop-camera surveys and CTD casts (Star Oddi *SeaStar* 8.17). CTD data were collected to provide baseline oceanographic information (temperature and salinity) that could influence benthic community distributions. At each site, 5-minute video transects were employed using a downward-looking *SubC Imaging* Coastal Rayfin camera (1920 x1080 pixels, 30 frames per second). Specifications for this camera include two Aquorea Mk3 LED (15000 lumens), two MantaRay parallel lasers spaced 10 cm apart, and 4K video recording capabilities. Video footage was geolocated using vessel GPS coordinates recorded at the start and end of each transect.

Environmental Data

Bathymetric Derivatives: The continuous bathymetric surface of Nain's inshore was used to derive continuous terrain features to help explain faunal assemblage patterns (Supplementary Table S1). Based on recommendations from Lecours et al. (2017), this study used a set of local terrain attributes that can account for approximately 70% of the structure of a topographic surface. These attributes included eastness and northness (i.e., orientation), slope (i.e., steepness gradient) (Wilson et al., 2007), relative difference to mean value (RDMV) (i.e., topographic position), and standard deviation (SD) (i.e., roughness) of bathymetry. Measures of curvature (mean, profile, and planar curvature) were derived to describe the rate of change of the seabed and to identify contours (e.g., ridges, valleys, mounds) (Wilson et al., 2007; Walbridge et al., 2018). To identify topographic highs and lows, relative seabed position was derived using the bathymetric position index (BPI) (Lundblad et al., 2006; Wilson et al., 2007; Misiuk et al., 2018; Walbridge et al., 2018). Vector ruggedness measure (VRM) (Sappington et al., 2007) was also derived to provide further information on seafloor structure, as it quantifies seafloor roughness by incorporating slope and aspect into a single measurement.

The spatial scale, referring to the spatial resolution and geographic extent (Lecours et al., 2015), of the explanatory features mentioned above is crucial for understanding the complex dynamics and ecological processes within a benthic ecosystem. Environmental variables like depth exhibit significance across a range of scales, from finer to coarser resolutions, while others like productivity exert stronger influences at relatively coarse scales compared to fine scales (Davies et al., 2008; Lecours et al., 2015). Benthic fauna exhibit habitat preferences across different hierarchical levels, emphasizing the significance of accounting for both fine and broad-scale terrain variability (McGarigal et al., 2016). Overlooking the scale at which species-environment relationships are most pronounced could lead to the neglect of key ecological associations (Jackson and Fahrig, 2014; Lecours et al., 2017). To capture these dynamics, the Multi-Scale Geomorphometric Terrain Attributes (MultiscaleDTM) package in R was employed (Ilich et al., 2021). This package utilizes the 'k×k-window' or 'roving window' method, as defined in Misiuk et al. (2021), to calculate terrain attributes from the gridded digital bathymetry raster at multiple scales. The scale of these attributes is dependent on the source data resolution and the size of the window used for analysis. In this context, features were derived at 10 scales, using focal window sizes ranging from raster cells at 3×3 to 21×21, totaling 100 features, and capturing information from 150 to 1050 m (Supplementary Table S1). This multiscale approach ensures that scale-dependent patterns and processes are effectively captured (Porskamp et al., 2018; Shang et al., 2021), although fine-scale features (e.g., complex surficial geology) may not be fully resolved due to the coarse resolution of the bathymetric data in this study.

Distance to Coast, Salinity, and Temperature: A continuous layer measuring the distance from the coast, defined as the nearest point of land, was calculated relative to each pixel using the 'Euclidean Distance' tool in ArcGIS Pro 2.8. This variable was included to account for potential gradients in benthic faunal and grain size distribution influenced by proximity to shore (Misiuk et al., 2018; Vassallo et al., 2018; Nemani et al., 2022). To derive continuous layers of bottom temperature (°C) and salinity (ppu), similarly to the continuous bathymetry layer, EBK was employed. While these data represent a temporal snapshot, they provide baseline oceanographic conditions that may influence benthic community distributions. Using 100 iterative semivariogram models, EBK simulated new data for all known temperature and salinity values from the CTD data (Krivorouchko, 2012; Novazcek et al., 2019). The weighted distribution of the 100 semivariograms was then used to interpolate unknown temperature and salinity values with neighbouring models assigned a high overlap (overlap factor = 5).

Video Survey Data

Video Analysis: The Monterey Bay Aquarium Research Institute's (MBARI) Video Annotation and Reference System (VARS) (Schlining and Stout, 2006) was used to review and annotate all 75 drop-camera video samples. All videos were annotated in a randomized order to reduce human annotation biases (e.g., fatigue) (Durden et al., 2016). Each video was standardized to annotate a consistent 5-minute segment of footage. For every organism greater than 5 cm (i.e., half the distance of the camera lasers) taxa identification was performed to the lowest taxonomic level possible. Species identification was not always possible due to suspended sediment, and rapid camera drift speed; therefore, identification required the use of morphotypes (Howell et al., 2019). It is important to note that the reported taxa in this study may encompass multiple species, suggesting that the actual species count at these sites is likely higher than documented. These morphotypes were based on the production of an image catalogue for the Nain region using this video footage (MacMillan-Kenny, 2024). Taxa identification was performed with aid from expert advice and published species identification guides (Nozères et al., 2014a, 2014b; Salvo et al., 2018; Lacasse et al., 2020). Observed faunal abundances were tallied in a site by morphotype matrix to facilitate analysis.

Substrates were classified into six substrate classes (Fig. 3) guided by the Coastal and Marine Ecological Classification Standard (Federal Geographic Data Committee 2012) and the guide for video monitoring of hard bottom benthic communities (Salvo et al., 2018). Detailed descriptions and representative images of each

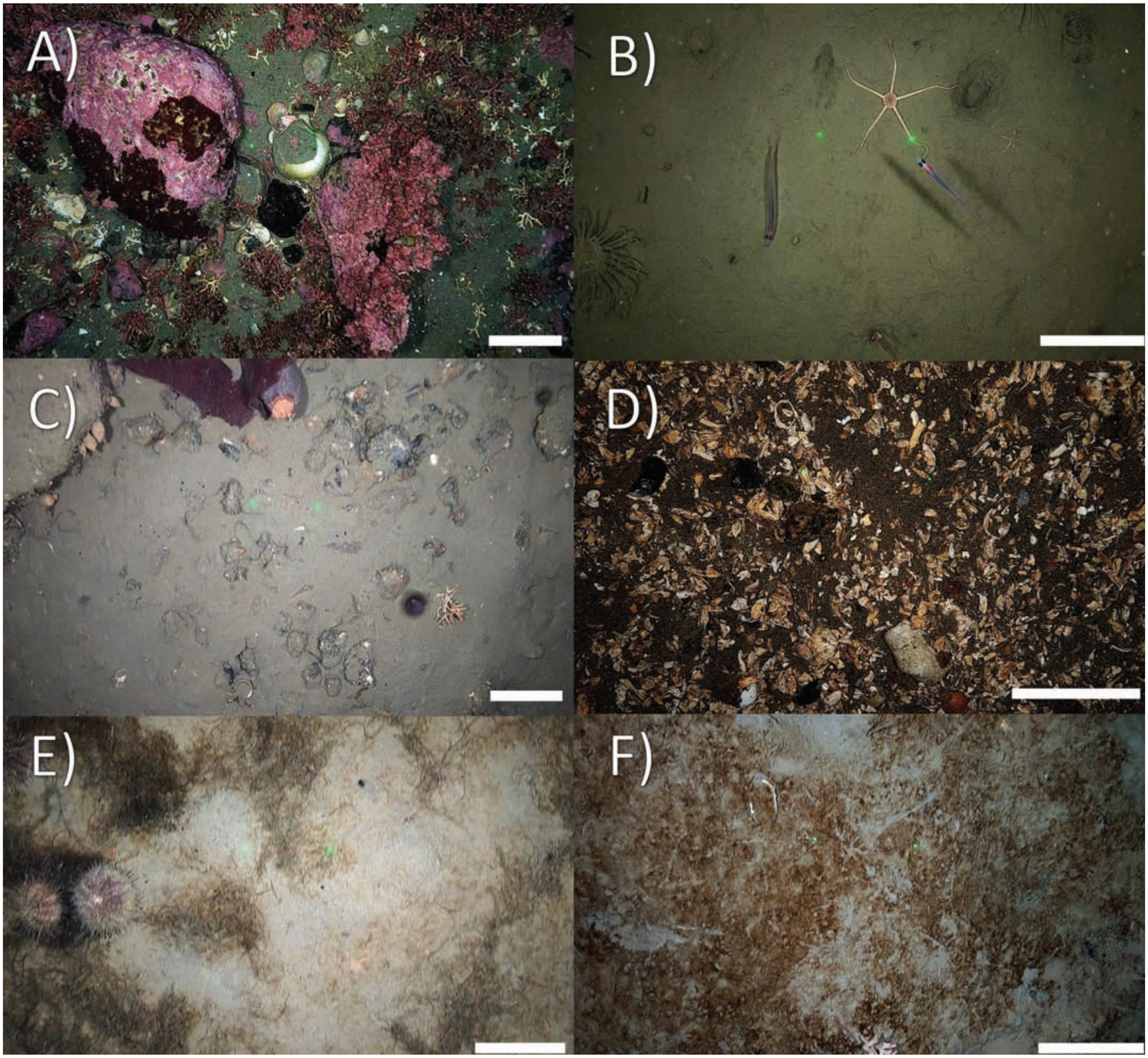

FIG. 3. Images of the substrate classes identified during video annotation: A) Rhodoliths with Mixed Gravel, B) Fine Sediments, C) Fine Sediments with Mixed Gravel, D) Fine Sediments with Shellhash, E) Fine Sediments with Seaweed, and F) Diatomaceous Fine Sediments. White bar for scale is 10 cm.

class are provided (Supplementary Table S2). Dominant substrate classifications were assigned to each site based on the most frequently observed substrate type in the ground-truthing videos. While small-scale variability in substrates exists within each site, fine-scale substrate data (e.g., percentage cover) were not quantified for this study.

Data Preparation and Analysis

Cluster Analysis: Faunal abundances were classified into benthic faunal assemblages using a Hellinger transformation and a hierarchical cluster analysis approach. The 'unweighted pair group method using arithmetic averages' (UPGMA) algorithm (Legendre and Legendre, 1998; Everitt et al., 2001; Borcard et al., 2018) was selected to derive faunal assemblages. Taxa with three or fewer observations across all videos were removed to reduce variability caused by rare taxa. To determine the size and cutoff of each cluster, fusion level values and silhouette widths were used (Borcard et al., 2018). To assess the dissimilarities between clusters, an Analysis of Similarities (ANOSIM) test was performed using the Bray-Curtis dissimilarity index to calculate the dissimilarity matrix.

Dominant and indicator taxa were both derived to demonstrate the biological composition of each assemblage. Dominant taxa consist of the most abundant species within a community that may highly influence the occurrence and distribution of other species and overall community structure (Smee, 2010; Nemani, 2022). These organisms have abundances greater than the individual group assemblage mean (Borcard et al., 2018). Indicator taxa, which primarily represented the assemblages, were then used to measure the association between a species and assemblage by assessing the relative abundance and frequency of each species per grouping. The indicator value index (0-1) contains estimates on (1) the probability that the surveyed site belongs to the target assemblage given that a specific species was present (i.e., specificity) and (2) the probability of finding a species in sites belonging to the assemblage (i.e., fidelity or sensitivity) (Dufrêne and Legendre, 1997; De Cáceres and Legendre, 2009). A value closer to 1 would indicate a higher probability for both estimates. For this study, the threshold to assign significant indicator species to an assemblage was an indicator value greater than 0.75 due to the high number of potential candidates for some assemblages. Essentially, the method aims to identify ideal indicator species found exclusively for each assemblage (Dufrene and Legendre, 1997; Mouillot et al., 2002) and is useful for monitoring changes to the sites associated with their specific assemblage (McGeoch and Chown, 1998; Kubosova et al., 2010).

Feature Selection and Collinearity: The Boruta Feature Selection algorithm (Kursa and Rudnicki, 2010; Kursa, 2020) was used to identify the most important multi-scale bathymetric derivatives for distinguishing between faunal assemblages. Multiple mapping studies have found success employing the Boruta algorithm for feature selection (Diesing and Thorsnes, 2018; Mackin-McLaughlin et al., 2022; Nemani et al., 2022), and it has outperformed other feature selection methods (e.g., Vita, Recurrent relative variable importance) (Degenhardt et al., 2019). This algorithm compares the importance of original variables with randomly shuffled “shadow attributes,” retaining only variables that consistently contribute more to the model than their shuffled counterparts (Kursa and Rucnicki, 2010). All variables across 10 scales were inputted, and those identified as “tentative” or “important” were selected for further analysis. After the Boruta algorithm identified the most important bathymetric derivatives (mean curvature [5×5], VRM [5×5], and SD [21×21]), these variables were combined with bathymetry, distance to coast, temperature, and salinity for a second round of feature selection. The Boruta algorithm was reapplied to this expanded set of variables, and collinearity was assessed using Spearman’s rank correlation (Dormann et al. 2013). Variables with a correlation coefficient > 0.7 were removed, retaining the feature with the lowest collinearity relative to the already selected variables. The final model included bathymetry, salinity, and the three selected bathymetric derivatives.

Statistical Modeling:A Random Forest (RF) model, implemented in the *R* package ‘caret’, was then used to predict faunal assemblage distributions based on the five selected environmental variables. Comparisons between different modeling techniques have consistently demonstrated the reliable and accurate performance of RF (Robert et al., 2015; Pillay et al., 2020; Nemani et al., 2022) for mapping benthic habitats. RF constructs multiple decision trees using bootstrap aggregation (“bagging”), where each tree is built from a random subset of predictor variables. Predictions are made by majority voting across all trees, with out-of-bag samples used to estimate model error and assess variable importance (Breiman, 2001; Franklin, 2009). Model parameters were optimized using a grid search, with mtry = 2 (two predictor variables per split) selected as the optimal configuration. The RF model was run with and without site-specific substrate classifications to evaluate their impact on performance. Full-coverage predictive maps were generated using the RF model and environmental data layers, excluding substrate classifications due to their lack of spatial continuity.

Model Assessment: A leave-one-out cross validation (LOOCV) approach was used to estimate model performance (Stone, 1974; Shao and Er, 2016). To assess prediction accuracy, a confusion matrix was computed containing the following measures:

- False positive errors: Number of times the model predicted a class was present, but it was not truly observed.
- False negative errors: Number of times the model predicted that a class would not be present, but it was truly observed.
- Sensitivity & Specificity: Probability that a class is correctly predicted (i.e., true positive rate & true negative rate).
- Precision score: number of correctly-identified members of a class divided by the number of times that class was predicted by the model.
- F1 score: Number of times the model made a correct prediction across the entire dataset (i.e., combination of precision and sensitivity scores).
- Balanced accuracy: The average sensitivity score obtained for each class.
- Overall accuracy: A general measure of accuracy calculated by summing and dividing correctly classified values by the total number of values (Congalton, 1991).
- Kappa statistic: Measures instances that may have been correctly classified by random chance (Cohen, 1960).

To rank the predictive importance of each variable in the model, a variable importance plot was derived. The Gini importance index was used for RF, which serves as a computationally efficient approximation to entropy. It calculates how frequently a specific variable was chosen for a split and the extent to which it contributes to distinguishing between different classes (Menze et al. 2009). Specifically, the decrease in Gini impurity from an optimal split is documented and summed up for every node across all trees in the forest (Nembrini et al., 2018). This process is carried out separately for each variable (Menze et al., 2009; Nembrini et al., 2018).

RESULTS

Substrate Classes

Rhodoliths with Mixed Gravel was a biogenic substrate class observed in 11 shallow sites distributed close to the shoreline (Supplementary Fig. S1). Similarly, Diatomaceous Fine Sediments was distributed in shallow sites near the coastline, often in sheltered bays, and was observed in nine sites. Fine Sediments was the most common substrate class and was observed in 31 sites that were mostly found within the fjord in the southern portion of the survey area. Fine Sediments with Mixed Gravel was patchily distributed within 19 sites that were commonly found on the outskirts of deep basins and channels. Fine Sediments with Shellhash was only observed in three sites distributed in close proximity south of Paul Island. The Fine Sediments with Seaweeds class was found in two sites near the town of Nain and south of Paul Island (Supplementary Fig. S1).

Epifaunal Assemblages

Across the 75 drift-videos, 44,809 individual organisms belonging to 50 morphotaxa were identified. The phyla with the largest representation throughout the entire survey were Echinoderms (40%) and Cnidarians (35%). Green sea urchins (*Strongylocentrotus droebachiensis*) (n = 8495), brittle stars (Ophiuroidea spp.) (n = 3298), and scarlet sea cucumbers (*Psolus fabricii*) (n = 2594) were the most common echinoderms, while Cnidarians were mostly dominated by Ceriantharia spp. (n =14,768). In comparison, the remaining phyla (Chordata (8%), Annelida (7%), Arthropoda (5%), Bryozoa (2%), Porifera (2%), and Mollusca (1%)) were represented in smaller proportions throughout the survey.

The benthic observations clustered into three faunal assemblages (Fig. 4) explained a large (R=0.707) and significant (p=0.001) amount of the observed variation in benthic fauna composition among these assemblages. Comprised mostly of sites with Fine Sediments with Mixed Gravel (76%; Fig. 5), and some classified as Fine Sediments *(*19%) and Rhodoliths with Mixed Gravel (5%), the first assemblage had the smallest spatial extent being observed in 28% of all video surveys (n = 21). This assemblage was found predominately within intermediate depths of 35 – 55 m. In total, 8,558 individuals across 47 morphotaxa were surveyed in Assemblage 1, where scarlet sea cucumbers were most common and formed dense aggregations on large boulders and cobbles. The indicator taxa for this assemblage were organisms that typically attach themselves to harder substrates, including tunicates (Ascidiacea spp. & *Halocynthia pyriformis*) and erect bryozoans (Bryozoa spp. 2). There were 18 dominant species within this assemblage (Supplementary Fig. S2), including scarlet sea cucumbers, sea potatoes (*Boltenia ovifera*), sponges (Porifera spp.), and Iceland scallop (*Chlamys islandica*).

Situated closest to the shoreline and found predominately in shallower depths (15-20 m), the taxa represented in Assemblage 2 occupied 25 sites (33%) of the 75 sites sampled. The most common substrate at sites where Assemblage 2 was found was Rhodoliths with Mixed Gravel (40%; Fig. 5). In addition, many sites hosting this assemblage showed evidence of high primary productivity, with a considerable coverage of seaweeds (*Agarum clathratum*, *Saccharina longicruris*, Lithothamnion spp., Rhodophyta spp.) and diatom mats. Across 47 morphotaxa, 14,096 individuals were surveyed within Assemblage 2, with green sea urchins (*Strongylocentrotus droebachiensis*) being most common (n = 7179) and the sole indicator taxon for this assemblage. Assemblage 2 consisted of 13 dominant taxa (Supplementary Fig. S2), including a variety of sea cucumbers (*Psolus fabricii*, *Cucumaria frondosa*, *Psolus phantapus*), scallops, anemones (*Urticina felina*) and sea stars (*Leptasterias polaris*).

While the other assemblages shared the most taxonomic similarities as shown in the dendrogram (Fig. 4), Assemblage 3 was most unique and had the largest spatial extent of all video surveys at 39% (n = 29). Sites within the third assemblage were mostly found further from the coastline at depths of 35-90 meters and were composed entirely of Fine Sediments (Fig. 5), with some sites overlain by diatoms. A total of 22,155 individuals across 41 morphotaxa were surveyed in Assemblage 3. Tube-dwelling anemones (Ceriantharia spp.; likely *Pachycerianthus borealis*) were most common and formed extensive fields across the seabed, particularly within sites covered in benthic diatoms. Characterized by tube-dwelling anemones, tube worms (Sabellida spp.), and brittle stars, this assemblage was the most homogeneous compared to the other assemblages. There were 10 dominant taxa (Supplementary Fig. S2) in the third assemblage which included the indicator taxa mentioned above as well as shrimp (*Pandalus* spp.), blennies (*Lumpenus lampretaeformis* and *Leptoclinus maculatus*), green sea urchins, sea cucumbers (*Psolus phantapus*), sponges, and slime tube worms (*Myxicola infundibulum*).

Assemblage 1 exhibited the highest taxa richness, followed by Assemblage 2 and 3 respectively. Species accumulation curves demonstrated adequate coverage, as the curves for each assemblage approached asymptotes, indicating that most detectable taxa were likely captured within the sampling effort (Fig. 6). However, the constraints of video surveys may have underrepresented the taxa richness of all or some of these assemblages.

Model Performance and Predicted Distribution

There were five variables included in the epifaunal models succeeding the Boruta selection algorithm and assessment of collinearity, and 10 variables in the second model containing substrate classifications (listed in Fig. 8). Without substrate classifications, the RF model accuracy was 86.7% (kappa

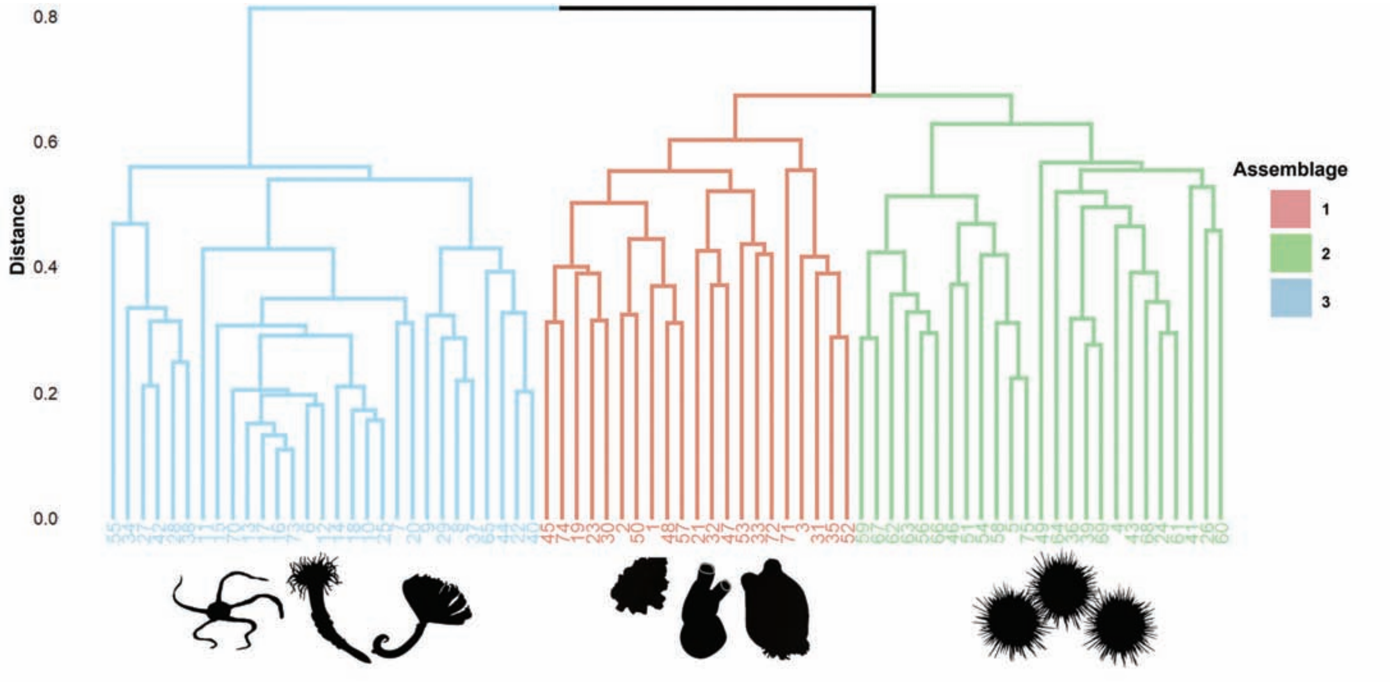

FIG. 4. Dendrogram, based on hierarchical clustering (UPGMA) with three epifaunal assemblages. Indicator taxa silhouettes represent each assemblage.

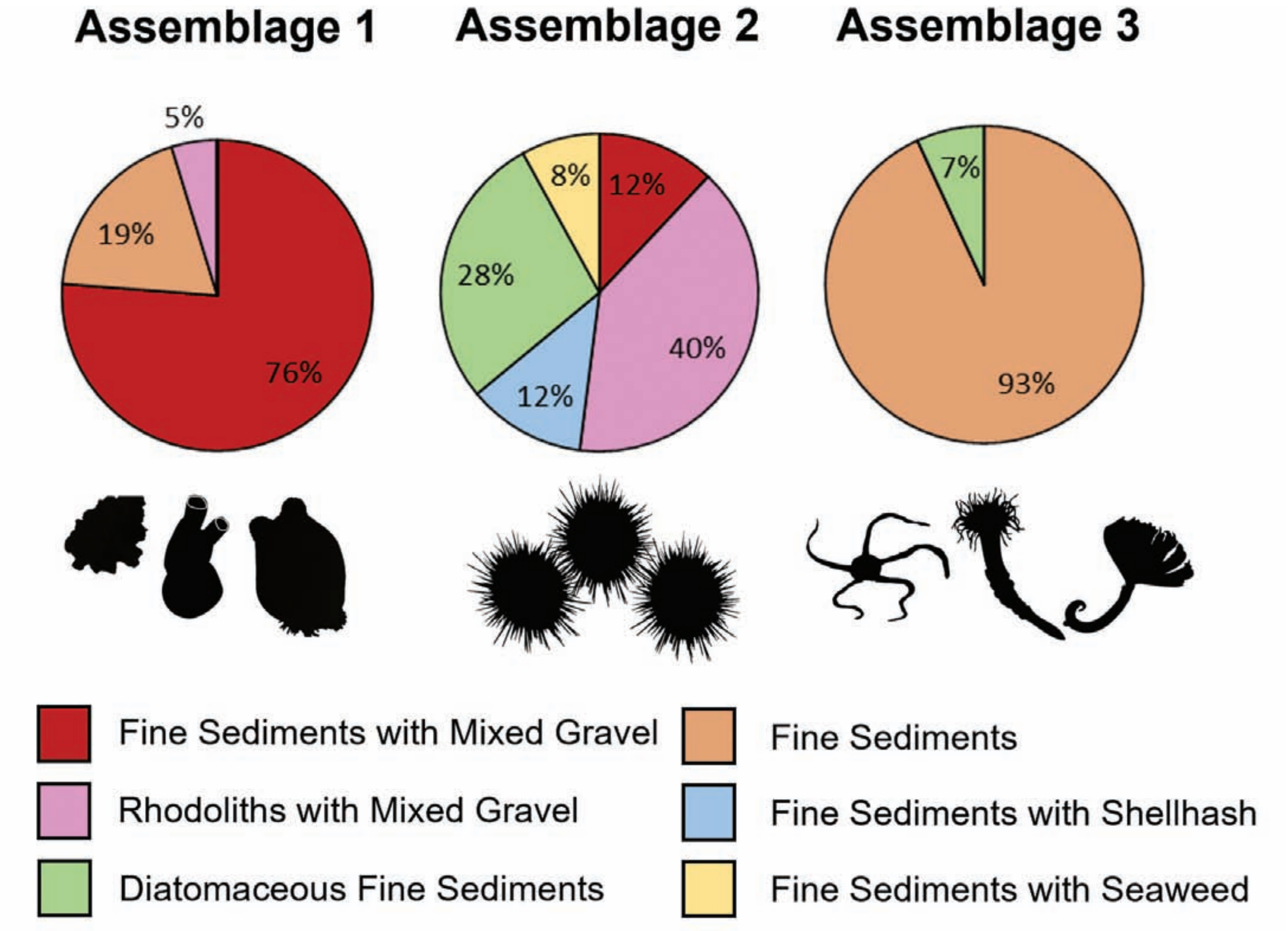

FIG. 5. Percentage of sites by substrate classification hosting each epifaunal assemblage.

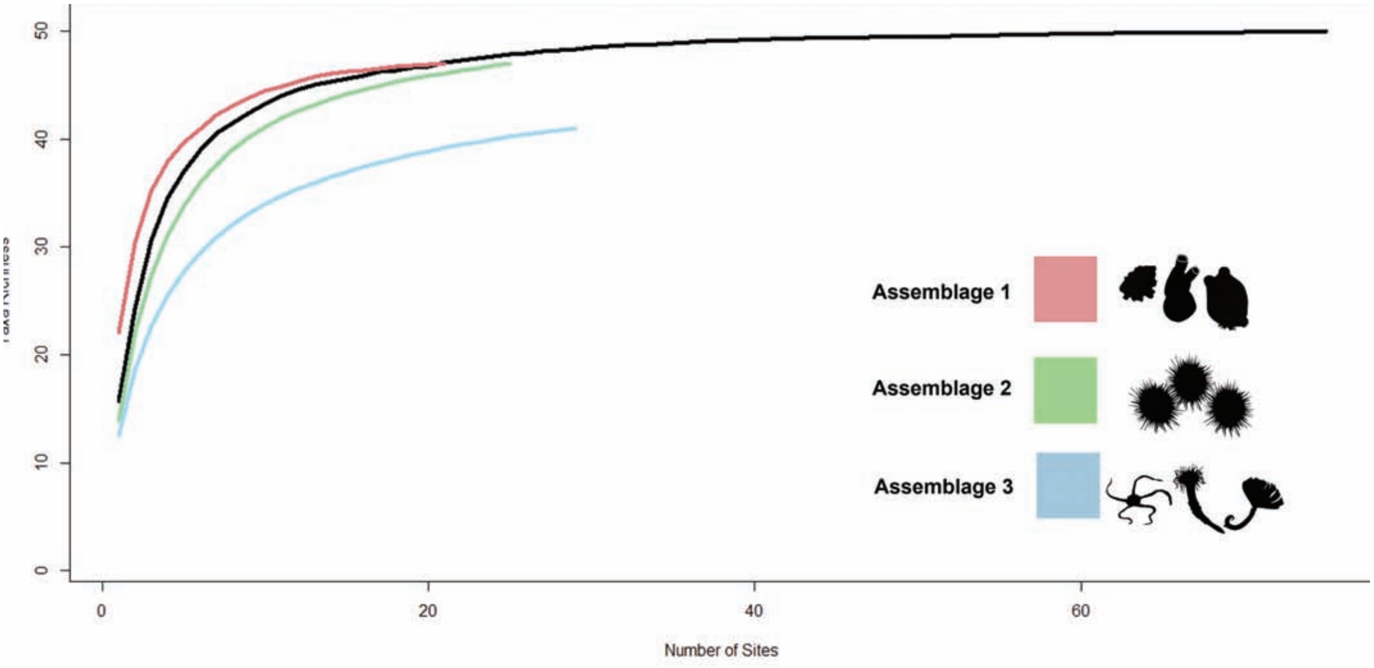

FIG. 6. Species accumulation curve for each faunal assemblage and for the total number of taxa observed across all sites included in the analysis (black).

= 0.80); however, when substrate features were included, model accuracy was improved to 90.7% (kappa = 0.86) (Table 1). The first assemblage was overestimated relative to the others in both RF models as displayed by the lower precision score (76.2% without substrate and 81% with substrate) and higher number of false positive predictions (n = 5 and 4, respectively). The model with substrate improved the sensitivity values for Assemblage 3 from 84.4% with 5 false negatives to 90% with 3 false negatives. Overall, the model without substrate accurately predicted the spatial extent of each assemblage with relatively high balanced accuracies, and both models predicted Assemblage 2 more confidently. The predicted distribution of these assemblages is illustrated in the habitat map (Fig. 7).

Assemblage-Environment Relationships

According to the RF model, bathymetry was the most important variable for predicting the distribution of the epifaunal assemblages (Fig. 8). Sites with intermediate depths were associated with Assemblage 1 (mean ± SD; 46.439 ± 20.271), while shallower areas distributed near the coastline were associated with Assemblage 2 (17.786 ± 9.086). Assemblage 3 was associated with deeper sites than both other assemblages (61.821 ± 31.898) and was mostly distributed farther from the coastline (e.g., the center of a fjord near the southern portion of the survey). Salinity was shown to be the second most important variable for predicting the distribution of these assemblages for the model without substrate (Fig. 8a). The first two assemblages were associated with lower salinity values (Assemblage 1: 28.14 ± 0.87; Assemblage 2: 28.47 ± 0.88), while Assemblage 3 was associated with higher salinities (29.50 ± 0.45). When substrate classifications were added to the RF model, Fine Sediments appeared to be more important than salinity for predicting assemblage distribution. Fine Sediments were associated mostly with Assemblage 3. Fine Sediments with Mixed Gravel was also important and was mostly associated with Assemblage 1. The remaining substrate classifications were ranked least important in the model, including Rhodoliths with Mixed Gravel found throughout the second assemblage.

Ogak Habitats

Three community-identified ogak fishing locations were associated with Assemblage 1, situated within and near Metre Bay and at the mouth of Ten-Mile Bay. These sites were characterized by Fine Sediments with Mixed Gravel. An ogak was observed on video at a site in this assemblage, characterized by Fine Sediments with Mixed Gravel, north of Metre Bay. Another ogak was recorded on camera at a site in Assemblage 2, situated south of Kauk Bluff Island, which featured Rhodoliths with Mixed Gravel. This assemblage also included two community-identified ogak fishing locations within Two-Mile Bay and north of Metre Bay and these were characterized by Fine Sediments with Gravel and Rhodoliths with Mixed Gravel. Assemblage 3 did not contain any community-identified ogak fishing locations or ogak observations on video.

DISCUSSION

The spatial representation of epifaunal assemblages in this understudied inshore marine environment addresses

TABLE 1. Performance metrics for assemblage prediction accuracy assessment. Both Random Forest models with (above) and without (below) substrate features are shown.

	Assemblage	1	2	3
Without substrate	Balanced accuracy (%)	87.600	93.000	90.000
	Precision	0.762	0.880	0.931
	Sensitivity	0.842	0.917	0.844
	Specificity	0.912	0.941	0.953
	F1-Score	0.800	0.898	0.885
	F+	5	3	2
	F-	3	2	5
With substrate	Balanced accuracy (%)	91.200	95.100	92.800
	Precision	0.810	0.960	0.931
	Sensitivity	0.895	0.923	0.900
	Specificity	0.929	0.980	0.931
	F1-Score	0.850	0.941	0.915
	F+	4	1	2
	F-	2	2	3

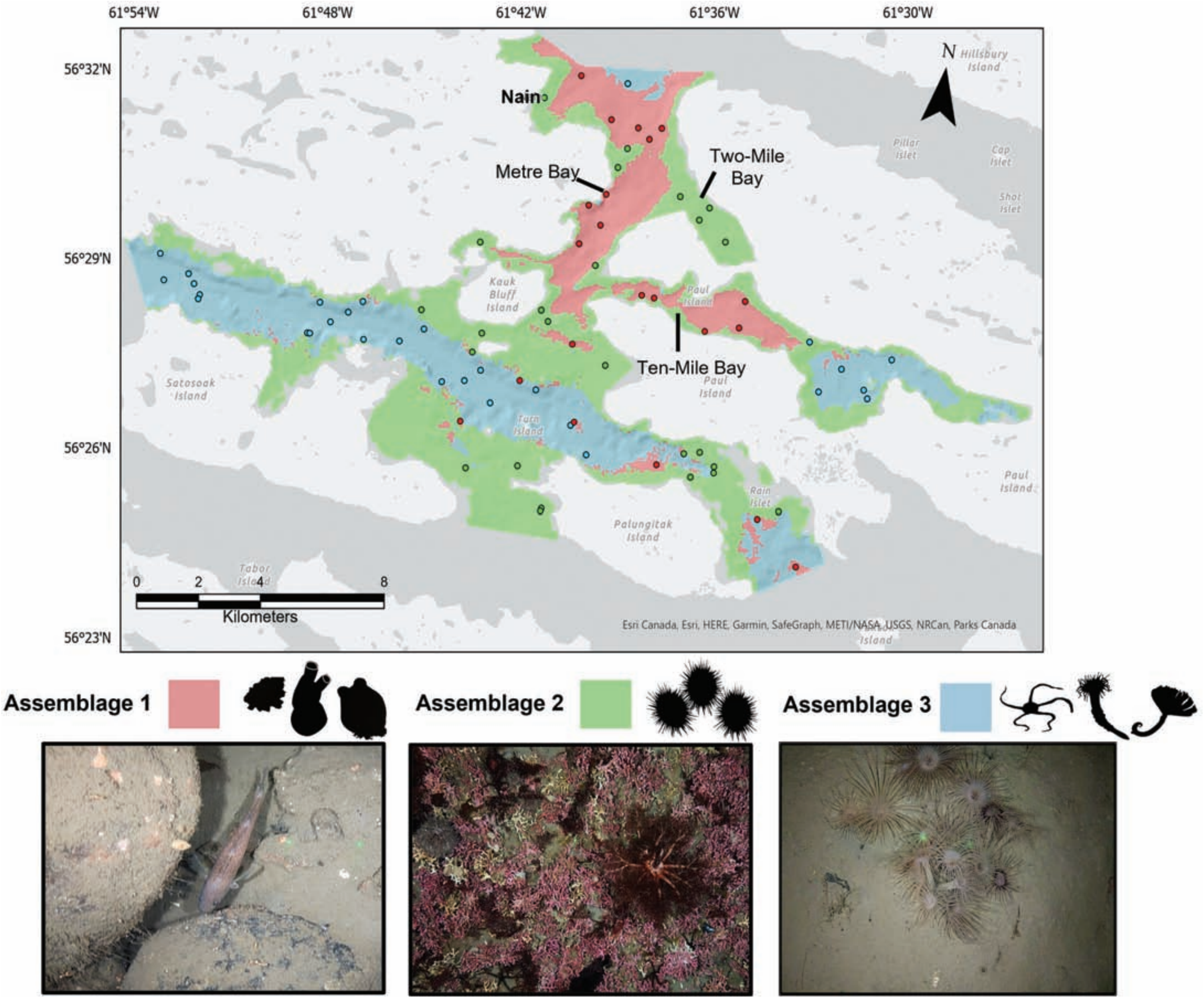

FIG. 7. Predicted spatial coverage of the three identified assemblages by the Random Forest model across the survey area in Nain, NL. Representative photographs of assemblages are included. Sample stations are coloured based on the observed associated assemblage.

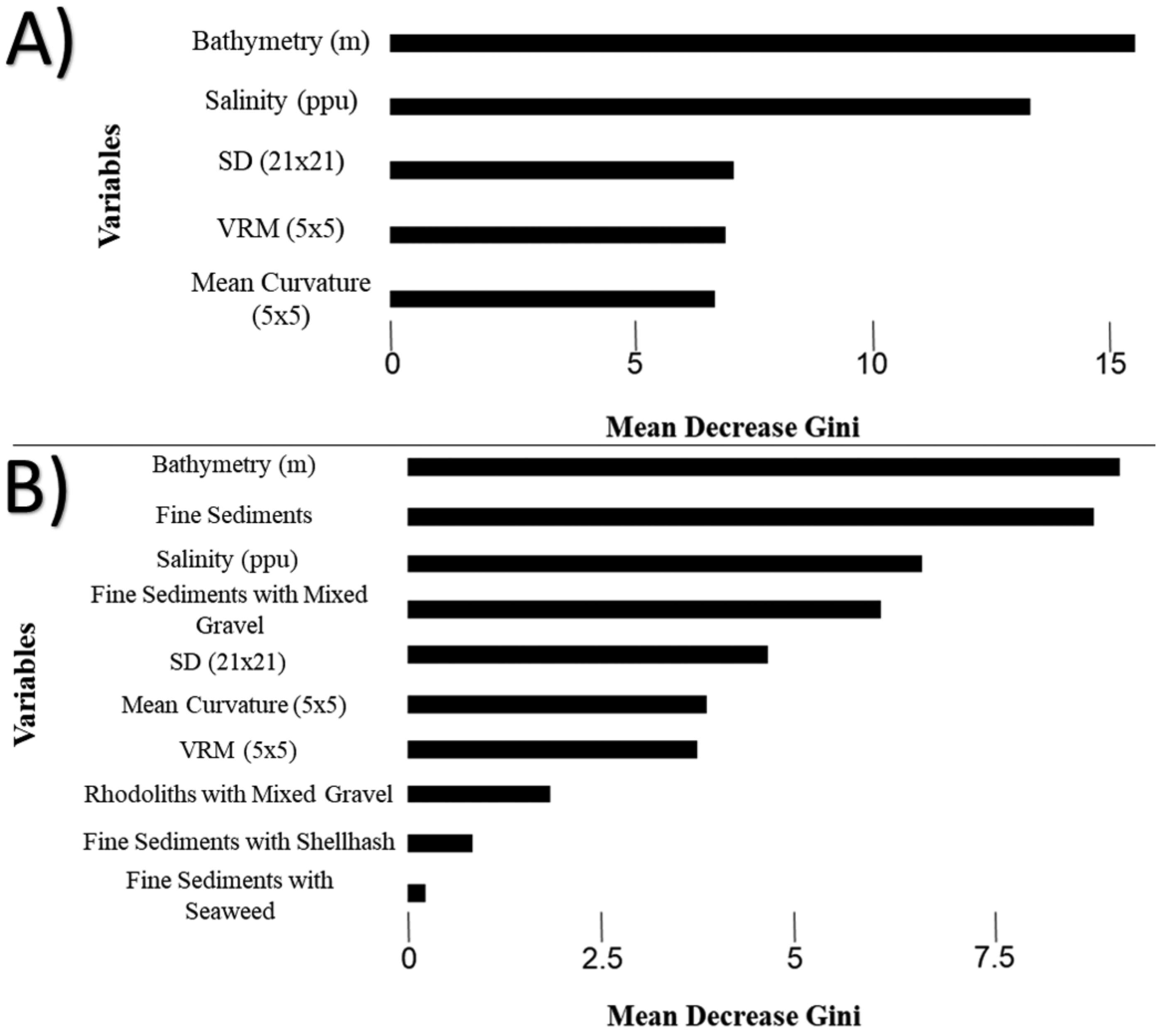

FIG. 8. Variable importance determined from the Random Forest (RF) model without (a) and with substrate (b) for the epifaunal assemblages.

key knowledge gaps identified by Labrador Inuit and the Nunatsiavut Government. By identifying the environmental drivers shaping benthic community distributions and characterizing habitats within local ogak fishing locations, this research supports Inuit subsistence practices and contributes to the Imappivut initiative. The study highlights the presence of structurally complex habitats, such as rhodolith beds, within ogak fishing locations. Given the potential vulnerability of these habitats to human disturbances, such as scallop dredging, further research is needed to assess their resilience and inform management strategies that balance conservation with sustainable resource use. The habitat map generated here is intended to inform conservation strategies and help resource users mitigate the impacts of a changing environment.

Listening to and Applying Traditional Ecological Knowledge

This study highlights the value of applying TEK and LEK in western science to enhance our understanding of northern benthic habitats. While the data collection and analysis were technical, the inclusion of community-identified ogak fishing locations provided critical context for the study. These locations, shared by local fishers and provided by the NG, guided the selection of sampling sites and enhanced the interpretation of results. Although TEK was not explicitly incorporated into the statistical modeling, its role in shaping the objectives, study design and enriching our findings highlights the importance of collaborative approaches in northern research. This collaboration aligns with broader efforts to address knowledge inequities and support Inuit self-governance and sustainable resource management (Berkström et al., 2019; Mulalap et al., 2020; Stern and Humphries, 2022). By acknowledging and applying TEK, this study contributes to initiatives such as Imappivut, which aims to enhance Inuit self-governance and sustainable resource management. However, it is not our role to determine how these findings should be integrated into Imappivut or decision-making processes. Rather, our research serves as a resource that the NG and Inuit communities may choose to use in ways that align with their priorities and governance objectives. This approach reflects the importance of respecting Indigenous leadership in marine stewardship and ensuring that scientific contributions complement, rather than dictate, locally driven decision making.

Epifaunal Assemblages, Spatial Distribution, and Environmental Relationships

Distinct differences in taxa composition, richness and substrate were identified within the three epifaunal assemblages identified. Ascidians and erect bryozoans characterized Assemblage 1, located in the center and northern part of the survey at intermediate depths, and were observed attached to large cobbles and boulders scattered on fine sediments. This assemblage featured a high abundance of sea cucumbers which were documented in video surveys as one of the most abundant organisms of Nain's inner archipelago (Rangeley et al., 2022; MacMillan-Kenny et al., 2025). Assemblage 2, located in shallow waters near the shoreline, featured rhodolith beds dominated by green sea urchins, a species commonly associated with coralline algae habitats due to their grazing behavior (Jørgensbye and Halfar, 2017). Similar sea urchin-dominated coralline habitats have been observed in Greenland (Jørgensbye and Halfar, 2017) and northern Nunatsiavut (Friedlander et al. 2023). Previous surveys also reported sea urchins in 40% of quadrats throughout the Nain archipelago, particularly on hard substrates (Rangeley et al., 2022). Brittle stars, tube worms (Sabellida spp.) and cerianthids (Ceriantharia spp.) were found to have widespread distribution and high abundance, especially in deep sites with fine sediment throughout Assemblage 3. This assemblage aligns with previously documented deepwater biotopes in fjords and fjards of Okak and Hebron (Rangeley et al., 2022).

Depth plays a significant role in shaping the distribution of benthic organisms, as it often acts as a proxy for multiple interconnected environmental factors such as light availability, temperature, salinity, and wave action (Elith and Leathwick, 2009). Our analysis further confirmed depth as the most influential factor in shaping epifaunal distribution, aligning with other studies that have highlighted its importance (Neves et al., 2014; Schückel et al., 2015; Bekkby et al., 2019; Mackin-McLaughlin et al., 2022). In addition to depth, substrate variability was a critical factor in the second model. Assemblages 1 and 2, found in shallower areas with more complex substrates, exhibited higher species richness compared to Assemblage 3, which was dominated by fine sediments and showed lower taxonomic richness. This finding aligns with previous studies highlighting the role of substrate variability in shaping benthic community structure (Snelgrove and Butman, 1994; Roy et al., 2014). In archipelagos like Nain, currents can vary significantly (Miettunen et al., 2024), with strong currents in tidal chokepoints and weaker currents in sheltered embayments. These variations influence the type of substrate and associated biota (Sarmiento and Gruber, 2013; Puccinelli et al., 2018). For example, filter feeders like sea cucumbers and anemones, dominant in Assemblages 1 and 2, thrive in high-current areas due to increased food availability (Thompson, 1982), while weaker currents promote fine sediment deposition (Chauvel et al., 2024), as observed in Assemblage 3. The sites in Assemblage 2, which exhibited more biogenic habitat complexity, typically support greater taxonomic diversity (e.g., Włodarska-Kowalczuk et al., 2012; Davies et al., 2015; Carpenter et al., 2020). However, these areas showed lower observed taxa richness than Assemblage 1, likely due to dense rhodolith and seaweed cover, which may have obscured smaller benthic organisms.

Structurally Complex Habitats and Their Ecological Significance

Vulnerable marine ecosystems (VMEs) are biodiversity hotspots characterized by benthic faunal assemblages that are sensitive to environmental disturbance, physically fragile, and slow to recover from damage. The term is typically applied to deep-water habitats (FAO, 2009). Rhodolith beds and other coralline algal communities were prominent features of Assemblage 2 (Fig. 9a). In this study, ogak fishing locations were linked to these habitats, highlighting their potential importance for subsistence fisheries and local food security. While rhodolith beds are not formally classified as VMEs, Jørgensbye and Halfar (2017) recommended their inclusion as VMEs in Greenland based on their functional significance, structural complexity, long lifespans, and slow recovery rates following disturbance (FAO, 2009; Chimienti et al., 2019). The structural characteristics and ecological role of the rhodolith beds observed throughout Assemblage 2 in this study appear to be similar to those described in the Greenlandic study (Jørgensbye and Halfar, 2017), suggesting that they may share traits associated with vulnerability to environmental disturbance. The association of rhodolith beds with scallops in previous studies (Barbera et al., 2003; Kamenos et al., 2004a) is particularly noteworthy, given the growing interest in the Icelandic scallop (*C. islandica*) fishery in Nunatsiavut (Barker, 2019; Schaible, 2019; Kourantidou et al., 2021A). The physical disruption caused by scallop dredging poses a significant threat to these habitats, as evidenced by studies documenting long-term damage and slow recovery (Hall-Spencer and Moore, 2000; Stewart and Howarth, 2016).

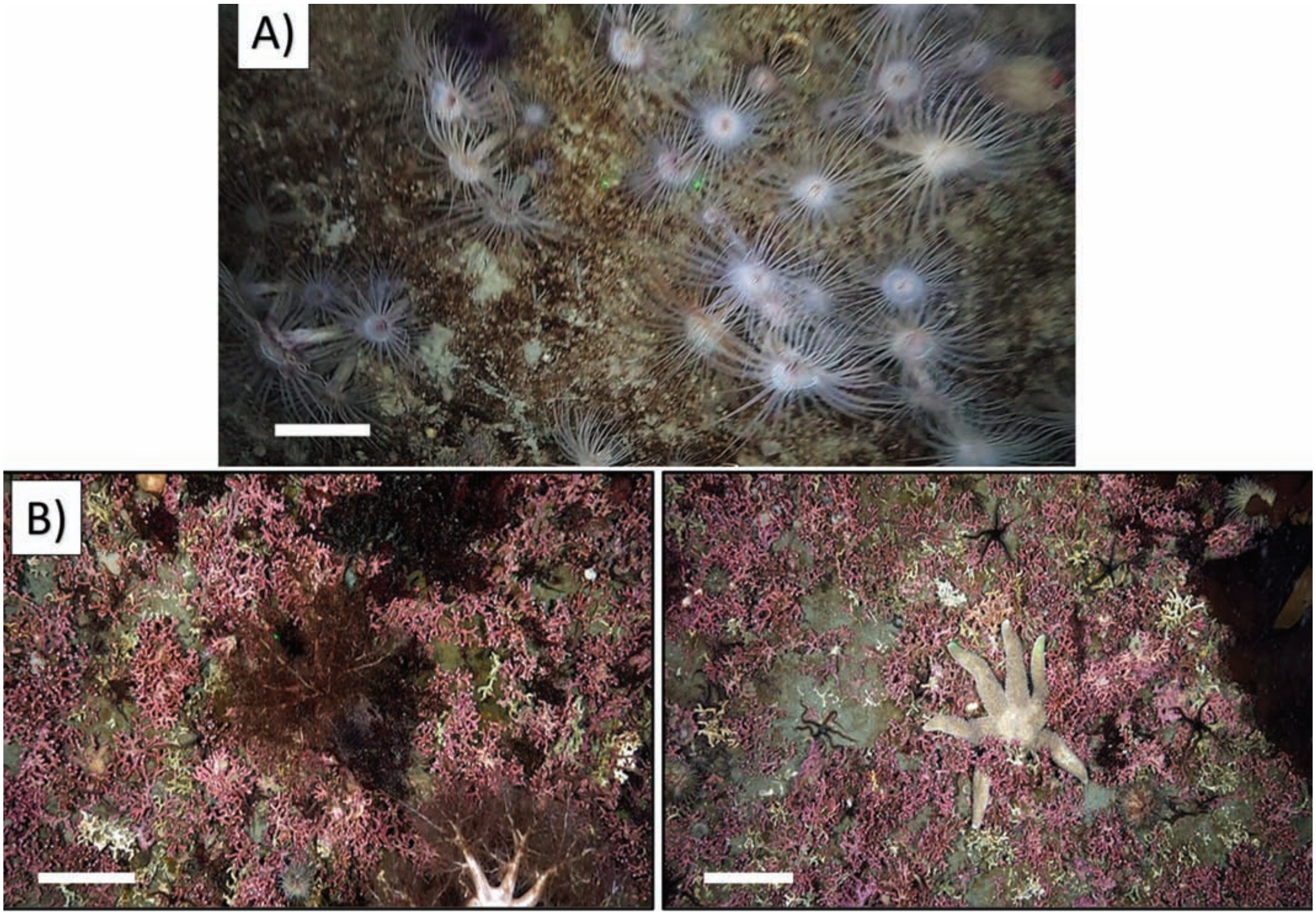

FIG. 9. Tube-dwelling anemone (Ceriantharia spp.) field (a) and rhodolith beds (b) in Nain. Commonly observed on fine sediments covered in diatom mats. White bar for scale is 10 cm.

Cerianthid tube-dwelling anemones, which formed dense fields in Assemblage 3 (Fig. 9b), are often considered indicators of VMEs in deep-water environments (FAO, 2009); however, their vulnerability in coastal systems remains less clear. While these populations are susceptible to damage from bottom-contact fishing gear (Fuller et al., 2008), their resilience in shallow, dynamic environments may differ from that of deep-water populations. Similarly, erect bryozoans and large ascidians, which were dominant in Assemblage 1, are VME indicators in deep-water contexts (Murillo et al., 2011) but may exhibit greater resilience in coastal systems.

Ogak Benthic Habitat Associations

The community-identified fishing locations fell within Assemblage 1 and 2, representing higher substrate complexity. As these areas contained only two observations of ogak during video surveillance, it is difficult to draw definitive conclusions about habitat associations based on such limited data. In contrast, the most homogeneous assemblage (i.e., Assemblage 3) did not contain any ogak observations and were not identified by Inuit as important fishing locations. This limited evidence, combined with local knowledge, suggests a potential association between important fishing locations and more structurally complex habitats, often characterized by elevated coverage of seaweed and rhodolith beds.

Supporting the association between ogak and complex habitats, previous studies have found ogak to prefer shallow, productive waters with high macroalgal coverage, and rocky outcroppings (Morin et al., 1991; Knickle, 2013; Knickle and Rose, 2014; Dalley et al., 2017). Recent underwater scuba surveys in Nunatsiavut found that outside Nachvak Fjord, ogak dominated fish biomass in areas with high coverage of kelp and boulders with few megabenthic invertebrates present (Friedlander et al., 2023). Interestingly, these fish were not found in high abundance within the fjord, which lacked kelp. A previous study in southwest Scotland determined through scuba and fyke net surveys that gadoids consistently favor feeding above rhodolith beds rather than gravel, despite the greater vegetation cover provided by gravel (Kamenos et al., 2004b). The presence of rhodolith beds and evidence of high primary productivity within Assemblage 2 may provide abundant food resources beneficial for supporting juvenile ogak and other gadoids and may enhance the capacity of shallow-water nursery zones (Kamenos et al., 2004b).

CONCLUSION

This study makes a valuable contribution to understanding the benthic habitats of a northern, understudied region by providing detailed descriptions and maps for these unique habitats. By identifying distinct faunal assemblages and potentially sensitive habitats, such as rhodolith beds and cerianthid fields, the research supports the Nunatsiavut Government's Imappivut initiative, which seeks to manage and protect marine resources in alignment with the values and priorities of Labrador Inuit. Applying TEK and LEK, through community-identified ogak fishing locations, enhanced site selection and contextualized findings, highlighting the importance of collaborative approaches in northern research. Identifying key habitats and the drivers of their distribution informs marine spatial planning strategies that balance conservation with sustainable resource use. These insights are critical for resource managers monitoring and mitigating environmental changes to preserve biodiversity and ecosystem functions. Additionally, the study suggests a potential association between *Gadus ogac* (ogak) and habitats with higher substrate complexity and extensive coverage of primary producers, such as rhodolith beds. While data on ogak habitat associations remain limited, this research provides important baseline information for future studies. By working with the local community and government, these findings offer valuable support for self-governance efforts, empowering local communities to make informed decisions and effectively manage and conserve their marine environments.

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