Recent expansion of erect shrubs in the Low Arctic: evidence from Eastern Nunavik

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Abstract
In order to characterize shrub response near the treeline in Eastern Nunavik (Québec), a region under extensive warming since the 1990s, we compared two series (1964 and 2003) of vertical aerial photos from the vicinity of Kangiqsualujjuaq. Our study revealed a widespread increase in erect woody vegetation cover. During the 40 years spanning the two photo series, erect shrub and tree cover increased markedly on more than half of the land surface available for new colonization or infilling. Within the 7.2 km$^2$ analysed, areas with dense shrub and tree cover (>90%) increased from 34% to 44% whereas areas with low cover (<10%) shrank from 45% to 29%. This increase in cover of trees and shrubs occurred throughout the landscape regardless of altitude, slope angle and exposure, although to varying extents. The main shrub species involved in this increase was *Betula glandulosa* Michx. (dwarf birch), which was present in 98% and dominant in 85% of the 345 plots. In addition, numerous seedlings and saplings of *Larix laricina* (Du Roi) K Koch (eastern larch) were found above the treeline (25% of the plots), suggesting that the altitudinal treeline might shift upslope in the near future. Sites that remained devoid of erect woody vegetation in 2003 were either characterized by the absence of a suitable seedbed or by harsh local microclimatic conditions (wind exposure or excessive drainage). Our results indicate dramatic increases in shrub and tree cover at a Low Arctic site in Eastern Nunavik, contributing to a growing number of observations of woody vegetation change from various areas around the North.

Keywords: shrub expansion, repeat photography, *Betula glandulosa*, *Larix laricina*, forest–tundra ecotone, climate warming

1. Introduction

Land cover change is a major response of arctic and subarctic terrestrial ecosystems to climate warming (Levis et al 1999, Kittel et al 2000, Beringer et al 2005). Under warmer temperatures, open-tundra ecosystems will likely be colonized by tree and shrub species (Euskirchen et al 2009). In a recent review, Harsch et al (2009) found evidence of latitudinal or altitudinal treeline shifts in more than half of the sites monitored since the beginning of the 20th century. However, in situ evidence of erect shrub species expansion in response to climate is scarce, even though they represent one of the dominant functional vegetation groups in the Low Arctic.

Shrub expansion was first reported by Sturm et al (2001a) who compared different series of vertical photos taken about 50 years apart in Alaska. Since then, quantitative data on the extent and on the species associated with shrub cover increase in North America were reported for Alaska (Tape et al 2006, Dial et al 2007), Yukon (Myers-Smith 2011, Myers-Smith et al 2011), Mackenzie Delta Region, Northwest Territories...
(Lantz et al. 2009), western Nunavik (subarctic Québec, Ropars and Boudreau 2012) and the High Arctic (Hudson and Henry 2009, Hill and Henry 2011). In addition, decadal scale increased greenness at high latitudes has been documented by Normalized Difference Vegetation Index (NDVI) studies (Silapaswan et al. 2001, Jia et al. 2004, Verbyla 2008, Forbes et al. 2010, Othlof and Pouliot 2010, Fraser et al. 2011). However, these coarse scale approaches cannot distinguish between growth forms (shrubs or graminoids) or processes responsible for such changes.

The expansion of shrub species has been shown to be associated with climate warming or release from grazing pressure (Myers-Smith 2011). Several dendrochronological studies identified positive correlations between shrub radial growth and summer temperatures (Bár et al. 2006, Forbes et al. 2010, Hallinger et al. 2010, Myers-Smith 2011, Blok et al. 2011, Boudreau and Villedune-Simard 2012) while others identified winter temperature and snow cover as the most important climatic variables (Schmidt et al. 2006, 2010, Rixen et al. 2010, Hallinger et al. 2010). Shrub species were also shown to respond positively to experimental warming (Chapin et al. 1995, Chapin and Shaver 1996, Hobbie and Chapin 1998, Bret-Harte et al. 2001, 2002, Van Wijk 2003, Jonsdottir et al. 2005, Wahren et al. 2005, Walker et al. 2006, Elmqvist et al. 2012). On the other hand, browsing and grazing are known to have notable impacts on shrub vegetation in Arctic Canada (Henry and Gunn 1991, Manseau et al. 1996, Post et al. 2009) and Fennoscandia or Siberian tundra (Speed et al. 2011, Hofgaard et al. 2010, Pajunen 2009). In fact, changing levels of browsing could inhibit shrub expansion (Olofsson et al. 2009).

An increased shrub cover and stature (from prostrate or dwarfed to erect or tall) in arctic and subarctic regions could have consequences on many ecological factors (reviewed in Naito and Cairns 2011, Myers-Smith 2011). For example, shrub expansion could result in lower albedo (Chapin et al. 2005, Sturm et al. 2005a, Loranty et al. 2011, Blok et al. 2011), greater snow accumulation, deeper active layer and higher summer evapotranspiration (Sturm et al. 2001a, Liston et al. 2002, Pomeroy et al. 2006, Strack et al. 2007, Marsh et al. 2010). Soil nutrient cycling could also be altered through changes in production and accumulation of woody material (carbon sequestration), through higher retention of windblown organic debris (Fahnestock et al. 2000) and through warmer soil winter temperatures (Sturm et al. 2001a, Myers-Smith et al. 2011). Such changes could enhance decomposition (Grogan and Chapin 2000, Schimel et al. 2004, Sturm et al. 2005b) which could promote further shrub expansion.

To date, the nature and extent of erect shrub cover increase remains unknown for most of the arctic and subarctic regions of North America, and gaining actual knowledge of land cover change is essential to understand how high-latitude ecosystems will respond to current and future climate changes. In this letter, we quantified land cover change over the last 40 years in Eastern Nunavik (Low Arctic Québec). We compared erect woody vegetation cover (which includes both shrub and tree species) on old (1964) and recent (2003) vertical aerial photos of areas surrounding the village of Kangiqsualujjuaq. Vegetation surveys in the field were conducted to validate the results of the aerial photo analysis and to identify and characterize the shrub and tree species associated with the shrubification process.

2. Methods

The study was conducted near Kangiqsualujjuaq (58°42’39” N–65°59’43” W) in Eastern Nunavik (figure 1), a community located on the southeast side of Ungava Bay, about 25 km upstream from the mouth of the George River. We chose a study site in the forest–shrub tundra transition zone to investigate recent vegetation change, because changes in plant communities in response to climate change are expected to happen first in ecotones (Silapaswan et al. 2001). All shrub growth forms are common in this region from prostrate species such as some berry producing plants to tall shrub species such as Salix planifolia Pursh. Two tree species are common, Larix laricina (du Roi) K Koch and Picea mariana (Mill.) BSP. These are mainly restricted to valley bottoms.

Long-term climatic data (1948–2008) from the nearest available meteorological station at Kuujjuaq (160 km to the southwest) indicate a mean annual temperature of about −5.5°C and mean annual precipitation of greater than 500 mm (Environment Canada 2011). A strong warming trend was recorded in the region over the last two decades (figure 2), consistent with observations from several other Canadian Eastern Arctic sites (Allard et al. 2007). Short-term data available for the study area (1993–2008) are well correlated to those from Kuujjuaq (Pearson correlation coefficient of 0.98),...
Figure 2. Mean annual temperatures recorded in Kuujjuaq (Québec, 58°06' N–68°25' W) for the period 1950–2010 (Environment Canada 2011).

with a difference in mean annual temperature of <0.5°C between the two locations.

The landscape of the study area is dominated by steep sided flat-topped hills which do not exceed 300 m of altitude. Bedrock is archaean gneiss, with some quartzites and amphibolites (Paradis and Parent 2002). Vegetation varies greatly with altitude, grading from boreal–subarctic on protected lowlands to arctic on mid slopes and hilltop plateaus. Small expanses of closed-coniferous forests are found on valley bottoms and lower parts of hillsides, where trees as high as 20 m grow. At higher altitudes, tree density and height decrease progressively. Local treeline is generally found at 80 m asl, but on some well protected and favourably exposed valley sides, it may reach 150 m.

2.1. Erect woody vegetation change analysis

2.1.1. Aerial vertical photograph analysis. Comparative analysis was conducted on two series of vertical aerial photographs covering the community of Kangiqsualujjuaq and the surrounding area (5–6 km radius). The first series of aerial photographs date back to 6th August 1964. Monochrome contact prints at 1:15 000 and 20 000 scales were obtained from the National Air Photo Library of Natural Resources Canada. Additional 1964 photographs of the area are available mostly at 1:40 000 scale. The recent aerial photographs were taken 24th July 2003 and are at a 1:10 000 scale. Monochrome orthophotographs at a 0.25 m resolution of these 2003 photos were obtained from the Géoboutique Québec of the Ministère des Ressources naturelles et de la Faune, Québec. Digital orthorectified files of the 1964 prints were created at a 0.5 m resolution based on the georeferenced 2003 orthophotographs and a digital elevation model at a 2 m resolution (1 pixel = 4 m²) generated using the vectorial data of the 1:50 000 maps of the area (24I12, 24I13, 24J09, 24J16). Third order polynomials and local spline adjustments were used to correct the image. Total area of overlap of the two photo series was 17 km², of which 14.3 km² was land surface and 13.2 km² were undisturbed by human activities and available for vegetation change analyses. More than half (55%) of this undisturbed area (7.2 km²) was analysed for erect woody vegetation cover on the two photo series representing at least 30% of each environmental parameter class (see below). Shrub-covered areas on the orthophotos can be detected visually by their darker shade and distinct texture created by the foliage and the roundish aspect of each shrub seen from above (figure 3, figure A.1). Trees are easily detected by the triangular shape of their projected shade. However, in this study, we did not separate the increase of shrub cover from the increase in tree cover. As a consequence, the term erect woody vegetation cover will be used hereafter.

During analyses with ArcGIS (version 9.2 from ESRI), we used a stretched symbology with standard deviations as stretch type (‘n’ values between 1.5 and 2.5) for orthophoto display. Images were analysed by one observer and contours of surfaces covered by erect woody vegetation were traced, delimiting them inside polygons. Minimum area for these surfaces to be considered was fixed at 100 m² and contours were traced in order to encompass them in the smallest possible polygons. Analysis was thus kept at the smallest scale above the minimum area, enclosing the least possible non-shrub/tree-covered land inside the polygons. With this method, analysis was generally made at a view scale between 1:400 and 1:800. At first, surfaces covered by erect woody vegetation were classified in three vegetation types according
to observed cover patterns. Those with 90% cover or more were classified as ‘continuous cover’. They presented dense shrubland and/or woodland with essentially no possibility of total cover increase (figure 3). Surfaces with cover between 10% and 90% were classified as ‘discontinuous cover’, displayed on the photos as patchy shrubs or shrub thickets and isolated or aggregated trees, all with a heterogeneous spatial distribution (figure 3). Surfaces that contained no erect woody vegetation or only very isolated individuals were classified as <10% shrub cover. We classified the limits of the discontinuous cover classes in such a way because of the difficulty in evaluating cover inside larger polygons with irregular contours.

To evaluate cover changes at a finer scale within the discontinuous cover zones, polygons were randomly selected for the following situations: (i) areas with a discontinuous erect woody vegetation cover in 2003 that were assigned to the <10% erect woody vegetation cover class in 1964 (50 polygons), (ii) erect woody vegetation cover change in areas assigned to the discontinuous cover class in both 1964 and 2003 (50 polygons each year) and (iii) areas with a discontinuous erect woody vegetation cover in 1964 that were assigned to the >90% cover class in 2003 (50 polygons). In each of these polygons, cover was evaluated in a randomly located 40 m x 40 m (1600 m²) quadrat and categorized into one of four narrower cover classes spanning the whole interval of the discontinuous cover class: 10–30%, 30–50%, 50–70% and 70–90%. Mid cover class values were used to calculate mean cover per type. A Welch Two Sample t-test was performed to compare vegetation cover in discontinuous polygons in 1964 that remained discontinuous in 2003 (R Development Core Team 2011).

To identify the landscape types in which changes in erect woody vegetation occurred, we used the following variables: altitude, slope and exposure. The digital elevation model previously created was used to generate raster datasets of slope and exposure with ArcGIS. Four classes were created for each environmental variable. The four cardinal points were used as centroid of exposure classes (90° each). In the case of altitude and slope, the boundaries of the classes were fixed based on the natural breaks of the distribution of values as plotted with ArcGIS, and on their ecological significance (table 1). Raster datasets of these variables were extracted for each erect woody vegetation cover category (<10%, discontinuous and continuous cover). The sum of pixels in each variable class was multiplied by pixel size (4 m²) to obtain net surface occupied by erect woody vegetation and vegetation cover type in each class.

### 2.1.2. Field surveys.

Prior to field sampling, areas where erect woody vegetation cover had changed was determined by superimposing and uniting the 1964 and 2003 polygons to extract new polygons. The three new polygon categories included: a change from the <10% erect woody vegetation cover class in 1964 to either discontinuous or continuous cover in 2003, or from discontinuous cover in 1964 to continuous cover in 2003, hereafter referred to as infilled areas. Each of these polygons was attributed values of altitude, slope and exposure based on mean value of these variables’ classes within a given polygon.

A stratified random selection of the different new polygons was conducted for ground-truthing to ensure that each combination of vegetation cover types and environmental parameters was represented. All polygons located 20 m or less from disturbed areas were excluded from the sampling. The centroid of each polygon selected was computed with ArcGIS and used as the field plot location. To provide information on habitats which had not been colonized by erect woody vegetation, ten plots were randomly positioned inside areas assigned to the lower cover class on both 1964 and 2003 orthophotos. Each 78.5 m² ground-truthing circular plot (5 m radius) was described (general habitat, drainage, soil, natural and anthropogenic disturbance); height, cover and presence of seedlings, saplings and suckers were determined for each erect woody species and close-up photos were taken. Ground-truthing took place during the summer of 2008, from 17th July to 2nd September.

### 3. Results

#### 3.1. Aerial vertical photograph analysis

In 1964, 325 ha of the study area was essentially devoid of erect woody vegetation while discontinuous and continuous cover occupied 149 and 246 ha (table 2). From 1964 to
2003, erect woody vegetation expanded substantially in the study area. New colonization was observed on land previously assigned to the lowest cover class. In fact, 95 and 19 ha of the <10% cover class in 1964 were reassigned respectively to discontinuous and continuous cover in 2003. As a result, the area occupied by the <10% cover class shrank to 211 ha over the period, now covering 29% of the study area compared to 45% in 1964 (figure 4). Newly colonized surfaces that were reassigned to the discontinuous cover class had a mean cover value of 37 ± 14%. Surfaces still devoid of erect woody vegetation in 2003 contained boulder fields, rock outcrops, exposed hilltop plateaus with abundant boulders and bare soil and sedge fields found mainly on valley floors and hillside nivation terraces.

Infilling occurred on surfaces for which erect woody vegetation cover was classified as discontinuous on the 1964 aerial photos. From 1964 to 2003, the area occupied by a discontinuous cover increased from 149 to 191 ha, even though 53 ha of the studied area classified as discontinuous in 1964 was re-classified as continuous in 2003 (table 2). The 1964 discontinuous cover surfaces that have remained in this cover class in 2003 have undergone partial infilling, with a significant increase in cover from 47 ± 18% in 1964 to 62 ± 12% in 2003 (t186,648 = −4.7866, P < 0.001). Finally, the area occupied by a continuous cover increased from 246 to 318 ha between 1964 and 2003. This increase resulted mainly from the infilling of sites initially classified as discontinuous (53 ha with a mean cover of 59 ± 18% in 1964), although new continuous cover (19 ha) was observed on previously shrubless and treeless surfaces.

Decreases in erect woody vegetation cover between 1964 and 2003 were observed infrequently (<10) on <1 ha surfaces. These decreases in cover were mostly associated with geomorphological disturbances such as landslides on steep talus along the George River.

3.2. Cover change and altitude, slope and aspect

The increase in erect woody vegetation cover was not spatially uniform at the landscape level. New colonization and infilling occurred for all environmental parameter classes, although to various extent (table 2). Decreases in the surfaces assigned to the lowest cover class (<10%) between 1964 and 2003 were inversely proportional to the altitude. For example, such areas shrunk by 60% in the lower altitudinal class compared to 20% in the higher one. Areas assigned to a discontinuous or continuous cover increased from 1964 to 2003 for all altitudinal classes with the relative increase being greater for both cover classes at higher altitudes (>70 m). Surfaces assigned to the lowest cover class (<10%) of erect woody vegetation showed similar relative decrease from 1964 to 2003, from 29% to 36%, for the different slope classes (table 2). Areas with a discontinuous cover increased from 1964 to 2003 for all slope classes but the steeper one, whereas areas with a continuous cover expanded for all slope classes, the increase being relatively higher as the slopes got steeper. Finally, new colonization and infilling of surfaces with an erect woody vegetation cover <10% was observed on all slope exposures, although it was somewhat lower on east-facing slopes (23%, table 2). Relative increase of areas with a discontinuous cover between 1964 and 2003 occurred mainly on south (32%) and west-facing slopes (31%), while the relative increase was higher on south (38%) and east-facing slopes (47%) for areas with a continuous cover.

Table 2. Changes in erect woody vegetation cover in the vicinity of Kangiqsualujjuaq (Nunavik, Québec) from 1964 to 2003 detailed by environmental parameter classes. Cover values represent analysed area occupied by either <10% cover, discontinuous (10–90%) or continuous (>90%) erect woody vegetation. (Note: 1964: cover evaluated on the 1964 aerial picture; 2003: cover evaluated on the 2003 aerial picture; Δ: percentage of change of the area occupied by the cover classes from 1964 to 2003; New: area assigned to the <10% cover in 1964 that was reassigned to either discontinuous or continuous cover; Lost to cont. or Gained from disc.: area assigned to the discontinuous cover in 1964 that was reassigned to a continuous cover in 2003.)

| Altitude (m) | <10% cover | Discontinuous | Continuous |
|-------------|------------|---------------|------------|
|             | Area (ha)  | Δ (%)         | Area (ha)  | Δ (%)         | Area (ha)  | Δ (%)         |
| 0–20        | 111        | −60.0         | 15        | −9           | 18        | 20.0         | 66        | 6           | 9           | 81          | 22.7        |
| 20–70       | 361        | −41.0         | 78        | −30          | 90        | 15.3         | 161       | 8           | 30          | 193         | 23.5        |
| 70–120      | 123        | −35.1         | 31        | −11          | 42        | 35.3         | 15        | 5           | 11          | 31          | 106.6       |
| >120        | 125        | −19.8         | 25        | −3           | 41        | 64.0         | 4         | 0           | 3           | 7           | 75.0        |
| Slope (deg) |            |               |           |              |           |              |           |              |             |             |             |
| 0–5         | 332        | −35.6         | 63        | −21          | 79        | 25.3         | 151       | 5           | 21          | 177         | 17.1        |
| 5–15        | 292        | −35.3         | 65        | −24          | 86        | 32.3         | 74        | 9           | 24          | 107         | 44.7        |
| 15–30       | 85         | −34.0         | 19        | −7           | 24        | 25.9         | 19        | 4           | 7           | 30          | 57.6        |
| >30         | 11         | −28.6         | 2         | −1           | 2         | 0.0          | 2         | 1           | 1           | 4           | 100.0       |
| Exposure    |            |               |           |              |           |              |           |              |             |             |             |
| North       | 105        | −33.3         | 26        | −7           | 32        | 23.0         | 37        | 7           | 45          | 45          | 21.9        |
| South       | 306        | −37.8         | 56        | −25          | 74        | 32.2         | 102       | 13          | 25          | 140         | 37.5        |
| East        | 82         | −23.4         | 18        | −6           | 21        | 16.4         | 17        | 2           | 6           | 25          | 47.3        |
| West        | 227        | −37.5         | 49        | −15          | 64        | 30.6         | 90        | 3           | 15          | 108         | 20.2        |
| Overall     | 720        | −35.1         | 149       | −53          | 191       | 28.1         | 246       | 19          | 53          | 318         | 29.5        |
Figure 4. Changes in erect woody vegetation cover in the vicinity of Kangiqsualujjuaq (Nunavik, Québec) from 1964 to 2003 detected through comparative analysis of past and recent aerial vertical orthophotos. All values are in per cent and represent proportions of studied area. Arrows show direction of change from one vegetation cover type to another, accompanied by amount of change indicated above.

3.3. Field surveys

Field surveys revealed that cover increases detected by repeat photography were mostly due to shrub new colonization or infilling. *Betula glandulosa* Michx. (dwarf birch) was the most common and abundant erect shrub species in areas where changes were detected. This species was recorded in 98% of the 345 plots, dominated (highest cover value) the erect woody vegetation cover in 85% of the plots and had an average cover of 48% (figure 5). In fact, it was the only erect woody species found in 22% of the plots. Aside from *B. glandulosa*, *Salix planifolia* Pursh (diamondleaf willow), *Salix glauca* L. var. *cordifolia* (Pursh) Dorn (grayleaf willow), *Larix laricina* (Du Roi) K Koch (eastern larch) and *Rhododendron groenlandicum* (Oeder) Kron & Judd (Labrador tea) were also frequently observed (>20% of plots) but their mean cover was lower (<20%, figure 5).

Overall, more than 41% of the plots contained erect shrub seedlings, suggesting that the increase of erect woody vegetation cover might continue. Seedlings of *B. glandulosa* were recorded in more than 37% of the field survey plots (figure 6) and were usually found on bare mineral soil exposures related to cryoturbation such as frost boils. However, some seedlings were also observed through dense lichen cover (on palsas) or on wet brown moss beds over mixed organic and loam deposits (in fens). The only other shrub species for which seedlings were frequently observed was *R. groenlandicum* (>12% of the plots).

Seedlings and saplings of *L. laricina*, one of the dominant tree species at the landscape level, were found in about 25% of the plots (figure 6), with densities greater than 1 seedling m⁻² in some plots. Most of the recruits were observed at low to mid-altitude sites (0–70 m) in valley sides above the current altitudinal treeline or in lowland openings (palsa summits). In comparison, seedling and sapling abundance of *Picea mariana* (Mill.) BSP (black spruce), the only other tree species present at the study site, was much lower and was recorded in <4% of the plots, all located at low altitude.

4. Discussion

Comparative analysis of old and recent aerial vertical photos of land surface surrounding the village of Kangiqsualujjuaq indicates a substantial increase of erect woody vegetation cover between 1964 and 2003. These findings are consistent with regional-scale NDVI analysis (Fraser et al. 2011, McManus et al. 2012) and other studies using repeated pairs of aerial vertical or oblique photographs in different regions of subarctic North America (Sturm et al. 2001a, Tape et al. 2006, Ropars and Boudreau 2012). However, the processes underlying the observed shrubification are still unclear because several changes in the abiotic or biotic environments could have triggered this phenomenon. Here, we first compare our results to other studies which have looked at recent shrub expansion in subarctic and arctic ecosystems before discussing the potential role of climate change and large herbivores on the phenomenon.
Figure 5. Proportion of total ground-truthing plots ($n = 345$) where each erect shrub and tree species is present, and where each species dominate the erect woody vegetation cover. Proportions are also shown by growth form (erect shrub, krummholz, tree) and stage (sapling). Straight $Picea mariana \geq 2.5$ m high (Lescop-Sinclair and Payette 1995) and $Larix laricina > 5$ m high are considered as trees; they are considered as saplings below these values. $L. laricina$ does not form krummholz in the study area. Number of plots is given above bars.

Figure 6. Proportion of total ground-truthing plots ($n = 345$) where seedlings of erect shrub species as well as seedlings and/or saplings of tree species occur. Proportions are also shown by growth form. Height for $Picea mariana$ to be considered as a sapling was $\leq 2.5$ m with a straight growth and $\leq 5$ m for $Larix laricina$. Number of plots is given above bars.

4.1. Betula glandulosa: a key species for shrub expansion near Kangiqsualujjuaq

Field surveys have shown that the recent increase of erect woody vegetation reported in this study was associated with the expansion of $B. glandulosa$, which is probably the most abundant erect shrub in the Canadian Eastern Low Arctic. Ropars and Boudreau (2012) also reported an increase of this species in the Boniface River area in western Nunavik. $B. glandulosa$ was previously identified by Tape et al (2006) as one of the key species in the pan-arctic shrub densification. It has a wide ecological niche, occurring in all types of habitats, from wet and peaty to dry, rocky and exposed environments. Growth of $B. glandulosa$ has
been shown to be associated with the thermal sum received during the growing season (Boudreau and Villeneuve-Simard 2012) and to increase in response to experimental warming in a birch hummock tundra community in the Northwest Territories (Grogan 2008). Similar response to simulated climate warming was observed for a closely related birch species, *Betula nana* L. (arctic dwarf birch), in Iceland and Alaska (Jonsdottir et al 2005, Wahren et al 2005). The growth response of *B. nana* appears to be linked to its ability to produce both long and short shoots and to its developmental plasticity in secondary growth (Bret-Harte et al 2001).

The contribution of other shrub species to the increase in shrub cover in the study area was low. Most *Salix planifolia* and *Salix argyrocarpa* Anders. (Labrador willow) stands were observed in the field inside polygons located on lowland peaty soil and alluvium for which shrub cover appears to have increased only slightly over the last decades. Unlike in Alaska where it played an important role in shrub expansion (Sturm et al 2001b, Tape et al 2006), *Alnus viridis* (Chaix) DC. *sensu lato* (green alder) was mainly restricted to favourably exposed slopes along the George River where some thickets have expanded and seedlings were observed.

The high number of *L. laricina* seedlings and saplings, which might lead to a treeline shift in a near future, contrasts with previous report of low *L. laricina* density above treeline along the Leaf River, on the west side of the Ungava Bay (Morin and Payette 1984). In 1984, the authors concluded that climate warming since the end of the Little Ice Age had probably resulted in the consolidation of pre-existing tree populations rather than in altitudinal expansion. Considering the accelerated warming of many arctic areas in recent years, the situation might have changed and *L. laricina* could be increasing in abundance in this region.

### 4.2. Processes underlying shrubification: climate change, caribou and anthropogenic disturbances

Although not spatially uniform, the observed expansion of erect woody vegetation was detected in all landscape types, suggesting that the environmental change which triggered the densification or colonization of new sites by shrub and tree species, was at least regional in scale. No evidence of anthropogenic disturbances that could explain such expansion was observed during the ground-truthing exercise. It is most likely that warmer temperatures since the beginning of the 1990s (figure 2), probably accompanied by a lengthening of the growing season, is the dominant factor explaining the expansion of erect woody vegetation in the study area. Repeated ground photos (1988 and 2008) taken in the vicinity of the village suggest that shrub expansion occurred mainly over the last two decades (figure 7), the period of the greatest climate warming (figure 2).

Aside from climate, caribou disturbance at the landscape scale could have triggered or inhibited erect woody vegetation expansion. The study area is located in the summer range of the George River Caribou Herd (GRCH) which occupies the eastern half of Nunavik (Couturier et al 2004). Decreased ground cover and leaf biomass of *B. glandulosa* in grazed stands has been shown in calving grounds on either side of the George River (Manseau et al 1996). Although erect shrub growth and expansion can be constrained to some extent during periods of high caribou abundance, grazing pressure release after the sudden demographic downfall of the GRCH in the 1990s (Boudreau et al 2003) cannot solely explain the observed shrubification in this region. The GRCH population estimates were higher in 2001 (385 000 ± 28.0%; Couturier et al 2004) than in 1964 (about 62 000; Messier et al 1988) when the aerial vertical photos used in this study were taken. On the other hand, the partial or complete destruction of the lichen cover observed in the GRCH summer range (Manseau et al 1996, Morneau and Payette 1998, Boudreau and Payette 2004a, 2004b, Théau and Duguay 2004) might have favoured *B. glandulosa* recruitment. Our field work around Kangiqsualujjuaq has shown that *B. glandulosa* seedlings are more abundant on mineral or organic bare soil. We cannot separate the influences of climate warming and changing caribou disturbance, and it is likely that both these factors are related to the observed woody vegetation increase in the Kangiqsualujjuaq region.

### 5. Conclusions

We observed a substantial erect woody vegetation increase in the vicinity of Kangiqsualujjuaq for the period 1964 to 2003. Sites previously devoid of erect woody vegetation underwent colonization by erect shrubs and/or trees and
pre-existing erect shrub or tree stands underwent partial or total infilling. The shrub *B. glandulosa* was the most abundant woody species in the areas undergoing vegetation change. The high frequency of erect shrub seedlings and *L. laricina* saplings observed in the field suggests that colonization and infilling are ongoing processes. Further expansion is therefore expected, especially of *B. glandulosa*, if favourable climatic conditions persist. How climate warming, caribou disturbance and other ecological processes interact to determine woody vegetation changes across the landscape remain uncertain. Identifying the determinants of the observed land cover change, including shrub and tree recruitment and growth will improve estimates of feedbacks to climate warming and future vegetation change in subarctic terrestrial ecosystems.

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**Appendix**

![Figure A.1](image-url)  
**Figure A.1.** Portions of the aerial photos (1964 and 2003) used to evaluate erect woody vegetation cover change in the study area, near Kangiqsualujjuaq (Nunavik, Québec). Erect shrub and/or tree cover increase can be clearly seen in each 2003 photo compared with its associated 1964 photo. Left panels reprinted with permission from Natural Resources Canada 2012, courtesy of the National Air Photo Library (A18324-11, 13, 19 (1964-08-06)). Right panels reprinted with the permission of Géoboutique Québec, Ministère des Ressources naturelles et de la Faune (24112-1502, 1603 and 1604 (2003-07-23); © Government of Québec).
References

Allard M, Fortier R, Sarrazin D, Calmels F, Fortier D, Chaumont D, Savard J P and Tarasov A 2007 L’impact du réchauffement climatique sur les aéroports du Nunavik: caractéristiques du pergélisol et caractérisation des processus de dégradation des pistes Final report to Ouranos, Natural Resources Canada and Transports Québec (Québec: Université Laval, Centre d’études nordiques)

Bärl A, Bräuning A and Löfler J 2006 Dendroecology of dwarf shrubs in the high mountains of Norway—a methodological approach Dendrochronologia 24 17–27

Beringer J, Chapin F S, Thompson C S and McGuire A D 2005 Surface energy exchanges along a tundra-forest transition and feedbacks to climate Agric. For. Meteorol. 131 143–61

Blok D, Sass-Klaassen U, Schaepman-Strub G, Heijmans M M P D, Sauren P and Berendse F 2011 What are the main climate drivers for shrub growth in Northeastern Siberian tundra? Biogeosciences 8 1169–79

Boudreau S and Payette S 2004b Caribou-induced changes in species dominance of lichen woodlands: an analysis of plant remains Am. J. Bot. 91 422–9

Boudreau S and Payette S 2004a Growth performance of Cladina stellaris following caribou disturbance in subarctic Québec Ecoscience 11 347–55

Boudreau S, Payette S, Morneau C and Couturier S 2003 Recent decline of the George River Caribou Herd as revealed by tree-ring analysis Arct. Antarct. Alp. Res. 35 187–95

Boudreau S and Villeneuve-Simard M-P 2012 Dendrochronological evidence of shrub growth suppression by trees in a subarctic lichen woodland Botany 90 151–6

Bret-Harte M S, Shaver G R and Chapin F S 2002 Primary and secondary stem growth in arctic shrubs: implications for community response to environmental change J. Ecol. 90 251–67

Bret-Harte M S, Shaver G R, Zoerner J P, Johnstone J F, Wagner J L, Chavez A S, Gunkelman R F, Lippert S C and Laundre J A 2001 Developmental plasticity allows Betula nana to dominate tundra subjected to an altered environment Ecology 82 18–32

Chapin F S and Shaver G R 1996 Physiological and growth responses of arctic plants to a field experiment simulating climate change Ecology 77 822–40

Chapin F S, Shaver G R, Giblin A E, Nadelhoffer K J and Laundre J A 1995 Responses of arctic tundra to experimental and observed changes in climate Ecology 76 694–711

Chapin F S et al 2005 Role of land-surface changes in Arctic summer warming Science 310 657–60

Couturier S, Jean D, Otto R and Rivard S 2004 Démographie des troncoupes de caribous migrateurs toundriques (Rangifer tarandus) au Nord-du-Québec et au Labrador (Québec: Ministère des Ressources naturelles, de la Faune et des Parcs, Direction de l’aménagement de la faune du Nord-du-Québec et Direction de la recherche sur la faune Québec)

Diach RJ, Berg E E, Timm K, McMahon A and Geck J 2007 Changes in the alpine forest-tundra ecotone commensurate with recent warming in southwestern Alaska: evidence from orthophotos and field plots J. Geophys. Res. 112 G04015

Elmendorf S C et al 2012 Global assessment of experimental climate warming on tundra vegetation: heterogeneity over space and time Ecol. Lett. 15 164–75

Environment Canada 2011 Climata Data Online, Kuujjuuaq, Québec (http://climate.weatheroffice.gc.ca/climateData/canada.html)

Euskirchen E S, McGuire A D, Chapin F S, Yi S and Thompson C C 2009 Changes in vegetation in northern Alaska under scenarios of climate change, 2003–2100: implications for climate feedbacks Ecol. Appl. 19 1022–43

Fahnstock JT, Povirk KL and Welker JM 2000 Ecological significance of litter redistribution by wind and snow in arctic landscapes Ecoscience 7 623–31

Forbes BC, Fauria MM and Zetterberg P 2010 Russian arctic warming and ‘greening’ are closely tracked by tundra willows Glob. Change Biol. 16 1542–54

Fraser RH, Othof I, Carrière M, Deschamps A and Pouliot D 2011 Detecting long-term changes to vegetation in northern Canada using the Landsat satellite image archive Environ. Res. Lett. 6 045502

Grogan P 2008 Birch shrubs in the Canadian low arctic may respond relatively quickly to climate warming Presented at Arctic Change (Québec) (www.arcticnet.ulaval.ca/pdf/talks2008/groganPaul.pdf)

Grogan P and Chapin F S 2000 Initial effects of experimental warming on above—and belowground components of net ecosystem CO2 exchange in arctic tundra Oecologia 125 512–20

Hallinger M, Manthey M and Wilming M 2010 Establishing a missing link: warm summers and winter snow cover promote shrub expansion into alpine tundra in Scandinavia New Phytol. 186 890–9

Harsch MA, Hulme PE, McGlone MS and Duncan R P 2009 Are treelines advancing? A global meta-analysis of treeline response to climate warming Ecol. Lett. 12 1040–9

Henry HR and Gunn A 1991 Recovery of tundra vegetation after overgrazing by caribou in Arctic Canada Arctic 44 38–42

Hill GB and Henry GH R 2011 Responses of High Arctic wet sedge tundra to climate warming since 1980 Glob. Change Biol. 17 276–87

Hobbie SE and Chapin F S 1998 Response of tundra plant biomass, aboveground production, nitrogen, and CO2 flux to experimental warming Ecology 79 1526–44

Hofgaard A, Lokken JO, Dalen L and Hyttebreen H 2010 Comparing warming and grazing effects on birch growth in an alpine environment—a 10-year experiment Plant Ecol. Div. 3 19–27

Hudson JMG and Henry GH R 2009 Increased plant biomass in a high arctic heath community from 1981 to 2008 Ecology 90 2657–60

Jia GJ, Epstein HE and Walker DA 2004 Controls over intra-seasonal dynamics of AVHRR NDVI for the Arctic tundra in northern Alaska Int. J. Remote Sens. 25 1547–64

Jonsdottir IS, Magnusson B, Gudmundsson J, Eimarsdottir A and Hjartarson H 2005 Variable sensitivity of plant communities in Iceland to experimental warming Glob. Change Biol. 11 553–63

Kittel TG F, Steffen WL and Chapin FS 2000 Global and regional modelling of Arctic-boreal vegetation distribution and its sensitivity to altered forcing Glob. Change Biol. 6 1–18

Lantz TC, Gergel SE and Kokejl SV 2009 Spatial heterogeneity in the Shrub Tundra ecotone in the Mackenzie Delta Region, Northwest Territories: implications for arctic environmental change Ecosystems 13 194–204

Lescop-Sinclair K and Payette S 1995 Recent advance of the arctic treeline along the eastern coast of Hudson Bay J. Ecol. 83 929–36

Levis S, Foley JA and Pollard D 1999 Potential high-latitude vegetation feedbacks on CO2-induced climate change Geophys. Res. Let. 26 747–50

Liston GE, McFadden JP, Sturm M and Piecik RA 2002 Modelled changes in Arctic tundra snow, energy and moisture fluxes due to increased shrubs Glob. Change Biol. 8 17–32

Loranty MM, Goetz SJ and Beck P A S 2011 Tundra vegetation effects on pan-Arctic albedo Environ. Res. Lett. 6 024014

Manseau M, Huot J and Crête M 1996 Effects of summer grazing by caribou on composition and productivity of vegetation: community and landscape level J. Ecol. 84 503–13
Marsh P, Bartlett P, MacKay M, Pohl S and Lantz T 2010 Snowmelt energetics at a tundra sundra site in the western Canadian Arctic Hydrol. Process. 24 3603–20
McManus K, Morton D C, Massé J G, Wang D, Sexton J O, Nagol J R, Ropars P and Boudreau S 2012 Satellite-based evidence for shrub and graminoid tundra expansion in northern Quebec from 1986 to 2010 Glob. Change Biol. 18 2313–23
Messier F, Huot J, Le Henaff D and Luttich S 1988 Demography of the George River Caribou Herd: evidence of population regulation by forage exploitation and range expansion Arctic 41 279–87
Monette A and Payette S 1984 Expansion récente du mélèze à la limite des forêts (Québec nordique) Can. J. Bot. 62 1404–8
Morneau C and Payette S 1998 A dendroecological method to evaluate past caribou (Rangifer tarandus L.) activity Ecology 6 64–76
Myers-Smith I H 2011 Shrub encroachment in arctic and alpine tundra: mechanisms of expansion and ecosystem impacts PhD Thesis University of Alberta
Myers-Smith I H, Hik D S, Kennedy C, Cooley D, Johnstone J F, Kenney A J and Krebs C 2011 Expansion of canopy-forming willows over the twentieth century on Herschel Island, Yukon Territory, Canada Ambio 40 610–23
Naito A T and Cairns D M 2011 Relationships between Arctic shrub dynamics and topographically derived hydrologic characteristics Environ. Res. Lett. 6 044506
Olofsson J, Oksanen L, Callaghan T, Hulme P E, Oksanen T and Suominen O 2009 Herbivores inhibit climate-driven shrub expansion on the tundra Glob. Change Biol. 15 2681–93
Olthof I and Pouliot D 2010 Trenle vegetation composition and change in Canada’s western Subarctic from AVHRR and canopy reflectance modelling Remote Sens. Environ. 114 805–15
Pajunen A M 2009 Environmental and biotic determinants of growth and height of Arctic willow shrubs along a latitudinal gradient Arct. Antarct. Alp. Res. 31 478–85
Paradis S J and Parent M 2002 Géologie des formations en surface, Rivière Koroc (moitié ouest), Québec Geological Survey of Canada, Natural Resources Canada, map 2014A, scale 1:125 000
Pomeroy J W, Bewley D S, Essery R L H, Hedstrom N R, Link T, Granger R J, Sicart J E, Ellis C R and Janowicz J R 2006 Shrub tundra snowmelt Hydrol. Process. 20 923–41
Post E et al 2009 Ecological dynamics across the Arctic associated with recent climate change Science 325 1355–8
R Development Core Team 2011 R: A Language and Environment for Statistical Computing (Vienna: R Foundation for Statistical Computing)
Rixen C, Schwoerer C and Wipf S 2010 Winter climate change at different temporal scales in Vaccinium myrtillus, an arctic and alpine dwarf shrub Polar Res. 29 85–94
Ropars P and Boudreau S 2012 Shrub expansion at the forest–tundra ecotone: spatial heterogeneity linked to local topography Environ. Res. Lett 7 015501
Schimel J P, Bilbrough C and Welker J M 2004 Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic tundra communities Soil Biol. Biochem. 36 217–27
Schmidt N, Baittinger C and Forchhammer M 2006 Reconstructing century-long snow regimes using estimates of high arctic Salix arctica radial growth Arct. Antarct. Alp. Res. 38 257–62
Schmidt N M, Baittinger C, Kollmann J and Forchhammer M C 2010 Consistent dendrochronological evidence of the dioecious Salix arctica to variation in local snow precipitation across gender and vegetation types Arct. Antarct. Alp. Res. 42 471–5
Silapaswan C S, Verbyla D L and McGuire A D 2001 Land cover change on the Seward Peninsula: the use of remote sensing to evaluate the potential influences of climate warming on historical vegetation dynamics Can. J. Remote Sens. 27 542–54
Speed J D M, Austrheim G, Hester A J and Mysterud A 2011 Growth limitation of mountain birch caused by sheep browsing at the altitudinal treeline For. Ecol. Manage. 261 1344–52
Strack J E, Piekel R A and Liston G E 2007 Arctic tundra shrub invasion and soot deposition: consequences for spring snowmelt and near-surface air temperatures J. Geophys. Res. 112 G04S44
Sturm M, Douglass T, Racine C and Liston G E 2005a Changing snow and shrub conditions affect albedo with global implications J. Geophys. Res.—Biogeosci. 110 G01004
Sturm M, Mcfadden J P, Liston G E, Chapin F S, Racine C H and Holmgren J 2001a Snow-shrub interactions in Arctic tundra: a hypothesis with climatic implications J. Clim. 14 336–44
Sturm M, Racine C and Tape K 2001b Climate change: increasing shrub abundance in the Arctic Nature 411 546–7
Sturm M, Schmelj M, Michaelson G, Welker J M, Oberbauer S F, Liston G E, Fahnestock J and Romanovsky V E 2005b Winter biological processes could help convert arctic tundra to shrubland Bioscience 55 17–26
Tape K, Sturm M and Racine C 2006 The evidence for shrub expansion in Northern Alaska and the Pan-Arctic Glob. Change Biol. 12 686–702
Théau J and Duguay C R 2004 Lichen mapping in the summer range of the George River caribou herd using Landsat TM imagery Can. J. Remote Sens. 30 867–81
Van Wijk M T et al 2003 Long-term ecosystem level experiments at Toolik Lake, Alaska, and at Abisko, Northern Sweden: generalizations and differences in ecosystem and plant type responses to global change Glob. Change Biol. 10 105–23
Verbyla D 2008 The greening and browning of Alaska based on 1982–2003 satellite data Glob. Ecol. Biogeogr. 17 547–55
Wahren C H A, Walker M D and Bret-Harte M S 2005 Vegetation responses in Alaskan arctic tundra after 8 yr of a summer warming and winter snow manipulation experiment Glob. Change Biol. 11 537–52
Walker M D et al 2006 Plant community responses to experimental warming across the tundra biome Proc. Natl Acad. Sci. USA 103 1342–6