



New distribution records of kelp in the Kitikmeot Region, Northwest Passage, Canada, fill a pan-Arctic gap

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Abstract

Kelps play important roles in ecosystems as they provide structural habitat and protection, and supply food. Given these beneficial roles and observed increases in seaweed biomass and distribution ranges across the Arctic, mapping kelp occurrence around Arctic coasts is both timely and necessary for future conservation. Here, we fill spatial gaps in the knowledge of kelp distribution in the southern Northwest Passage, Canadian Arctic Archipelago; specifically, we report the occurrence of *Laminaria solidungula*, *Saccharina latissima* and *Alaria esculenta* from Victoria and Dease straits and Bathurst Inlet in the Kitikmeot Region at depths mostly from 10 to 30 m (max. 40 m; upper extent vessel-limited). Kelp specimens were found at bottom water temperatures from sub-zero to 1 °C (surface-T to ~6 °C) and bottom water salinities of ~28 (surface-S < 20) in August–September. Kelp sites were characterized by both strong tidal currents (max. estimates from a tidal model 20–70 cm s⁻¹ in center of passages) and hard substrates, interspersed with finer sediments. Co-occurring identifiable epibenthos was dominated by suspension-feeders preferring currents (sea cucumbers, soft corals, *Hiatella* clams), potential kelp consumers (sea urchins *Strongylocentrotus* sp., *Margarites* snails, limpets) and predatory invertebrates (sea stars, lyre crabs). At the same and some deeper nearby sites, loose kelp fragments were also found at the seabed, suggesting that kelps contribute to the regional detrital food web by supplying carbon to less productive sites. Kelps in the region may expand their ranges and/or growing season with reduced ice cover and warming, although constraints through local turbidity sources, extreme temperatures, low salinity and low nutrient concentrations are also recognized.

Keywords Arctic · Kelp · *Alaria esculenta* · *Laminaria solidungula* · *Saccharina latissima* · Northwest Passage · Habitat

Introduction

Kelps, which are large brown seaweeds in the order Laminariales, play many important roles in marine socio-ecosystems. Kelp systems are a prominent feature of temperate and high latitude rocky coasts (Wiencke and Amsler 2012, Filbee-Dexter et al. 2019) and are characterized as biomass-rich and diverse structural biotopes (Steneck et al. 2002). They provide a living habitat for many other species, for example: numerous crustaceans and polychaetes

live inside kelp holdfasts (Schuster and Konar 2014); diatoms, bryozoans, hydrozoans are epiphytic on kelp blades (Forbord et al. 2020); sea urchins directly ingest kelp, while predatory crabs and other invertebrates use kelp systems as habitat (Konar and Estes 2003). Kelp systems also serve as important habitat for certain fishes, including commercial species such as cod, herring and rockfish at high latitudes (Norderhaug et al. 2005; Costa et al. 2020). In addition to the structural roles (habitat and shelter), kelps are part of the food web both directly as a food source for kelp grazers (Norderhaug and Christie 2009), and indirectly as detrital material. In form of detritus, kelp can be distributed to regions much farther from, and deeper than, their growth sites (Krumhansl and Scheibling 2012; Pedersen et al. 2020). Kelps and other seaweeds also provide a food source to humans and livestock through in situ harvests (Makkar et al. 2016) as well as increasingly through ocean farming, even at high latitudes (Forbord et al. 2020). Finally, as large and fast-growing primary producers with high productivity

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rates (Krause-Jensen et al. 2012), kelps along with other macroalgae, can sequester and store substantial amounts of atmospheric CO₂ (Chung et al. 2011). As a consequence of these various functions, these seaweeds play a role in conservation planning of kelp systems (Costa et al. 2020 and references therein) and blue carbon strategies (Krause-Jensen et al. 2018). Recent comprehensive compilations of pan-Arctic kelp and other macroalgal data sets show that in many remote Arctic regions including the Canadian Arctic the extent of kelp distribution mapping shows large gaps (Filbee-Dexter et al. 2019; Krause-Jensen et al. 2020).

The occurrence of kelps and other seaweeds is constrained by a combination of environmental factors, some of which display more extreme seasonality in the Arctic marine system than found in boreal regions (see Johnsen et al. 2020 for a summary). Long periods of darkness limit photosynthesis, winter temperatures at or near freezing affect metabolism, and sea-ice scour of the seafloor cause mechanical disturbance, rendering many shallow areas uninhabitable for most macroalgae (Fredriksen et al. 2019). As an adaptive measure, however, the minimum light requirement for growth, photosynthesis and completing the life cycle tends to be particularly low for polar species, and the tolerance of long dark periods is particularly high (Wiencke and Amsler 2012). Low temperatures are tolerated in particular by typical Arctic species such as the endemic kelp *Laminaria solidungula* while boreal species extending into the Arctic were thought to have higher growth optima (tom Dieck (Bartsch) 1992). Challenging this paradigm, however, Bringloe et al. (2020) recently proposed that Arctic macroalgae communities are in fact adapted to Arctic conditions rather than merely tolerating them since, so they argue, they persisted through glaciations. Seasonally and diurnally low salinities due to large amounts of freshwater run-off and ice melt at Arctic coasts in general (Carmack et al. 2016), and in the study area in particular (Williams et al. 2018) require osmotic adaptation, generally found in intertidal macroalgae (Karsten et al. 1991), while subtidal habitats are less variable and subtidal kelps may thus be comparatively less adapted (Johnsen et al. 2020). The requirement for hard substrate for attachment further constrains distributions around the Arctic (see Lantuit et al. 2012 for coastal classification) resulting in seaweeds being most widespread in Arctic Norway, Canada and Greenland in addition to various island groups and small patches of boulders (Wilce and Dunton 2014; Filbee-Dexter et al. 2019; Krause-Jensen et al. 2020). Despite the extreme Arctic conditions, Wilce (1994) reported that upwards of 150 species of largely widespread macroalgae have successfully colonized in Arctic waters, and Fredriksen et al. (2019) reported 197 species in a recent survey in Svalbard waters. Archambault et al. (2010) estimated 210 macroalgal species for the Canadian Arctic. While less than a dozen are kelp species (order Laminariales), including the Arctic endemic

Laminaria solidungula as well as widespread kelps in the genera *Saccharina* and *Alaria* (Wilce and Dunton 2014; Filbee-Dexter et al. 2019), these kelps are often the biomass dominant macroalgae in the subtidal due to their large size (Johnsen et al. 2020).

Given the ecological and emerging economic role of kelps in high latitudes in general, and the coastal Arctic in particular, mapping their distribution and the biological communities they support or are associated with has been showcased as both urgent and critical (Filbee-Dexter et al. 2019). In addition, kelp and other macroalgae have been increasing in extent and biomass across the Arctic (and decreasing at southern boundaries), and/or depth distributions have shifted over the past decades in response to decreasing sea ice cover (Kortsch et al. 2012, Krause-Jensen et al. 2020), yet regional knowledge on their distribution is incomplete. A recent, pan-Arctic compilation of kelp distributions provides a comprehensive status overview (Filbee-Dexter et al. 2019). In this compilation, Arctic Canada was identified as one of the areas with the most extensive gaps in mappings of pan-Arctic kelp distributions. As the Northwest Passage in particular is increasingly being used by vessel traffic (Silber and Adams 2019) a baseline of habitat types is much needed. To address these needs, here we present new records of several kelp species from the Kitikmeot Region of the southern Northwest Passage in the Canadian Arctic Archipelago in a small-scale survey. We further characterize relevant habitat and oceanographic conditions (substrate, temperature, salinity, nutrient concentrations and irradiance) where these species were found, and speculate how kelps may fare under changing environmental conditions in the area.

Methods

Study area

Sampling was conducted onboard the R/V Martin Bergmann in the Kitikmeot Region of the southern Northwest Passage between Bathurst Inlet to the west and Victoria Strait to the east (66.8–69.0° N, 101.8–108.1° W, Fig. 1) from 11 to 15 August 2016, 23–29 August 2017 and 19 August–5 September 2019. Survey depths ranged between 10 and 93 m. The Kitikmeot Region in Canada's Nunavut Territory comprises Coronation Gulf and Bathurst Inlet to the west and Queen Maud Gulf and Chantrey Inlet to the east, connected through Dease Strait in the center (Fig. 1). The study area is an oceanographically unique part of the Canadian Arctic Archipelago due to its massive freshwater input relative to the area's size (Brown et al. 2020), and its shallow (< 30 m) bounding sills at Dolphin-Union (west) and Victoria straits (to the northeast) that constrain surface outflows of low salinity waters and sub-surface inflows of more saline waters

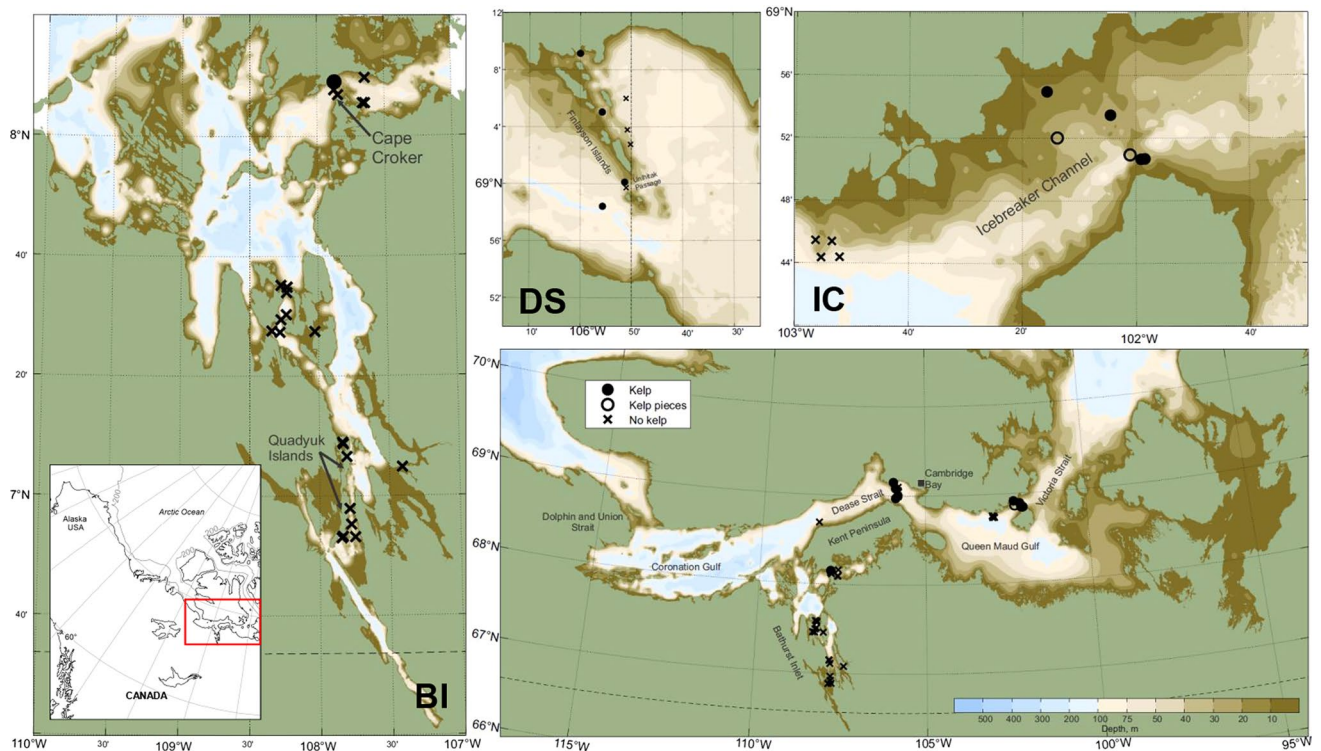


Fig. 1 Study region in the Northwest Passage with locations where we found attached kelp (black circles), unattached kelp pieces only (unfilled circles), and no kelp (crosses). *IC* Icebreaker Channel, *DS*

Dease Strait, *BI* Bathurst Inlet. The inset shows the location of the study area within Nord-America

(Williams et al. 2018; Nelson et al. 2019). Strong tidal currents through shallow sills and narrow passages (Hannah et al. 2009; Rotermund et al. 2021) are thought to enhance vertical heat and nutrient flux and maintain ice-free or near ice-free conditions in these places in winter and early melt in spring, as demonstrated by satellite images and Indigenous knowledge (Williams et al. 2018). Substrates include a variety of types including rocky and gravelly coasts, interrupted by sedimentary river estuaries with low-gradient shores and mixed sediments (pers. obs.) while deeper sediments include softer muds and clays (Roy et al. 2014; Dumais 2020).

Biological collections and processing

Imagery of the seafloor was the basis for the kelp records and was collected using a drop camera and a remotely operated vehicle (ROV). In 2016 and 2019, a GoPro camera mounted on a metal frame was set to take one still image every 10 s. An onboard screen displayed the live video feed from an additional video camera which was used to guide the amount of cable deployed to keep the distance to the seafloor around a target of 1–1.5 m. In 2017, a small ROV (LBV300-5 Seabotix) was equipped with a near-downward oriented video camera (720 pixels), thrusters and LED light (ca. 1000 lm). Camera and ROV transects, oriented along the

current drift direction, had a target duration of 15 min at bottom while the vessel drifted with wind and currents at drift speeds between ~0.2 and 1.5 kn (resulting in unequal areal coverage). At a drift of around 0.8 kn the imagery became increasingly blurry, and very blurred images (in fast drift; see Table 1) as well as clearly overlapping images (in slow drift; see Table 1) were omitted from analysis. From 29 to 201 images per site were usable and were screened for kelp occurrence by viewing them in IrfanView software, and where needed enhancing contrast and applying the sharpening function. The percentage of images where kelp was detected was calculated per station and the kelp species present were noted for each location. The proportion of frames where unattached larger kelp pieces (detritus) could be detected as such was also recorded; small pieces would have gone undetected. Substrate was categorized as hard (boulder, gravel) or soft (sands, mud, silt). Fish were not visible in the imagery, and were likely scared away by the camera if present.

To obtain physical specimens that aided in identification of kelp and invertebrate taxa on the images, a small dredge was deployed at five sites each in Icebreaker Channel and Dease Strait; only one haul was possible in Bathurst Inlet (Cape Croker). The opening of the dredge was 55 cm wide and 25 cm high, and the attached bag 80 cm long with a

Table 1 Locations of new distribution records of kelp species in the Kirikmeot Region, Northwest Passage: Dease Strait, Bathurst Inlet and Icebreaker Channel

Region	Lat (dec °N)	Long (dec °W)	Date	Depth (m)	Bottom T (°C)	Bottom salinity	PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Substrate	Kelp species	Images with kelp (%) (loose kelp in parentheses)	N° of images screened	Common identifiable epibenthos on imagery
Icebreaker Channel, Victoria Strait (VS)	68.845	–101.974	13-Aug-19	15–20				small boulders, mostly ≤ 5 cm	<i>Alaria esculenta</i> , <i>Saccharina latissima</i> /L. <i>solidungula</i>	61	41 (b)	conspicuously absent, not clearly identifiable
Icebreaker Channel, VS	68.844	–101.985	14-Aug-19	12				boulders, gravel, shell hash	a few <i>A. esculenta</i> , <i>S. latissima</i> /L. <i>solidungula</i>	26	95	many Nephthidae corals, <i>Strongylocentrotus</i> sp., a few <i>Cucumaria frondosa</i> , <i>Hiatella</i> shells
Icebreaker Channel, VS	68.891	–102.075	14-Aug-19	25–27	–1.10	28.6	0.10	boulders with some soft sediment	<i>Laminaria solidungula</i>	34	100	<i>P. solus</i> sp., <i>Strongylocentrotus</i> sp., <i>Crossaster</i> sp.
Icebreaker Channel, VS	68.849	–102.017	15-Aug-19	70–93				small to large boulders	a few unattached pieces	(19)	48 (b)	dense with <i>Cucumaria frondosa</i> , <i>P. solus</i> sp., anemones, stalked ascidians, <i>Strongylocentrotus</i> sp., <i>Crossaster</i> sp.
Icebreaker Channel, VS	68.916	–102.261	15-Aug-19	10–13				boulders and light colored bedrock or sand	highest density of all sites, many <i>S. latissima</i> , some pale and torn (some may be loose), a few <i>L. Solidungula</i>	89	90	<i>Strongylocentrotus</i> sp.

Table 1 (continued)

Region	Lat (dec °N)	Long (dec °W)	Date	Depth (m)	Bottom T (°C)	Bottom salinity	PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Substrate	Kelp species	Images with kelp (%) (loose kelp in parentheses)	N° of images screened	Common identifiable epibenthos on imagery
Icebreaker Channel, VS	68.867	-102.231	15-Aug-19	31–34				boulders with half soft sediment (or white bedrock)	<i>S. Latissima/L. solidungula</i> , both attached and unattached ^a	54	48 (b)	<i>Psolus</i> sp., <i>Strongylocentrotus</i> sp., <i>Crossaster</i> sp.
Outside Icebreaker Channel	68.7575	102.940	16-Aug-16	25			boulder (ca. 2–15 cm) mixed with soft bottom	A few, small <i>S. latissima/L. solidungula</i>	8		51 (d)	high density of <i>Strongylocentrotus</i> sp.; also <i>Psolus</i> sp., anemones, ophiuroids (likely <i>O. sericeum</i>)
Dease Strait, Unihiktak Passage, Finlayson Islands	69.002	-105.855	16-Aug-16	20	-0.58	28.9	0.58	mostly boulders	<i>A. esculenta</i> , <i>S. latissima</i> , <i>L. solidungula</i>	76	29	<i>C. frondosa</i> , <i>Psolus</i> sp., <i>Strongylocentrotus</i> sp., Nephtheidae, <i>Crossaster</i> sp.
Dease Strait, Unihiktak Passage	68.974	-105.928	18-Aug-19	43–53	-1.23	28.30	0.27	mostly small boulders	<i>S. latissima</i> , <i>L. solidungula</i> , high density per image in one transect section	60	40	<i>C. frondosa</i> , Crinoidea
Dease Strait, Finlayson Islands	69.084	-105.929	20-Aug-19	41	-1.15	28.4	0.14	mostly small boulders	Mostly <i>A. esculenta</i> , a few <i>S. latissima</i> , few <i>L. solidungula</i> , unattached pieces	34 (35)	141 (b)	high density of <i>C. frondosa</i> and <i>Psolus</i> sp., some anemones, <i>Crossaster</i> sp., soft corals

Table 1 (continued)

Region	Lat (dec °N)	Long (dec °W)	Date	Depth (m)	Bottom T (°C)	Bottom salinity	PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Substrate	Kelp species	Images with kelp (%) (loose kelp in parentheses)	N° of images screened	Common identifiable epibenthos on imagery
Dease Strait, Starvation Cove	69.152	-106.000	20-Aug-19	33	-0.96	28.2	2.38	mostly small boulders, often 2–15 cm	<i>L. solidungula</i> , <i>S. latissima</i> , <i>A. esculenta</i>	20	201	many <i>C. frondosa</i> , some <i>Psolus</i> sp. and <i>Crossaster</i> sp.
Cape Croker, Kent Peninsula, Bathurst Inlet	68.152	-107.870	4-Sep-19	22	-0.44	27.5	0.1	dense cover of boulders, mostly 2–5 cm, some sediment on top	few and mostly small <i>A. esculenta</i> , <i>S. latissima/L. solidungula</i> ; unattached pieces	8 (32)	74 (o)	high density of <i>Strongylocentrotus</i> sp., <i>Hyas</i> sp., <i>Psolus</i> sp., cerianthid anemones

Sites were images taken along the 15 min drift were omitted are indicated with (o) in case of overlapping images (typically at low current flow conditions) and (b) in case of blurry images (typically at high flow conditions)

^a% of images with kelp is combined for attached kelp and loose pieces since it could not always be clearly seen

mesh of 1 cm; ca. 30 kg additional weight was added to aid bottom contact in high flow regimes. The dredge was towed for 5–15 min at the bottom at ~0.5–1 kn vessel speed (distances ca. 75–500 m) at depths from 20 to 90 m. Kelp and invertebrates (the latter constituted the vast majority of the catch) collected were sorted and identified to the lowest practical taxonomic level. Taxonomic names were standardized to AlgaeBase (macroalgae) and the World Register of Marine Species (invertebrates). At camera-locations where kelp was detected, abundant detectable epifaunal invertebrates were also noted from the images for a given station.

Characterization of oceanographic and habitat conditions

During the field campaigns bottom temperature and bottom salinity were characterized at or in the vicinity of kelp sites with a Seabird SBE19 + conductivity-temperature-depth (CTD) rosette or an RBR Maestro CTD. To get a coarse approximation of the underwater light climate at kelp sites, PAR was measured with a LI-COR Li-193 spherical quantum sensor integrated into the Maestro or a LI-COR SN1018 sensor affixed to the SBE19 +. Discrete samples for the determination of Nitrate + Nitrite (herein referred to as Nitrate) were collected in duplicate from rosette-mounted 6-L Niskin bottles, frozen immediately after collection and analyzed following the methods reported in McLaughlin et al. (2012). Samples were analyzed either at the Institute of Ocean Sciences (Sidney, BC) or aboard the CCGS Louis S. St. Laurent as part of the Joint Ocean Ice Study program on an Astoria nutrient auto-analyzer.

Typical current velocities at the kelp collection sites were estimated using output from a three-dimensional, unstratified, unstructured triangular grid mesh system tidal model. Water velocity is a relevant measure because it can enhance nutrient supply and thereby support seaweed growth (Hepburn et al. 2007). The model had variable horizontal resolution of down to 200 m in narrow straits, thereby even resolving passages through the Finlayson Islands, to as much as 10 km in wide gulfs (details in Rotermund et al. 2021). To characterize seasonal variability in temperature and salinity, data from an oceanographic mooring in Dease Strait (Unihiktak Passage) were used. The mooring was deployed annually from September 2016 to September 2019 and was equipped with three Seabird SBE37SM MicroCat CTD data loggers deployed at ca. 10 m, 20 m and 40 m depth. For Bathurst Inlet, the early spring/late winter hydrography was characterized using a CTD survey of Bathurst Inlet conducted in May 2009 via Twin Otter as part of the International Polar Year—Canada's Three Ocean's (IPY-C3O) project, while summer hydrography was determined during our 2019 field season aboard the RV Martin Bergmann, as described above.

Results

Kelp taxa

Three species of kelp were found across three areas of the study region and at multiple locations within each area (Table 1, Fig. 1). The species that were identified included *Laminaria solidungula*, *Saccharina latissima*, and *Alaria esculenta* (Fig. 2). Physical specimens of all three species were obtained from Unihiktak Passage in Dease Strait where taxonomic identification could be confirmed (Table 1, Fig. 2). All three species were found in both Victoria Strait in the area of Icebreaker Channel and in Dease Strait in the area of the Finlayson Islands to Unihiktak Passage. *A. esculenta* could be definitively identified from images at Cape Croker in Bathurst Inlet, though another kelp species was also present, *S. latissima* or *L. solidungula*. Other macroalgae species were also present on images but were not retrieved as physical specimens or systematically recorded. These included the genera *Desmarestia* and *Fucus*, a richly-branched, erect, filamentous red alga, a foliose red alga, and encrusting coralline algae.

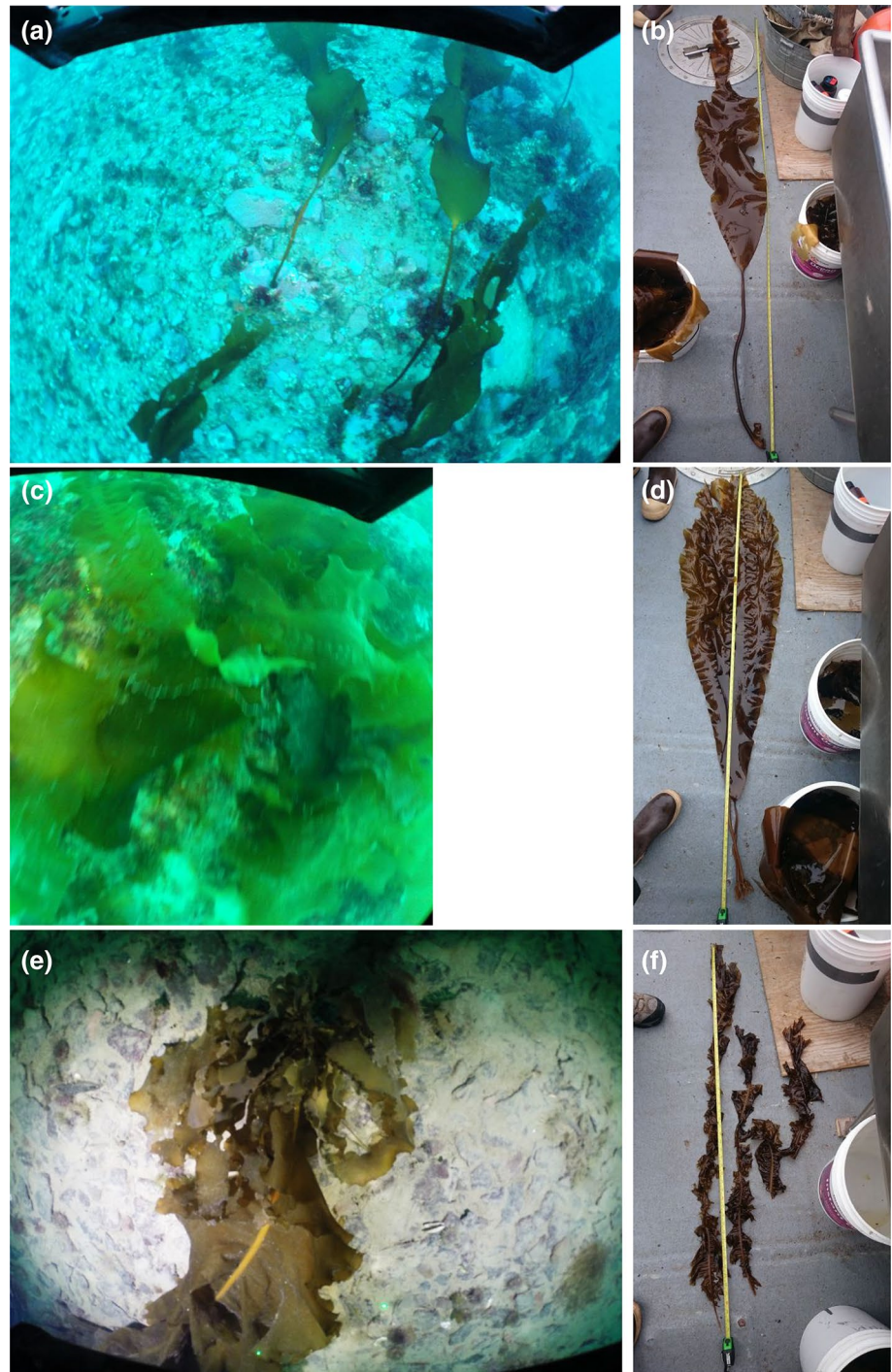
At sites where kelp was present, proportions of images in which attached kelp was present varied from 8 to 89% (Table 1). Proportions were variable in all three regions; highest values were found at one of the shallowest sites, in Icebreaker Channel (10–12.5 m: Online Resource 1), and lowest at one of the sites at Cape Croker, compared to the other two regions. Unattached kelp pieces of unknown identity were seen in images from the seafloor in all three regions; where quantifiable, proportions were 32% and 35% (Table 1).

Characterization of habitat conditions

Kelp was observed over a wide range of depths (Fig. 3). For navigational safety reasons, vessel draft (5 m) limited our observations to sites generally deeper than 10 m. Sites with attached kelp ranged in depth from 10 to at least 43 m, with most to 30 m or less (Table 1). Unattached drifting kelp pieces were seen (Online Resource 1e, f) near sites of attached kelp out to waters as deep as our maximum observation depth transect of 70–93 m in Icebreaker Channel, Victoria Strait.

At all locations where kelp was present at least some hard substrate was available. Based on visual assessment rock size ranged from gravel to smaller cobble and boulders (Fig. 2, Online Resource 1). Most sites in the matching depth range where kelp was absent (Fig. 1) were characterized as soft sediment, depositional bottoms with fine-grained sediments. Kelp was, however, also absent

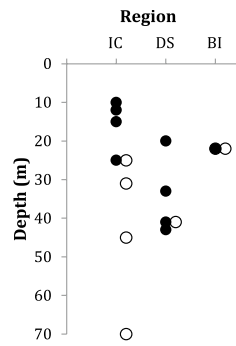
Fig. 2 Kelp species found in the Kitikmeot Sea, Northwest Passage. **a** *Laminaria solidungula* in Icebreaker Channel, **b** *L. solidungula* from Dease Strait on deck, **c** *Saccharina latissima* in Icebreaker Channel, **d** *S. latissima* from Dease Strait on deck, **e** *Alaria esculenta* from Cape Croker, **f** *A. esculenta* from Dease Strait on deck



from a number of sites where interspersed hard substrate was available within the above depth ranges, specifically in narrow passages around Algak Island (sill depths around 10 m, 67.4904° N, 108.2730° W and 67.4555° N, 108.2799° W) and off North Quadyuk and Quadyuk islands (66.9213° N, 107.7764° W at 17 m; 66.9647° N, 107.7863° W at 27 m), all in Bathurst Inlet (Fig. 1, Online Resource 1g).

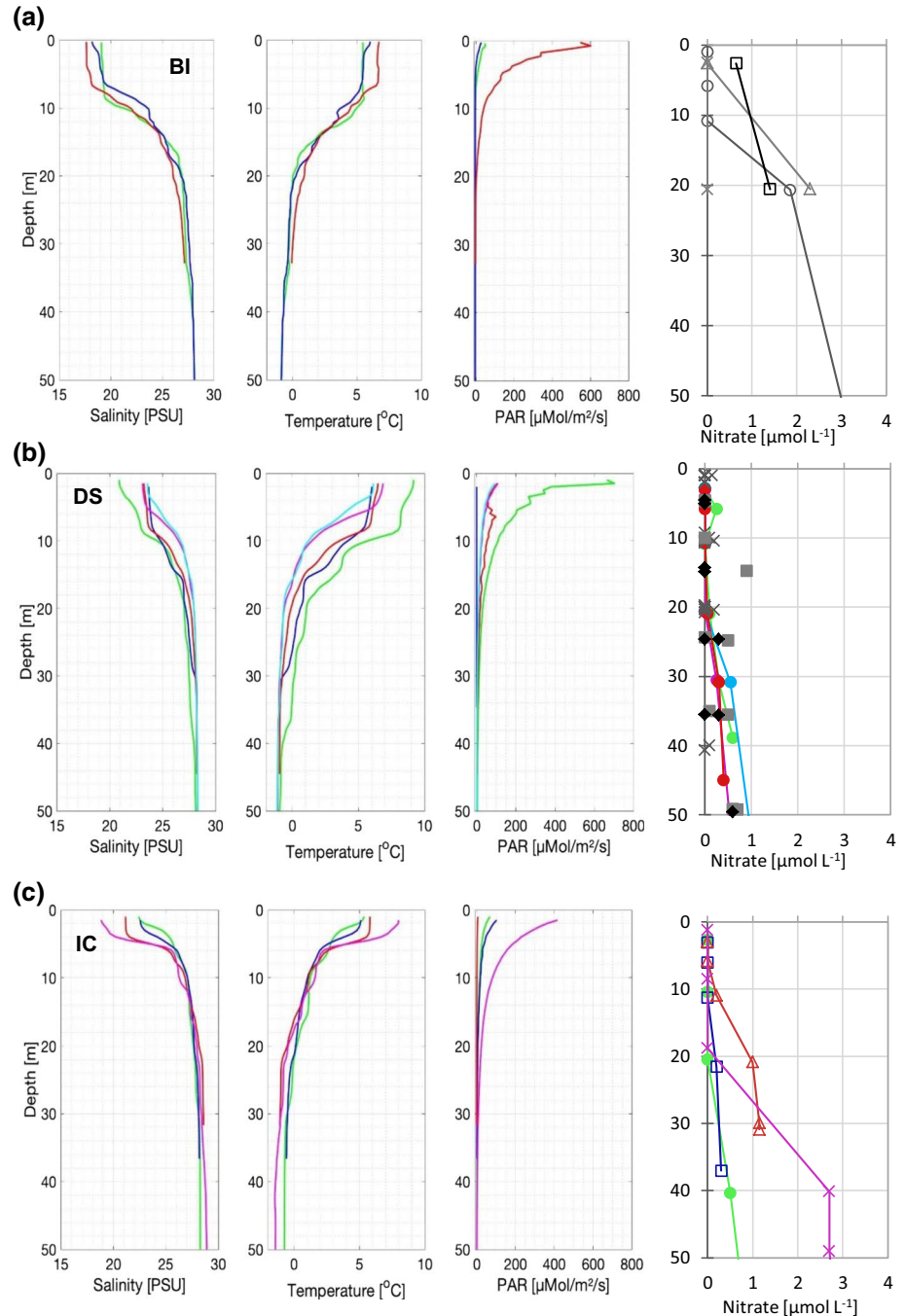
A consistent pattern was shown in temperature and salinity profiles taken in August–September at sites where kelp was found: the upper ~10 m were relatively warm and freshened by ice melt and river discharge; the pycnocline (resulting from both temperature and salinity gradients) was between roughly 10–20 m; in some profiles a secondary step was evident near 40 m, indicative of convective mixing the previous winter (Fig. 4). Bottom temperatures at kelp sites

Fig. 3 Depth distribution of kelp recorded in the three study regions. *IC* Icebreaker Channel, *DS* Dease Strait, *BI* Bathurst Inlet. Each circle represents one location which can include multiple images of which one or more contained kelp (filled circles) or unattached fragments (unfilled circles)



at ~20 m and below in summer were in the sub-zero range to no higher than 1 °C. Profiles taken near the shallower sites indicated that temperatures can reach 4–6 °C in the 10–14 m range where kelp was found (Fig. 4). Winter temperatures near the kelp sites in Dease Strait and Bathurst Inlet were in the subzero range in both surface and deeper layers (Fig. 5a, c). Bottom salinity was between 26 and 30 at kelp sites ≥ 20 m in summer, but dropped to as low as 20 in the 10–14 m range where our shallowest kelp sightings were (Figs. 3, 4). Winter salinity was between 26 and 28 throughout the water column near kelp sites (Fig. 5b, d). At sites

Fig. 4 Water column characteristics at and near sites where kelp was found during sampling days in Aug–Sept 2019. Temperature, salinity, irradiance and nutrients **a** Dease Strait, **b** Bathurst Inlet, **c** Icebreaker Channel. Colors represent different CTD casts at and near kelp sites with locations shown in Online Resource 3. Nutrient data are from discrete depths from Niskin bottles attached to the CTD. See Online Resource 2 for example profiles from regions where no kelp was found



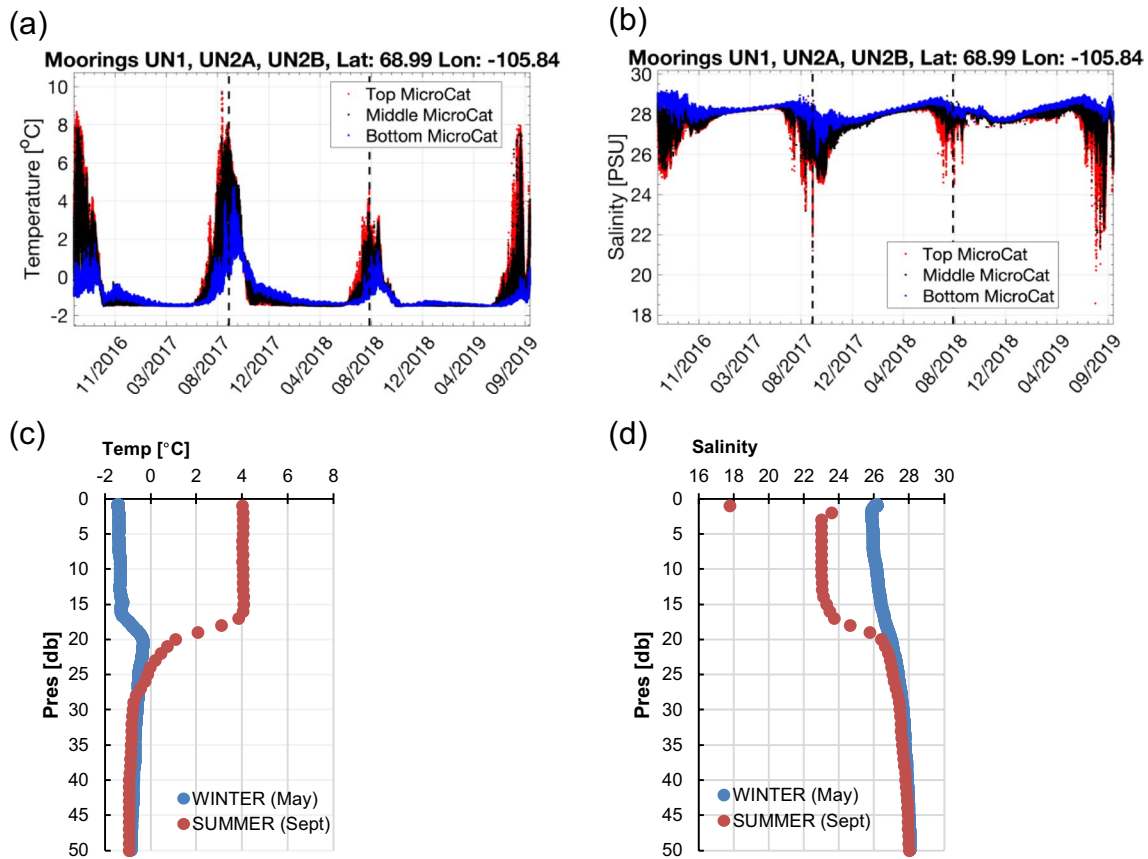


Fig. 5 Seasonal variation in temperature (a, c) and salinity (b, d) at locations near kelp sites. a, b Dease Strait at Unihiktak Passage from three years of mooring deployments. CTD data loggers were deployed at ~12 m (top), ~18–22 m (middle), and 38–40 m (bottom);

strong tidal currents and wind events led to an intermittent mooring drawdown of ~5 m; c, d CTD profiles near Cape Crooker in May and Sept of 2009. Note that kelp recorded below ~20 m experiences comparatively little seasonal variation

where kelp was absent but substrate appeared suitable (near Algak and Quadyuk Islands, see previous paragraph) the fresher and warmer surface layer was thicker in August–September than at sites where kelp was found and extended to ~15–20 m, followed by a sharper pycnocline (Online Resource 2); here we had no winter profiles available.

Irradiance was highly variable seasonally, spatially, throughout the day and depending on weather, so our measurements do not give an adequate reflection of this variation. In each region, however, one surface to depth profile was taken around local noon in mid-August–early September when surface PAR was in the range of 400 (Icebreaker Channel) to 600 (other two regions) $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ in the surface water (Fig. 4), while the other profiles showed lower irradiances during afternoon or evening hours. The 1% light depths for mid-day, indicative of the approximate euphotic zone limit, were at ~20–35 m, suggesting some kelps were near the lower limit of the euphotic zone during the study period. At and near Algak and Quadyuk Islands where no kelp was found, mid-day light profiles indicated extremely low light levels below 10 m depth (Online Resource 2).

Water column profiles of nitrate (locations in Online Resource 3) showed depletion above the pycnocline in all three regions where kelp was found (Fig. 4). Nitrate reservoirs remaining below the pycnocline (where most of our kelps were recorded) increased with depth. While concentrations varied among sites they did not exceed $3 \mu\text{mol L}^{-1}$ at 50 m and remained below 2 and often below $1 \mu\text{mol L}^{-1}$ at 20 m. The sites where kelp was absent showed a similar pattern (Online Resource 2).

Maximum tidal current velocities over a 30-day period extracted for the kelp sites from the tidal model ranged from 20 to 70 cm s^{-1} (Fig. 6). Highest maximum velocities were found at the kelp sites off Jenny Lind Island in Icebreaker Channel (Victoria Strait region) and in Unihiktak Passage (Dease Strait region) (Fig. 6, Online Resource 4).

Invertebrate species that regularly co-occurred at kelp sites included suspension-feeding epifaunal taxa that also benefit from water motion such as nephtyid soft corals such as *Gersemia* sp., dendrochirotid sea cucumbers, *Hiatella* clams, and various anthozoan anemones (Table 1). In addition, potential kelp-grazers including limpets, trochid snails

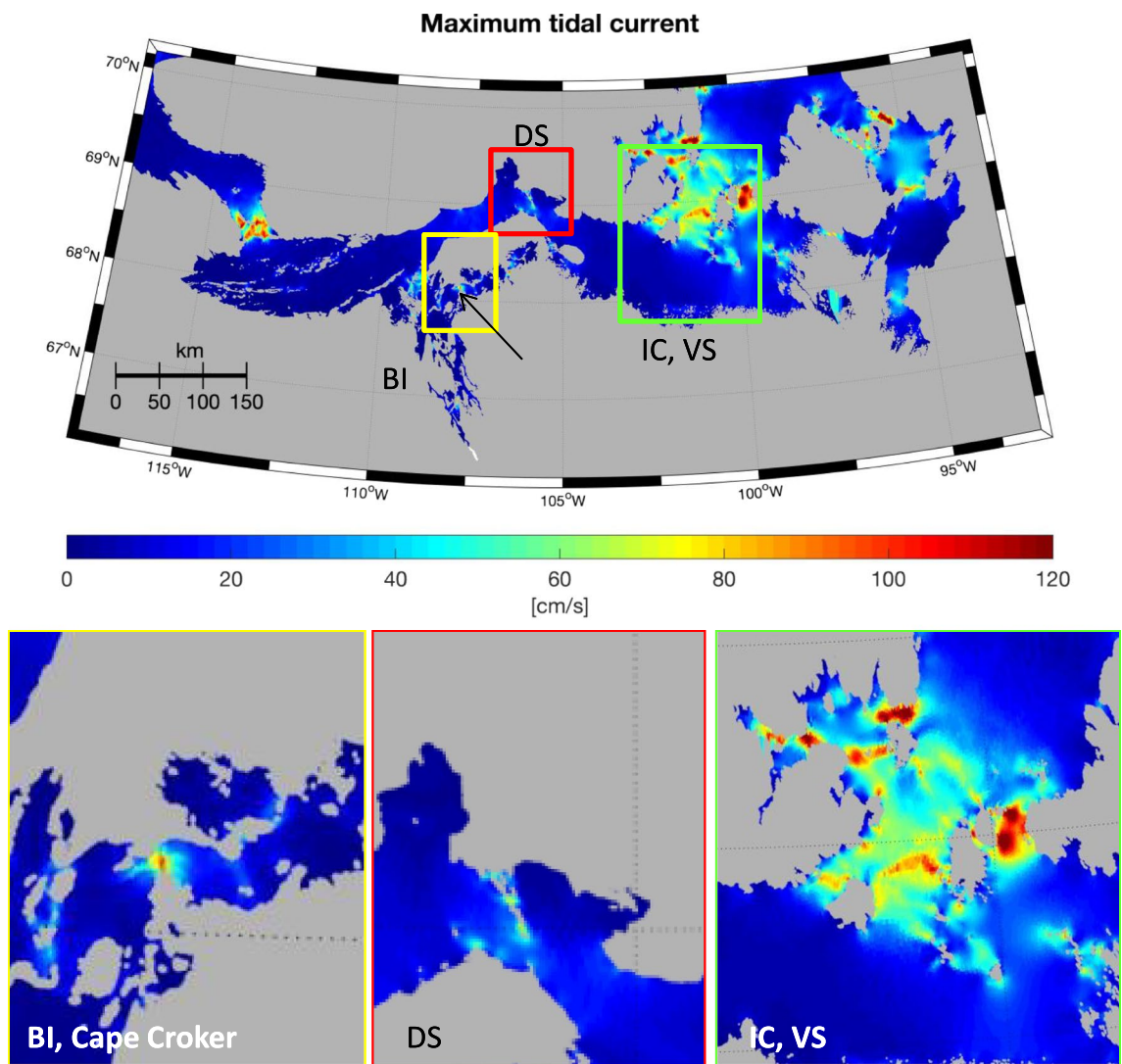


Fig. 6 Map of the maximum tidal current speed [cm/s] over a 30-day period in the Kitikmeot Region showing peaks in areas where kelp was observed. Insets show the three regions where kelp observations

were made: *BI* Bathurst Inlet, *DS* Dease Strait, *IC* Icebreaker Channel/VC Victoria Strait

and sea urchins *Strongylocentrotus* sp. were found in the same habitat at some locations, as well as predatory sea stars *Crossaster papposus* and lyre crabs *Hyas* sp.. Hard substrates were often covered with encrusting coralline algae indicating light availability to the seabed was sufficient for at least these algae that require little light to persist.

Discussion

Kelp distribution in the Kitikmeot Region

The kelp distribution records presented here for *Laminaria solidungula*, *Saccharina latissima* and *Alaria esculenta* in the Kitikmeot Region are a new addition to the recent

pan-Arctic compilation by Filbee-Dexter et al. (2019). Kelp has, however, long been known to occur in the general study area by residents of local communities, yet this local knowledge was only recently documented in a coastal resource inventory (Nunavut Coastal Resource Inventory Cambridge Bay 2015; Table 2). This inventory mentions ‘edible kelp’ and ‘hollow-stemmed kelp’ (probably *A. esculenta* and *S. latissima*, respectively, R. Wilce Univ. Massachusetts Amhurst, pers. com.) for coastal stretches between Cambridge Bay, the Finlayson Islands and the northern side of the Kent Peninsula. Another recent coastal inventory, based on SCUBA transects along the 10 m isobath, also mentions the presence—yet very low abundance—of *S. latissima* in the areas of Cambridge Bay and the Finlayson Islands (Schulz et al. 2018; Table 2). In addition, the

Table 2 Summary of available observations of kelp occurrence in the Kitikmeot Region study area

Location	Species	Depth	References
Between Cambridge Bay and Finlayson Islands, to northern coast of Kent Peninsula	Edible kelp (likely <i>Alaria esculenta</i>), hollow-stemmed kelp (likely <i>Saccharina latissima</i>)	Not specified, but likely shallow and nearshore	Nunavut Coastal Resources Inventory Cambridge Bay (2015)
Cambridge Bay, Finlayson Islands	<i>S. latissima</i>	10 m	Schultz et al. (2018)
Unihitak Passage	Unspecified kelp	19 m	CHS Nautical Chart 7750
Eastern Queen Maud Gulf	<i>Laminaria</i> sp., perhaps <i>S. latissima</i>	24 m and 12 m	Parks Canada 2019 video of HMS Terror and HMS Erebus
Simpson Strait, eastern Queen Maud Gulf	<i>S. latissima</i>	21 m	Brown, DFO, pers. obs. in 2017
O'Reilly Island, SE Queen Maud Gulf	Unspecified kelp	n.d	Carmarck, DFO, pers. obs., in 2014
Icebreaker Channel, Victoria Strait	<i>A. esculenta</i> , <i>S. latissima</i> , <i>Laminaria solidungula</i>	20–27 m	This study
Dease Strait at Finlayson Islands and Unihitak Passage	<i>A. esculenta</i> , <i>S. latissima</i> , <i>L. solidungula</i>	20–43 m	This study
Cape Croker, Kent Peninsula in Bathurst Inlet	<i>A. esculenta</i> , likely <i>S. latissima</i>	22 m	This study

navigation chart used during our field campaigns (CHS Nautical Chart 7750: Approaches to Cambridge Bay) had kelp noted in the center of Unihitak Passage in Dease Strait, which inspired our sampling at that location where we confirmed the current occurrence of kelp. Finally, we point out that kelp (probably *Laminaria* sp. and perhaps *S. latissima*) grows on the recently discovered vessels, HMS Terror (at 24 m depth) and HMS Erebus (12 m) of Sir John Franklin's Northwest Passage expedition, in the eastern part of Queen Maud Gulf (Parks Canada 2019, <https://www.youtube.com/watch?v=OxyTZ3F7mkA>). In nearby Simpson Strait (68.5409° N, – 97.4596° W) KB also found a viable-looking piece of *S. latissima* in a grab sample at 21 m, and EC saw kelp in situ below the RV Bergmann in SE Queen Maud Gulf near O'Reilly Island in 2014 (Table 2).

The three kelp species noted here are typical features of Arctic rocky coasts of the Canadian Arctic Archipelago, Greenland, northern Norway, and various island groups such as Svalbard, Franz Josef Land and Novaja Semlja (Wilce 1994; Wiencke and Amsler 2012; Gavrilov et al. 2020; Johnson et al. 2020; Krause-Jensen et al. 2020). *Laminaria solidungula*, the only Arctic endemic kelp, has a broad distribution range across the Arctic and into temperate areas (Lüning 1990). *Alaria esculenta* and *S. latissima* are common around the temperate North Atlantic (Araujo et al. 2016; Wilson et al. 2019) and extend northward to Svalbard and Greenland (at least 78° N; Krause-Jensen et al. 2012; Bartsch et al. 2016). Bringloe et al. (2020), however, found that a separate Arctic lineage may in fact exist for at least *A. esculenta* rather than the Arctic records being a 'tolerant temperate outpost'. The closest reported occurrences to the west of our sites are, to our knowledge, in the so-called

Boulder Patch in Stefansson Sound, an assemblage of glacial drop stones in the otherwise soft permafrost-bordered coast of the central Beaufort Sea (Dunton and Jodwalis 1988; Wilce and Dunton 2014) and slightly further east of that in Camden Bay (Dunton et al. 1984). To the north, kelp was recorded from the coast of Devon and Somerset Islands, and to the east from (northern) Baffin Island (Cross et al. 1987; Küpper et al. 2016; Wilce 2016; Filbee-Dexter et al. 2019). While dispersal range is generally thought to be comparatively low for large brown seaweeds, genetic similarity patterns in an *Alaria* species suggested long-range dispersal, supported by regional and swift currents, does occur (Kusumo and Druehl 2000), and rafting blades can also produce viable spores. It seems, however, more likely that the observed and perhaps other kelp species also occur along the long, poorly-surveyed coast between the referenced sites and our observation sites, given rocky substrate is widely distributed throughout the Canadian Arctic Archipelago, and ice conditions do not massively differ along the southern parts of the Archipelago (Sou and Flato 2009). Other kelp species one might expect to find could, for example, include *Agarum clathratum* and *S. longicuris*, both found on Baffin Island (Küpper et al. 2016) and in West Greenland (Krause-Jensen et al. 2012).

Habitat characteristics and requirements

Most kelp occurrences reported here were between 10 and 30 m. We could not determine the upper depth distribution limit of these kelps in the study area which tends to be determined by ice scouring at Arctic shores experiencing regular and long ice cover (Johnsen et al. 2020). In other areas,

and likely within the study area, kelp occurs shallower than we were able to sample, e.g. *A. esculenta* and *S. latissima* peaked at 2.5 m in Kongsfjorden, Svalbard, an area however that rarely experiences sea ice cover today (Bartsch et al. 2016; Johnson et al. 2020). Ice scouring in the areas of the Finlayson Islands and Kent Peninsula is expected to extend no farther down than 2–3 m given the tidal range being typically below 1 m (Rotermund et al. 2021, tide-forecast.com), average ice type being first-year ice (Dalman et al. 2019; Derksen et al. 2019) and the lack of a reported stamukhi zone or substantial ridging. Icebreaker Channel, however, is known for ridging by sea ice including multi-year ice (Derksen et al. 2019), a fact early polar explorers seeking to find the Northwest Passage learned the hard way. Such ridging may affect the upper kelp limit in Icebreaker Channel. Based on observations from NW Baffin Island where the tidal range was 2.5 m at a maximum, sea ice tends to occur for a longer period than in our study area and perennial algae were absent from the upper 3 m under the low tide level (Küpper et al. 2016), we assume the upper limit for kelp in the Kitikmeot Region may be around 2–4 m (Fig. 7).

The lower distribution limit is driven by light limitation with the three species reported as rare below ~15 m at some Arctic locations (Bartsch et al. 2016), yet may reach 30 m or more in clear water at other Arctic locations (Johnson et al. 2020, this study). Rare finds of kelps (*Agarum clathratum* and *Saccharina* spp.) to over 60 m were reported from Disco Bay (Boertmann et al. 2013). We found attached and viable-looking kelp to ca. 40 m. Our observed maximum depth extent approximately matches the vertical extension of the euphotic zone (when defined as 1% surface irradiance in clear ocean water; Johnsen et al. 2020). Of the three species,

A. esculenta occurred deepest in Svalbard (Johnsen et al. 2020), but no difference in depth distribution was apparent among species in the present study; perhaps we had too few observations. Our deepest records around 40 m were in Dease Strait away from coastal run-off and where swift currents presumably keep visibility high and substrate coarse (and hence resuspension low) (Fig. 7).

In addition, several kelp sites were in passages of high tidal current flow and tidal mixing (Hannah et al. 2009; Rotermund et al. 2021). We propose that these sites may be particularly suited as kelp habitat for several reasons: Tidal currents maintain patches of open water in winter and spring (Williams et al. 2018), thereby resulting in a higher overall annual light amount than kelp specimens outside these tidal polynyas would experience. Also, the water movement may act to replenish nutrients through the regular flux, shear leading to vertical mixing and/or thinning the boundary layer between kelp and water (Fig. 7). Coastal run-off transporting low salinity water and enhancing turbidity may be the reason for absence of kelp at otherwise seemingly suitable sites such as around Algak Island in Bathurst Inlet as the thicker fresher layer and decreased light penetration at those sites suggest. Indeed, sedimentation effects have been documented to limit growth in the Boulder Patch in the Beaufort Sea, a coast with high erosion rates and nearby river run-off (Bonsell and Dunton 2018).

The temperature range we measured is at the lower end of the known thermal ranges for *S. latissima* and *A. esculenta*. It is within the thermal range for *L. solidungula*, though generally below the proposed optimal growth temperatures. The optimal growth temperature for *S. latissima* is reported as around 10 °C (Fortes and Lüning 1980) and

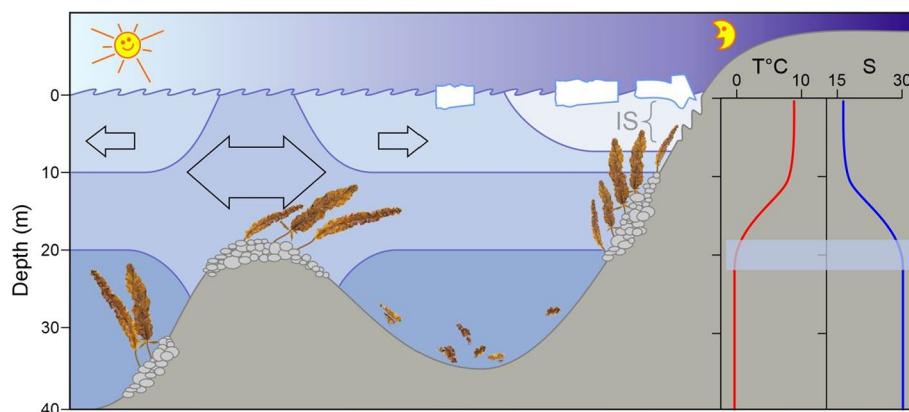


Fig. 7 Conceptual schematic showing kelp distribution and habitat conditions encountered in the study area. The (proposed) roles of high current flows in passages and of ice scour (IS) in shore areas are shown. Specifically, environmental conditions are more favorable underneath the warm (in summer) and very cold (in winter) and fresh surface layer (light blue) and ice-scoured coastal zone (whitish) that limits light penetration and though mechanical disturbance pushes

depth distribution deeper. Tidal currents (thick arrow) are thought to enhance nutrient supply (in the mid-blue shaded layer) through mixing and regular advective flow and—indirectly through reducing sea ice cover and/or duration—total light amount. Off-shore, little turbidity may allow kelp to occur deep in stable and fully marine, nutrient rich conditions. Kelp detritus may reach deeper areas away from sites where kelp grows

that of zoospores of *S. latissima* and *A. esculenta* for photosynthesis at 7–13 °C (Svalbard, Roleda 2009). In a latitudinal test-farming experiment some of the best growth rates for *S. latissima* sporophytes were, however, observed at temperatures below 10 °C at 69°N in northern Norway (Forbord et al. 2020), a latitude comparable to this study yet with generally warmer temperatures than in our study area. The temperature range for optimum growth of *L. solidungula* sporophytes was somewhat lower, at 5–10 °C (Wiencke and Amsler 2012 and references therein). In terms of salinity tolerance windows, quantum yield of the photosynthetic system was high (upwards of 80% compared to a control) at salinities between 10–50, 20–50 and 25–55 for *A. esculenta*, *L. solidungula* and *S. latissima*, respectively, in an experimental set-up in Svalbard (Karsten 2007). A more recent multi-stressor experiment showed that the combined treatment of increased temperature and reduced salinity (25), resulted in decreased maximum quantum yield in *L. solidungula* (the other two species were not studied; Diehl et al. 2020). Based on these findings, the specimens we found—mostly below the pycnocline—were likely not salinity stressed at these sites, but the upper occurrence limit of kelp in the study area may be influenced by low salinity (and potentially combined temperature) stress. Perhaps the absence of kelp from two sites that were shallow enough and had hard substrate could be related to the thicker freshwater-influenced layer and low light levels there. Exposure to low salinity may not only reduce photosynthetic activity and growth (Diehl et al. 2020; Forbord et al. 2020) and the ability of gametophytes to produce sporophytes (Muth et al. 2021) but eventually also result in bleaching or mortality (Karsten 2007).

The invertebrate community associated with kelp occurrence is likely explained by a combination of shared habitat preferences, trophic interactions and shelter. Several of the taxa co-occurring with the observed kelps also require hard substrate for attachment and sufficient water flow for suspension feeding. For example, suspension-feeding sea cucumbers such as *Cucumaria frondosa* and *Psolus* spp., soft corals such as of the genus *Gersemia*, *Hiatella* clams and Crinoidea (feather stars) were dominant in high-flow tidal passages in the study area where kelp occurred (when sites were shallow enough) (Online Resource 5), while deposit-feeding brittle stars and polychaetes dominated soft bottom and low-flow sites (Fredriksen 2018). Grazing taxa such as sea urchins *Strongylocentrotus* sp., snails including *Margarites* spp., and limpets, *Lepeta caeca*, previously found associated with kelps and other macroalgae in other Arctic locations, can feed on kelp (Lippert et al. 2001; Schuster and Konar 2014; Johnsen et al. 2020). The sea urchins were in fact among the most numerous taxon in dredge hauls at all three kelp sites and have elsewhere been shown to both reduce kelp biomass (Sivertsen 1997; Konar and Estes 2003)

and enhance kelp detritus dispersal through transferring kelp into urchin feces (Wernberg and Filbee-Dexter 2018). Yet other taxa occurring in kelp systems are known to benefit from the protective environment of these systems including their holdfasts (Orland et al. 2016).

At deeper locations where drifting pieces of kelp were observed in our study, they add to the detrital food web after degradation, as has been documented for areas in the vicinity of macroalgal coasts and fjords around the Arctic (Dunton and Schell 1987; Renaud et al. 2015; Pedersen et al. 2020). The Kitikmeot Region is an oligotrophic system (Ardyna et al. 2011; Crawford et al. 2018; Brown and Williams, Dept. Fisheries & Oceans Canada, unpubl. data) though recent data suggest the region may be more productive than previously thought (Dezutter et al. 2021). In either case macroalgal carbon in addition to other potential sources such as terrestrial carbon and microphytobenthos in shallow waters may provide relevant contributions for the consumers in the ecosystem.

Considerations on future kelp occurrence in the Kitikmeot Region

Given local knowledge confirms the historical presence of kelp in the study area it seems unlikely that our observations of kelp occurrence per se are related to recent ecosystem changes. At other Arctic locations, however, abundance and composition of macroalgae are currently undergoing change (Keck Al-Hababeh et al. 2020; Krause-Jensen et al. 2020). Where observational time series could be compiled, in many—yet not all—areas biomass had increased over the past decades, some boreal species had expanded their ranges northward, and/or biomass had shifted to shallower depths (Kortsch et al. 2015; Bartsch et al. 2016; Krause-Jensen et al. 2020). Modeling approaches predicted northward extensions of kelp distributions (including *Saccharina latissima*) to continue, along with a coincident contraction in the southern distribution range by 2100 under a high emissions scenario (RCP8.5; Wilson et al. 2019). These studies explained these trends as due to reduced ice cover and scour, and thereby increased light availability. While sea ice has declined more slowly in the Canadian Arctic Archipelago than in other parts of the Arctic, declines have still been observed (Derksen et al. 2019) and model runs projected this trend continue (Sou and Flato 2009) though recent changes in the seasonal, fast ice zone have been much smaller than those more commonly reported from a perennial, pack-ice perspective, where changes are much greater (Humfrey Melling, Inst. of Ocean Sciences, pers. comm.). For example, records from Cambridge Bay extending back over 60 years showed thinning rate of only 0.025 m/decade (Niemi et al. 2019). Yet, declines in extent and/or thickness will yield

increasingly more open water days and/or higher light transmission through thinner ice.

As such, in situ temperatures in the summer surface mixed layer will increasingly overlap with the growth optima of the observed kelp species in the future, and summer temperatures in the upper subtidal may also exceed the optimum growth optimum of *L. solidungula* at times (5–10 °C, tom Dieck 1992) in the future. Perhaps this species would, however, continue to fare well below the surface mixed layer. For the coming decades, temperature conditions and open water days combined with the availability of rocky substrates for attachment suggest expansion of kelp occurrence in the Kitikmeot Region is conceivable. The combination of advective and vertical nutrient flux will remain highest in the high flow passages studied, and combined with more open water days and absence of turbidity likely render these passages suitable and perhaps optimal habitats as long as they are not below the euphotic zone. While shallow subtidal shore areas have more preferable light levels, they suffer from seasonal nutrient limitation, higher turbidity and sub-optimal salinity. Increased turbidity from river estuaries throughout the Kitikmeot Region's coastline, tundra and wetlands primarily of the southern shores of the study area (CAVM team 2003) could counteract kelp biomass increases from ice decline in some nearshore regions as shown elsewhere (Bonsell and Dunton 2018) and suggested by models (Scherrer et al. 2019). In addition to the increasing number of ice-free days, we hypothesize that the interplay of bottom depth (limiting light) and strength of stratification (limiting nutrient availability) will play a role in setting future trends in kelp growth in the study area, and that horizontal through-flow and vertical nutrient flux in tidal passages may be the key to enhanced growth in such locations (conceptually depicted in Fig. 7).

Systematic transects perpendicular to shore, perhaps as part of community-based monitoring efforts, would greatly expand knowledge of present (depth) distribution patterns and environmental envelopes of kelp in the Kitikmeot Region and could also feed into the characterization of coastscape types as set as a goal by the Conservation of Arctic Fauna and Flora (CAFF 2019). From this type of habitat mapping the potential for future expansion, and perhaps human consumption, could be inferred. We conclude that our study, while limited in regional coverage and taxonomic resolution, provides evidence (1) that the Kitikmeot Region generally contains habitat suitable for kelp occurrence and growth, and (2) that locations with strong tidal currents, located in particular in narrow passages between islands or island and mainland, may be locations particularly suited for kelp growth. We propose such locations are suitable because they contain a combination of hard substrate, limited turbidity from run-off from land, a longer open water period with, time-integrated, more light and tidal currents providing a

mechanism that moves up nutrients through breaking the elsewhere strong pycnocline.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00300-022-03007-6>.

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Authors contribution EC conceptualized the study idea. All authors participated in the field work. BB screened the images for kelp occurrence. WW, LR, KB, SD and EC acquired the physical–chemical oceanography data, and LR and KB quality controlled and visualized these. WW made the study area map. BB wrote the draft manuscript, and all co-authors commented on and approved it.

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Data availability The physical–chemical oceanography data and images can be made available through contacting the authors. Code availability – not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This publication is part of the Kitikmeot Sea Science Study which operates under a scientific research license issued by the Nunavut Research Institute (#04 028 17 N-M; 04 019 18R-M; #04 026 19R-M).

Consent to participate Not applicable.

Consent for publication Not applicable.

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