The potential for seaweed resource development in subarctic Canada; Nunavik, Ungava Bay

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Abstract Ungava Bay is ice covered 6–7 months of the year and evidence of ice scouring of seaweeds is extensive in the intertidal and shallow subtidal. Maximum tidal amplitudes of 16 m, among the highest in Canadian waters, compound this impact. Despite this level of annual perturbation, very extensive and dense beds of fucoids in the intertidal and laminarians in the subtidal are common on the western shores of Ungava Bay. Ground surveys of 24 intertidal stations combined with satellite images delineated 82,000 tons standing crop of *Fucus vesiculosus* and *Fucus evanescens* in Payne Bay, of which 36,000 tons were considered harvestable. Subtidally, kelp cover reached peak biomass at 5–10 m consisting of three primary species, *Saccharina longicruris*, *Laminaria digitata*, and *Laminaria solidungula*. In the area of Payne Bay, kelp beds of 100 ha were common, averaging 9–12 kg m^{-2} wet weight. The productivity of brown algae at these latitudes has been assumed to be low relative to southern latitudes. Direct measurement of lineal growth indicates productivity is intermediate between arctic and temperate populations. The potential for medium level industrial harvest exists under conservative management strategies within the constraints of subarctic logistics.

Keywords Kelp · *Laminaria* · *Saccharina* · *Fucus* · Abundance · Harvest

Introduction

The Inuit communities of the Canadian north and more specifically Nunavik have made land claim agreements over the past 30 years that have provided more control over natural resources and a limited co-management role since the 1980s (JBNQA 1976). In 2006, an offshore resource claim was negotiated, and an agreement will be implemented for the coastal waters and islands of the near shore Nunavik region in 2007. As responsible stewards, the Inuit have initiated research to delineate, assess and evaluate these resources. Early marine research noted that seaweed was more common and abundant than first assumed in this region.

A number of macrophytes have been a part of the traditional food sources in the arctic and subarctic for the Inuit (Wein et al. 1996). These resources of the arctic and subarctic are now subject to the symptoms of global warming (Moritz et al. 2002). Although there is knowledge of algal diversity and distribution, we lack quantitative abundance and productivity information for this region (Wilce 1959; Lee 1980). The first priority has been to quantify those resources within a normal travel radius of isolated villages. These are also the resources that have the greatest potential for further management and possible development at a scale related to people and infrastructure available in a village. This study was designed to define the abundance, diversity, and distribution of dominant intertidal and subtidal brown macrophytes in the region of Payne Bay accessible to the Inuit village of Kangirsuk in Ungava Bay.

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Materials and methods

Ungava Bay, located in the Nunavik region of northern Quebec, begins below the Arctic Circle at 58°20′N and extends to 61°00′N at the Hudson Straits. The bay and its inlets are covered by shore-fast ice from early December until open water leads develop in May, and by July open water predominates. The day length in mid-July is 18.4 h and in January it is 5.7 h. Water temperature ranges from −1.8°C in winter to a maximum of 5–8°C in summer in sheltered inlets. The bay is noted for its tidal amplitude ranging from an average of 10 m to extremes of 16 m creating currents of 5 to 16 km h^{-1}. During the period of ice break-up, the ice scouring of the intertidal extends down to −5 m (chart datum). Payne Bay is a 30-km inlet midway northward on the western side of Ungava Bay that receives the water of two rivers. The foreshore of the Payne Bay consists of bedrock ledges and mixed sand gravel flats with glacial till (Fulton 1995). Boulder foreshores are characterized by clusters of boulders of 0.3– 1.5 m diameter interdispersed with gravel or sand patches on gently sloping shores. Subtidally, the foreshore geology changes to sediment dominated bottoms at depths below 20 m.

Subtidal

Eleven diving stations were chosen to represent a range of environments from inner Payne Bay to the open waters of Ungava Bay. Diving safety issues dictated that each diving station had to be chosen in regard to currents and tide level. Transects started at 3 m below chart datum on a compass bearing perpendicular to the shoreline. Divers made qualitative observations of species, including an estimate of relative abundance of individuals (scale low <1 m^{-2}, moderate 1–5 m^{-2}, high >5 m^{-2}). The presence of other algae and bottom types were recorded at 3-m-depth intervals. Five 0.25 m^2 samples were taken at four stations at five depth intervals. All kelps were identified and total length, stipe length, blade width measure to 1 cm and wet weight to 1 g. GPS (Garmin™ position accuracy 15 m) was used to locate the transect beginning and end points.

At 11 stations a remote drop camera (Shark) was lowered in the shallow portion (<1–3 m) of kelp beds and the vessel motored slowly towards deeper water stopping at 25 m. The camera was held approximately 1 m off the bottom and the area observed was approximately 1 m^2. Low visibility forced us to move the camera lower, thus at times underestimating density. Observations of species and relative densities of individual kelp plants within the view of the camera (<1 m^{-2} low density, 1–5 m^{-2} moderate density, >5 m^{-2} high density) were made at three to five depth intervals ranging from −5 to –15 m. Since there was no recording of the image, an estimate of plant density and identity had to be made in real time while viewing a video display. At densities higher than 5 individuals m^{-2}, plant cover obscured any estimates of maximum density. The camera position was recorded with GPS and depth with a Raymarine™ digital sounder to 1 m.

Growth of kelps

At 8 m depth in a *Saccharina longicruris* (Bachelot de la Pylaie) Kuntze dominated ledge, a 10×10 m plot was marked with lead line. Within the plot, 40 *S. longicruris* plants were tagged from 30 cm to 2.0 m long and punched with a 2-cm hole 20 cm from the base of the blade on 10 August 2005. A 2 h search of the plot was conducted on 8 August 2006 for tagged plants. Recovered plants were removed, and stipe length, blade length to blade constriction, total blade length and distance from blade base to the punched hole was measured to the nearest cm.

Intertidal

The survey area was determined by the radius of daytime operation for standard freighter canoes, 10 km from the village of Kangirsuk (Fig. 1). These shorelines were divided into lines of longitude 30 s apart from 70°08′00″ N to 69°52′00″N on a hydrographic map. The north and south shores of Payne Bay each had a total of 66 points of intersection with the lines of latitude. The intersections with the shore were numbered and 30 sites were selected by random numbers for ground survey. These positions were entered as waypoints in a Garmin GPS. The survey began on 1 August 2005 and 24 of the 30 sites were completed by 15 August 2005 (Fig. 1).

The survey crews landed as close to the GPS coordinate as possible and began their survey either at the top of the intertidal or bottom depending on the state of the tide. Three temporary transects were established at each station; at the top of the intertidal zone (+8 to +9 m chart datum) in the highest area of continuous algal cover, midway (+5 to +6 m) in the zone and just above the low tide mark (0 to +2 m). Each transect was a 30 m line placed parallel to the shore. Along this line at 5 m intervals, a 0.25 m^2 quadrat was placed at the mid-point of the mark. All algal biomass was removed from the quadrat with a knife to a height of 2 cm. The biomass was separated into two fucoid species, *Fucus evanescens* C.Ag. and *F. vesiculosus* L. and the wet weight of each species was measured to 50 g. The type of substrate was classified into five sedimentry grades: sand (0.05–2 mm), gravel (2–64 mm), cobble (64–100 mm), rock (100–500 mm), boulder (>500 mm) or a mixture of these grades.

Payne Bay was subdivided into seven distinct areas defined by wave exposure and resource accessibility

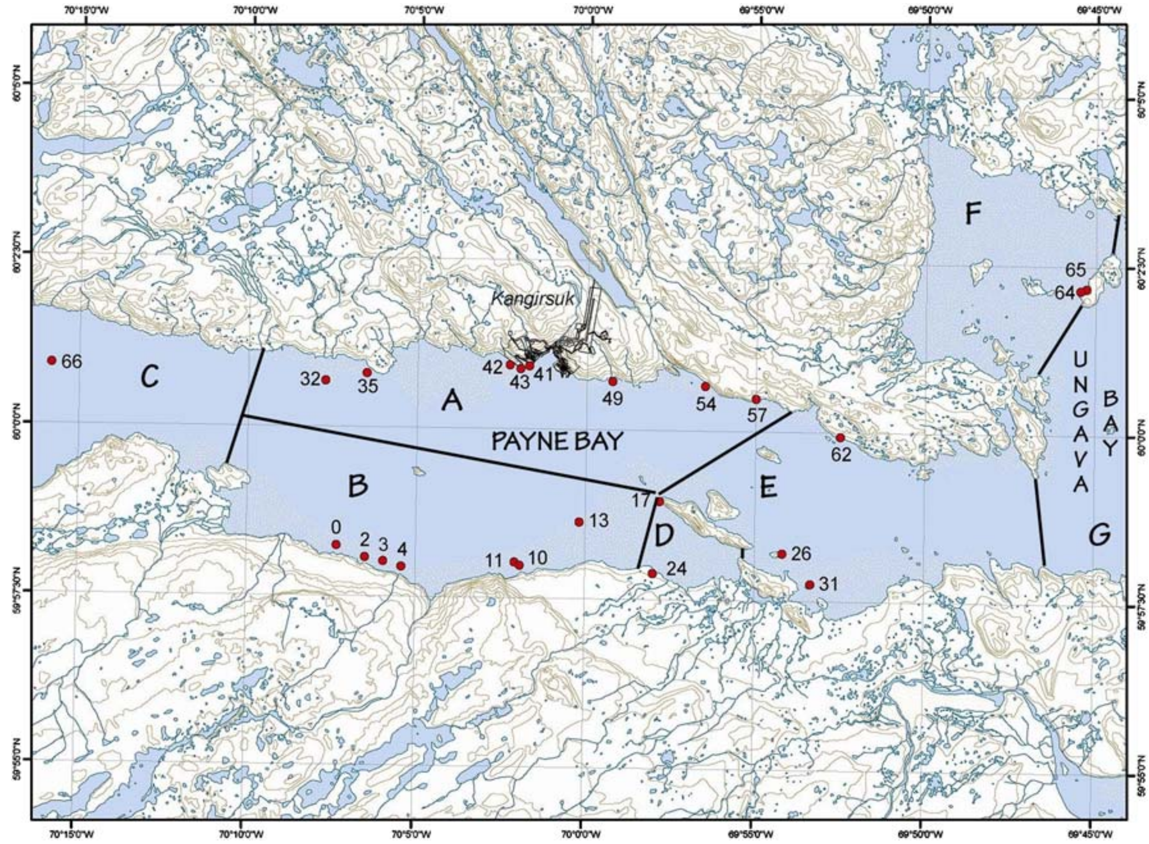

Fig. 1 Location of intertidal survey stations (●) in Payne Bay and Ungava Bay, Quebec, Canada. Subdivisions of the fucoid resources *A–G*

(Fig. 1). The index of wave exposure was a function of fetch (distance waves travel unimpeded) and open angle (the angle that waves travel over the fetch). Resource accessibility was a function of distance from the village of Kangirsuk, wave exposure, the necessity of an open water crossing by local harvest vessels and the existence of barrier reefs.

To calibrate the Landsat image, discrete areas of fucoid cover were outlined by a Trimble GeoXM (accuracy 1–2 m) with ArchPad software by walking their perimeter. These areas were converted from a line point shapefile to a line shapefile, and lines were formed from consecutive points and converted to polygons. The perimeters that represented fucoid cover were used in ERDAS Imagine remote sensing software as training areas for an unsupervised classification. The software identified areas in the Landsat image similar to those entered as training areas and calculated the total area of fucoid cover. The Landsat image resolution of 30 m provided an underestimate of true coverage since smaller fucoid stands would not have been identified.

Based on the analysis of the Landsat image the total standing and harvestable crop of fucoids was calculated for four of the seven harvest areas. These were the harvest areas closest to Kangirsuk with sheltered to semi-sheltered shores and where there was sufficient ground truthing data. To obtain the standing crop of fucoids for each harvest area, the fucoid cover was divided into three equal areas based on the three tidal strata: upper, middle and bottom. The average biomass for each species from all stations in the harvest area for each tide strata was multiplied by the total area of the strata. The total biomass of these three strata for each area was discounted according to accessibility. Discounts of the total wet biomass for each area were based on the proportion of harvest days during the summer when it would be safe to cross open water to access the harvest area. The low access areas distant from the village with high wave exposure had the harvestable biomass discounted by 75%, moderate access and low wave exposure areas were discounted by 50%, and areas of high accessibility and low wave exposure resources were not discounted. An exploitation rate of 10% was chosen as a precautionary level based on the annual rates for fucoid species from the Canadian Maritimes between 17 and 25% annually (Ugarte and Sharp 2001).

Growth of fucoids

In the mid-intertidal, six plots of 0.5×0.5 m were permanently marked with pins for tagging of individual *F.*

evanescens. Fully intact fronds were chosen that were in good condition. Fifty-six fronds were tagged from 3.0 cm to 30.0 cm long evenly distributed in the plots. A monofilament tag was used with a number on embossed Dymo™ labeling tape. The tag was held around the base of the frond with a slider made of neoprene rubber. The total length of each plant from base to the distal tip and the total number of dichotomous branches were recorded to 0.1 cm and 1 cm, respectively.

Results

On every dive and drop camera transect, kelp species were observed to −15 m if there was solid substrate. A high density of kelp plants (>5 m^{-2}) was observed on all but 2 of 11 diving transects (Fig. 2). A moderate kelp density (1–5 m^{-2}) was observed in 6 of 10 camera transects, while 2 had low kelp densities (Fig. 2).

In the shallow (<3 m) part of the subtidal, there were obvious signs of ice scouring at every station. This took the form of a cover of filamentous brown and green algal species and very young of the year kelp plants (Fig. 3). *Alaria esculenta* (L) Greville was common in this zone as small plants, but this species also extended down to 3–6 m in wave-exposed environments. Below this ice-impacted zone there were perennial stands of kelp. The most prolific species was *S. longicruris* particularly in the more sheltered and shallow portions of the beds, for example, Basking Island (Fig. 3). At locations like Pikyuluk Island, with very strong (5 km h^{-1}) currents, *Laminaria digitata* (Hudson) J.V. Lamouroux was the predominant species in the 3- to 6-m-depth range. *Laminaria solidungula* J. Ag was a common species in depths of 6–12 m. *Agarum clathratum* Dumortier was also associated with the deeper parts of the zone, at 10 m in sheltered sites but occurring at 3 m in exposed sites. Total kelp biomass was greatest in the 5- to 10-m-depth range (Fig. 3). Below 12 m, kelp species were in low abundance and a community of small tufted reds were mixed amongst sponges. *Saccharina groenlandica* (Rosenvinge) Lane, Mayes, Druehl & Saunders was only present in deeper water on the outer coast, at Tuvalik Point (Fig. 3).

The four kelp sampling stations represent the range of diversity and abundance of kelp species in the entire survey area (Table 1). The outer coast is represented by Tuvalik Point, where there was a mix of five kelp species. *S. longicruris* and *L. solidungula* together were 43% of the

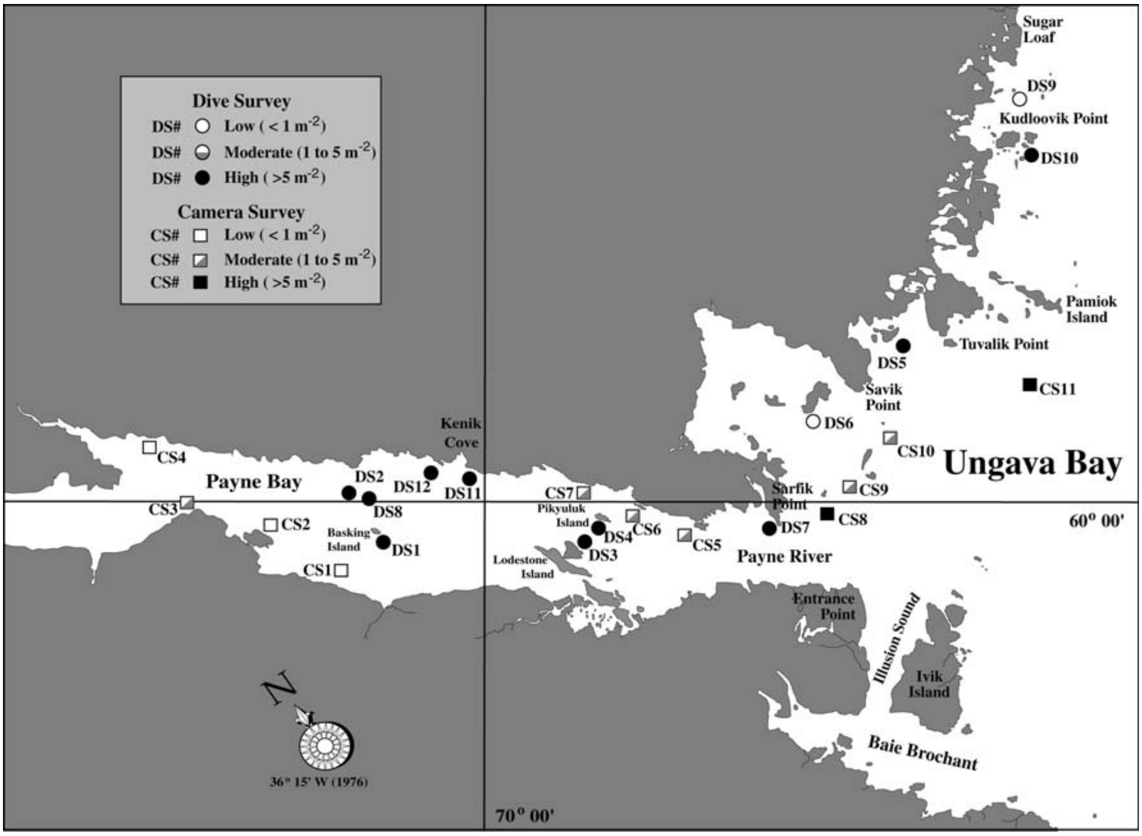

Fig. 2 Location of diving and remote camera transects in Payne Bay and Ungava Bay, Quebec, Canada, and relative densities of Laminariales recorded on each transect

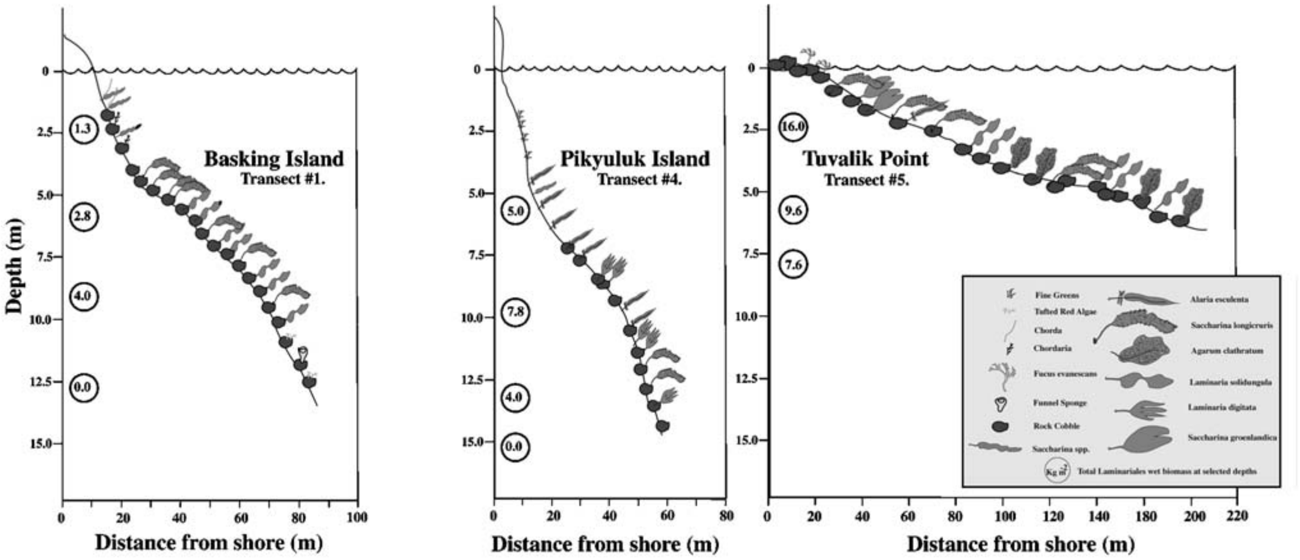

Fig. 3 Laminariales distribution in Payne Bay at three sites on depth profiles, and wet biomass kg m^{-2} (○) at selected depths

biomass (Table 1). The overall biomass was the second lowest of the sites but samples containing *S. longicruris* reached a maximum 16.7 kg m^{-2} and *L. solidungula* 10.4 kg m^{-2}. *Laminaria digitata* dominated the biomass at Pikyuluk Is., a site with very high current speeds (>10 km h^{-1}) (Canadian Hydrographic Service chart). The Kangirsuk shore site was a semi-sheltered ledge dominated by *S. longicruris* attaining the highest single sample weight of all stations, 19.0 kg m^{-2}, and highest mean biomass (Table 1). Basking Island was a very steeply sloping site and had the lowest biomass of all sites with a 50/50 mix of *S. longicruris* and *L. solidungula* (Table 1).

The total length of *S. longicruris* averaged 225±55 cm to a maximum of 900 cm. *L. digitata* was smaller at 88±29 cm as was *L. solidungula* at 121±42 cm. *Alaria esculenta* averaged 115±63 cm in the shallow ice scoured zone, it is usually less than 100 cm long, but below this depth it attained 300 cm. *Agarum clathratum* rarely reached 100 cm total length.

Growth of kelp

Thirteen of the original 40 tagged *S. longicruris* plants were recovered. The total length averaged 425±23 cm, the punched holes moved an average of 323±16.5 cm in one year (.9±.3 cm d^{-1}). The average distance to the blade constriction was 201±9 cm in the recovered plants.

Intertidal

In Payne Bay, *F. evanescens* averaged 1.47±.12 wet kg m^{-2} and *F. vesiculosus* averaged .28±.02 wet kg m^{-2} (n=460). The frequency distribution of biomass density of both species was skewed to the first quartile of distribution, the value 0. The greatest biomass of *F. evanescens* occurred on rock substrate reaching a maximum biomass of 13.1 kg m^{-2}. The second highest mean biomass occurred on boulders (Fig. 4). Boulders were ice scoured on the top and had 100% fucoid cover on their sides. Rocks were frequently protected

Table 1 Density and biomass (± SE) of kelp species at four sites in Western Ungava Bay

Station	Basking Is	Kangirsuk	Pikyuluk Is	Tuvalik Pt
Density m^{-2}	24±2	12±1	39±3	24±2
biomass g m^{-2}	2.9±.2	11.8±1.3	9.2±2.0	8.4±1.1
% species composition	*Sl* 53	*Sl* 87.5	*Ld* 75	*Ac* 40, *Ls* 35
	Ls 47	*Ls* 12.5	*Ae* 23	*Sl* 8, *Sg* 7
			Sl 2	*Ae* 5

Saccharina longicruris (Sl), *Laminaria solidungula (Ls) Laminaria digitata (Ld) Saccharina groenlandica (Lg)*, *Alaria esculenta (Ae)* and *Agarum clathratum (Ac)* from ice scour by the larger boulders in mixed substrates. While *F. evanescens* was abundant on boulder substrate it was absent on bedrock (Fig. 4). Bedrock was normally at the upper part of the intertidal where maximum *F. vesiculosus* biomass was 8.4 kg m^{-2}. Any area with a cobble substrate had very low fucoid biomass (Fig. 4). *F. vesiculosus* dominated the upper intertidal transects at each station while *F. evanescens* was the predominant component of the biomass in the lower station area (Fig. 5). Fucus biomass in the middle region of the zone was a mix of the two species (Fig. 5).

Most of Payne Bay was in the wave exposure catagory of semi-sheltered to sheltered (Table 2). However, based on distance from Kangirsuk, only Area A had high resource accessibility (Table 2). Area D was wave sheltered, but had two access problems: distance across open water and outlying barrier reefs exposed at low tide (Table 2). Areas E to G were over 10 km from Kangirsuk and required travel to the outer area of Ungava Bay.

Area A closest to the village of Kangirsuk was not discounted for access, but still had the lowest harvestable biomass of all areas due to lower fucoid cover (Table 3). Moderately accessible shoreline, Area B, discounted 50% for access, was still 3–4 times the annual harvestable biomass of the high access area. Area C and D, with low access due to travel distance and wave exposure had the standing crop discounted by 75% and also exceeded the high access area A in harvestable crop (Table 3). Total fucoid biomass in Payne Bay was 82,801 wet t 70% *F. evanescens* (Table 3). Following discounting for access, the total was 35,920 wet t harvestable biomass of fucoids.

Growth of fucoids

Thirty-one of the original 56 *F. evanescens* tags were recovered and measured. The mean length increment was 3.6±0.7 cm and dichotomies increased by 3.0±1.0 over the year.

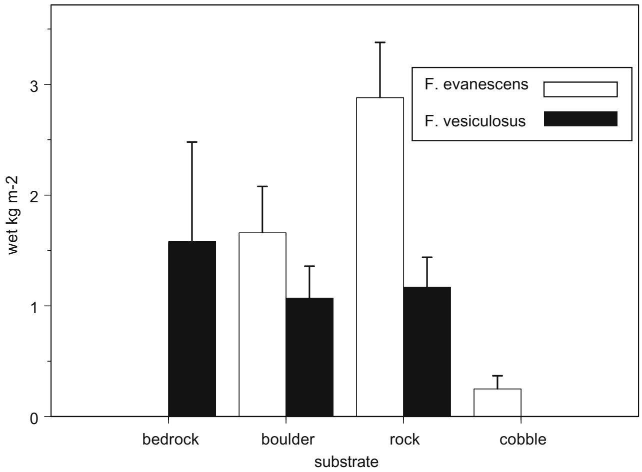

Fig. 4 Mean biomass density of fucoid species on five bottom types within 0.25 m^2 quadrats sampled from Payne Bay and environs in August 2005 (*bars* 1 SE)

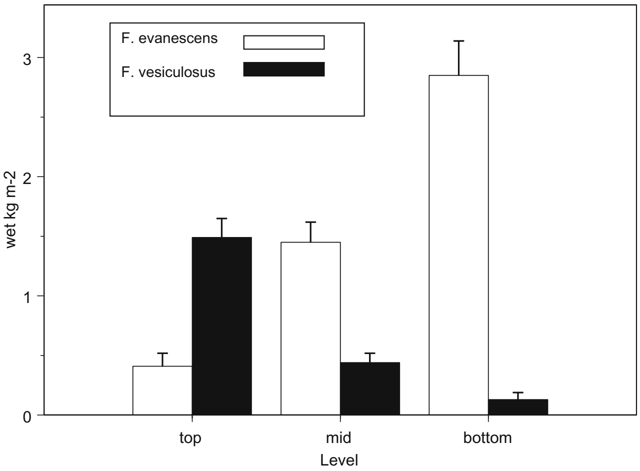

Fig. 5 Fucoid species biomass at three tide levels on transects in the intertidal of Payne Bay and environs, top (8–9 m), mid (5–6 m), bottom (1–2 m) (chart datum) (*bars* 1 SE)

Discussion

Although the fucoid resource base in Payne Bay is extensive and there is a moderately high standing crop and fucoid cover, it is very patchy. Patchiness is related directly to the presence or absence of optimal bottom type, rock and boulders. In the northern environment, the intertidal is more or less vulnerable to ice scour depending on the degree of substrate relief and the movement of ice by current and wind during ice break-up. The combination of boulders and rocks provide a high relief bottom protecting the fucoid biomass from the scouring effects of ice. Boulders scattered in piles on a gravel or sand matrix provide shelter within the piles from the pressure of moving ice. *Fucus vesiculosus* has a similar distribution in the St. Lawrence River estuary (Guichard et al. 2000). Small scale topographical heterogeneity ≤20 cm has a strong influence on relative abundance of seaweeds that are subjected to ice scour annually (Bourget et al. 1994). The mean biomass of *Fucus* spp. in the ice-scoured St. Lawrence River estuary, 1.5 kg m^{-2}, was within the range recorded in Ungava Bay (Archabault and Bourget 1996).

There may be other factors that allow fucoid species to develop significant biomass in the intertidal zone of ice scoured environments. *F. vesiculosus* in the Baltic has two strategies to survive ice scour. In sheltered waters, the plants lose buoyancy in the winter and sink below the ice level, while they also have a high vegetative regenerative capacity to allow recovery from annual ice scour even from small residual pieces of stipe and holdfast (Kiirikki and Ruuskanen 1996). The persistence of *F. vesiculosus* on

Table 2 Wave exposure (*Exp*), accessibility (*Acc*) and classification of seven potential harvest areas of the fucoid resource in Payne Bay and classification

Region	Fetch km	Open angle °	Distance to port	Open water	Barrier reefs	Classification	
						Exp.	Acc.
A	≤10 >5	≤90	≤10	−	−	SS	HA
B	≤10 >5	≤90	≤10	+	−	SS	MA
C	≤10 >5	≤90	>10	+	−	SS	LA
D	<5	≤90	>10	+	+	S	LA
E	≤10	>90 ≤180	>10	+	−	SE	LA
F	<5	≤90	>10	+	+	S	LA
G	Unlimited	>180	>10	+	−	E	LA

bedrock substrate at the highest level of the intertidal in Payne Bay supports these observations. Severe ice scour events in temperate waters require less than 1 year for *F. vesiculosus* to recover density (McCook and Chapman 1997). Five years may be required for complete recovery of biomass after an intensive (>80%) harvest in the subarctic. Annual exploitation rates in temperate populations of fucoids are limited to 20–25% of harvestable biomass (Sharp and Semple 1997). Preliminary results of harvesting experiments and these growth measurements suggest 10% of the harvestable standing crop is a conservative limit for Payne Bay.

Robert Wilce (1959) found in a survey of seaweeds in the south and eastern parts of Ungava Bay in the mid-1950s found "immense kelp in large and more often discrete beds, the bulk of which consists of *S. longicruris*". Wilce could have been describing a general conclusion for our survey area on the western part of Ungava Bay. The list of kelp species found at five stations was very similar to our list with the exception of *L. nigripes*. *Laminaria digitata* has not been reported for this subarctic region, but has been reported for the Canadian arctic (Lee 1980).

The mean biomass of 1.2–7.5 kg m^{-2} in temperate waters is well within the range of values for Ungava Bay (Sharp and Carter 1986). At the southern limit of *S. longicruris* in Long Island Sound, USA, a maximum biomass was 24 kg m^{-2} compared to 18 kg m^{-2} in Payne Bay (Egan and Yarish 1990). *Laminaria saccharina* (=*Saccharina latissima*) populations in a high arctic Greenland fjord averaged 49 g m^{-2} (Borum et al. 2002). The maximum size of plants of *L. digitata* and *S. longicruris* was also very similar for these species from temperate waters (Sharp and Carter 1986).

The density and biomass of these populations may be similar in the subarctic and temperate waters but there is the question of annual productivity. On most dives, we observed an understory of small kelp plants that suggests recruitment is a regular if not annual event. Reduction in canopy plant density allows these shade inhibited plants to grow rapidly to replace the lost plants. There is also a high abundance of small (<1 m) Laminariales in the ice scour zone of the sub tidal suggesting that in this highly perturbed zone recruitment pulses are strong.

The limited data from Payne Bay tagging experiments indicate *S. longicruris* in Ungava Bay grows at yearly rates similar to rates recorded for this species or conspecifics in temperate waters 1.0–2.0 cm day^{-1} (Chapman and Craigie 1978; Egan and Yarish 1990; Parke 1948). In the high arctic, *L. saccharina (S. latissima)* retains old leaf blades, thus the specific growth rate in terms of growth per unit length of blade is lower than in southern populations (Borum et al. 2002). *S. longicruris* in Payne Bay only retained blades if over 200 cm and usually only a small portion of the blade, meaning that annual elongation did reflect specific growth rate in smaller plant sizes. The peak growth period for *L. solidungula* in arctic Alaska was from February to April and for *L. saccharina* (*S. latissima*) was during the ice-free period of late April to late July (Dunton 1985). At 74°N in Greenland, photosynthesis in *L. saccharina* (*S. latissima*) was able to balance and exceed respiration during the ice-covered period (Borum et al. 2002). The subarctic climate of Ungava Bay at 59°N

Table 3 Estimates of fucoid cover, total standing crop (wet weight) and harvestable standing crop discounted for access and annual harvestable tonnage of *Fucus evanescens* (*Fe*) and *Fucus vesiculosus* (*Fv*) in Payne Bay in four selected harvest areas, August 2005

Area	Discount %	Fucoid cover km^2	Total biomass wet t Fe	Total biomass wet t Fv	Harvestable wet		Annually harvestable 10% exploitation	
					t Fe	Fv		
A	0	2.27	3,563	1,565	3,563	1,565	356	156
B	50	15.68	24,110	10,744	12,055	5,372	1,205	537
C	50	6.61	9,254	2,908	4,627	1,454	463	145
D	75	13.09	20,109	9,028	5,027	2,257	503	226
∑		37.66	57,836	24,245	25,272	10,648	2,527	1,064

provides June to December as an ice-free growth period for *L. longicruris*. It appears the environment of Payne Bay yields standing crops and annual Laminariales growth rates intermediate between high arctic and temperate waters.

We did not present any estimates for standing crop for these species because the survey was not designed to estimate total area covered by kelp. However, we have confirmed by spot survey and aerial reconnaissance that 100s of km of the subtidal in Ungava Bay supports mature kelp beds. Recent aerial surveys of Leaf Bay, 200 km to the south of Payne Bay, indicate there is a similar distribution of kelp species.

It is unlikely that the Ungava Bay seaweed resources will follow the industrial development and exploitation path of the Canadian Maritime provinces (Ugarte and Sharp 2001). The remoteness of Ungava Bay from regular heavy transport prevents easy export of raw or processed material. The short open water period narrows the time for resource access. Similarly, the natural air drying season is short and affected by rapid changes in weather systems and mechanical methods incur very high fuel costs.

There are also important factors of logistics, culture and economics that will affect the successful utilization of these resources. A tidal range of over 10 m restricts the access time to shallow parts of the kelp resource from 1 to 2 h per day. Despite this limitation, the Inuit have continued to utilize traditional foods, and kelp species are among those consumed regularly (Wein et al. 1996). Gathering mussels and fresh seaweeds are as much a part of tradition as are gathering berries and hunting caribou. Fucoid species are accessible on all low tides by simply walking on the shore. Intertidal hand gathering of these species would be similar to shore based rockweed harvesting in Nova Scotia, Canada. The local vessel capacity and travel radius is limited by vessel size and power. It is more likely this resource will be exploited for a high unit value final product than any large industrial processing. A cottage type industry would have very little impact on the habitat and subarctic ecosystem as well as harmonize with local culture.

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