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Recent Shrub Proliferation in the Mackenzie Delta Uplands and Microclimatic Implications

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Abstract

Local observations, repeat photos, and broad-scale remote sensing suggest that tall shrubs are becoming an increasingly dominant component of Low Arctic ecosystems. This shift has the potential to alter the surface energy balance through changes to the surface albedo, snow accumulation and melt, and ground thermal regimes. However, to date there have been few quantitative estimates of the rate of tall shrub expansion. We used soft copy stereo visualization of air photos to map fine-scale changes in tall shrub tundra and green alder density in the upland tundra north of Inuvik, NT between 1972 and 2004. We also used 2004 photos to map tall shrub tundra in areas affected by fires that occurred between 1960 and 1968. To assess the potential impact of vegetation change on microclimate, we used pyranometers to measure albedo and net solar radiation, thermistors attached to data loggers to record ground temperatures, and field surveys to record winter snow conditions in three common vegetation types. Fine-scale mapping shows that green alder stem density has increased by 68% (±24.1) since 1972. Average tall shrub tundra cover has also increased by 15% (±3.6) since 1972. Historical tundra fires had the highest proportion of tall shrub cover of all areas mapped using 2004 photos, ranging from 92 to 99%. Based on these results, we suggest that predicted increases in the size and frequency of tundra fire are likely to drive rapid shrub proliferation in the Low Arctic. Shrub-dominated sites have decreased albedo, increased net solar radiation, deeper snow pack, and elevated near-surface ground temperatures, indicating that continued increases in shrub cover will affect regional climate, hydrology, permafrost temperatures, and terrain stability.

Key words: global change; shrub tundra; climate warming; Low Arctic; willow; green alder; microclimate; fire.

Introduction

Several lines of evidence indicate that tall shrubs are becoming more abundant across the Low Arctic. In Alaska, the analysis of repeat photos (1945–2002) shows that increases in tall shrub cover have been widespread (Tape and others 2006). Local observations in other regions combined with broad-scale remote sensing studies suggest that similar changes have taken place across the northern hemisphere (Beck and Goetz 2011; Forbes and others 2010; Fraser and others 2011; Jia and others 2003; Silapaswan and others 2001; Stow and others 2004;

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Thorpe and others 2002). In the Northwest Territories and Alaska, anecdotal observations and population age structure data suggest that the proliferation of the nitrogen fixing species green alder [*Alnus viridis* subsp. *fruticosa* (Ruprecht) Nyman] has contributed significantly to the observed vegetation changes (Lantz and others 2010a; Tape and others 2006).

Despite a growing consensus that shrub encroachment is occurring across the Low Arctic there have been relatively few quantitative studies to estimate the rate and pattern of change (Tape and others 2006). The expansion of tall shrub tundra has the potential to influence a number of abiotic parameters (albedo, heat flux, and snow pack depth and duration), which can affect the near-surface ground thermal regime, active layer thickness, terrain and infrastructure stability and regional climate (Chapin and others 2005; Epstein and others 2004a, b; Kokelj and others 2009, 2010; Loranty and others 2011; Sturm and others 2005). Regional estimates of the rate of shrub expansion and detailed investigations of the influence of shrub cover on microclimate and ground temperatures are needed to understand the potential impacts of this ecological change.

Changes in the abundance of tall shrubs have generally been attributed to recent warming trends (Forbes and others 2010; Tape and others 2006). However, the dominance of tall shrubs on thaw slumps (Lantz and others 2009), drained lake basins (Marsh and others 2009), pingos (Mackay and Burn 2011), tundra fires (Lantz and others 2010a), old seismic tracks (Kemper and Macdonald 2009a), and drilling mud sumps (Johnstone and Kokelj 2008) suggests that increases in natural and anthropogenic disturbances may be contributing to their spread. Because the magnitude and frequency of disturbance is likely to continue increasing in northern regions (Forbes and others 2001; Gillett and others 2004; Holroyd and Retzer 2005; Jorgenson and others 2001; Lantz and Kokelj 2008) understanding its landscape-scale impact on vegetation development is critical to predicting the rate and nature of ecological change in the Low Arctic.

In this article, we use aerial photographs to quantify recent changes (1972–2004) in tall shrub cover and green alder density in the upland tundra east of the Mackenzie Delta. To examine the rate of shrub proliferation associated with tundra fires, we used air photos to compare tall shrub cover tundra between 1972 and 2004 at undisturbed tundra sites and at sites that were burned in the 1960s. To assess the impact of changes in shrub cover on microclimatic conditions we also compared albedo, net solar radiation, end of winter snow cover, and shallow ground temperatures at three sites in the study area: (1) a dwarf shrub tundra site, (2) an open canopy tall shrub tundra site, and (3) a dense canopy tall shrub tundra site.

Methods

Study Area

Our study area in northwestern Canada is located in the upland tundra to the east of the Mackenzie River delta (Figure 1). This area is characterized by

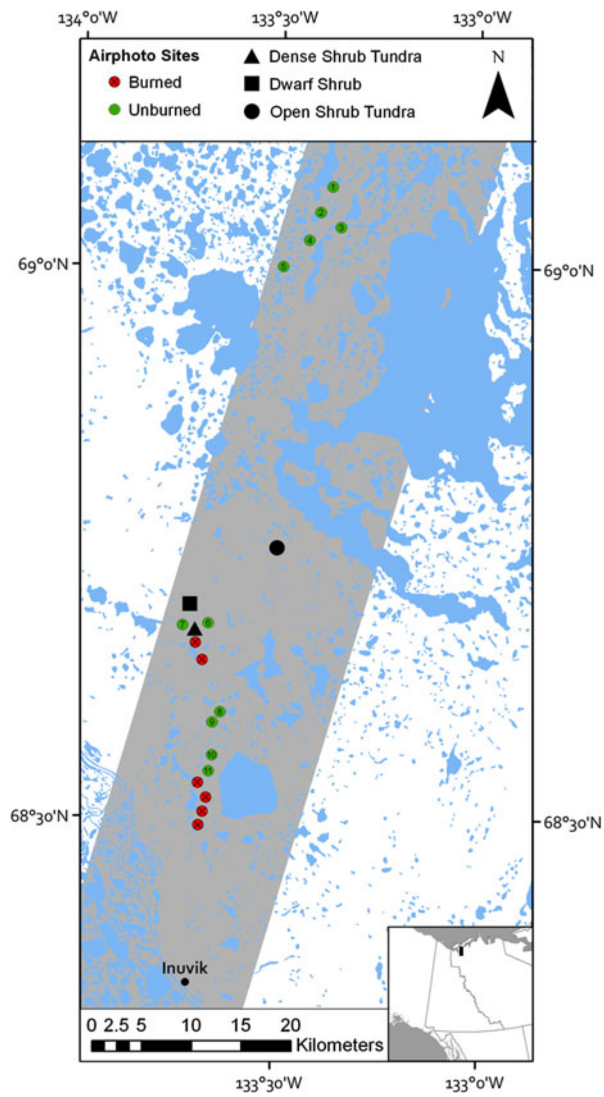

Figure 1. Map of the study area showing the location of photo plots and microclimate sites. The labels on the unburned sites correspond to the site numbers in Table 1. The *shaded area* of the main map shows the approximate area covered by the high-resolution (1972) photos. *Inset map* shows the position of the study area in northwestern North America.

rolling hills and thousands of small lakes (Burn and Kokelj 2009). Fine grained tills with hummocky microtopography constitute the dominant terrain type (Aylsworth and others 2000; Mackay 1963; Soil Landscapes of Canada Working Group 2007). Peatlands are also common in lacustrine basins, which developed following the drainage of lakes throughout the Holocene (Mackay 1992; Marsh and others 2009). During summer, there is a linear temperature gradient across the study area, where mean air temperatures decrease from 9.4°C (south) to 6.8°C (north) (Lantz and others 2010a). Air and ground temperatures in the study region have increased in the last three decades (Burn and Kokelj 2009) and have likely contributed to observed increases in disturbances associated with ground ice thaw (Lantz and Kokelj 2008). The spatial extent of anthropogenic disturbance is also anticipated to grow as exploration and development intensify in the region (Holroyd and Retzer 2005; Johnstone and Kokelj 2008; Kemper and Macdonald 2009b).

The vegetation in the study area is primarily a mosaic of tall shrub tundra and erect dwarf shrub tundra. Tall shrub tundra is dominated by willows (*Salix pulchra* Cham. and *S. glauca* L.), scrub birch (*Betula glandulosa* Michx), and green alder. Erect dwarf shrub tundra is characterized by a mix of shrubs and herbaceous vegetation typically shorter than 40 cm [*Ledum decumbens* (Ait) Lodd., *Vaccinium vitis-idaea* L., *Arctostaphylos rubra* (Rehd. & Wils.) Fern, *Rubus chamaemorus* L.] and sedges (*Eriophorum vaginatum* L., *Kobresia hyperborea* Porsild). For simplicity, we refer to these zones as the shrub tundra (tall shrub tundra) and dwarf shrub tundra (erect dwarf shrub tundra).

Stereomodels

To examine changes in vegetation cover, we randomly selected plots from a 3,000 km^2 area covered by a high-resolution air photo survey conducted in 1972. These images are available through the National Airphoto Library of Canada (Rolls: A22936, A22957–A22961). Plots were randomized by using Hawths Analysis Tools for ARCGIS (V 3.2.7) to select 200 points at least 2 km apart. From these, we chose the first 12 points that did not fall within large water bodies. Subsequently, one of these plots was discarded because of poor image quality. These sites are representative of the upland tundra that is common across the Mackenzie Delta region (Lantz and others 2010b). The same procedure was used to select six plots in areas affected by tundra fire (Wein 1975). Plots were 500 × 500 m and were located between 68°26′N and 69°06′N (Figure 1).

To create soft copy stereomodels that covered plots in each time period, we used the DVP photogrammetry suite (DVP-GS, Québec, Canada). Color photos from 2004 were scanned from negatives at 1,814 dpi (1 pixel = 0.41 m), and 1972 grayscale photos were scanned from prints at 1,200 dpi (1 pixel = 0.25 m). Absolute orientation (georeferencing) of these models was performed in DVP using existing orthophotos and a 30 m digital elevation model (Duchesne and others 2007). Mean standard error of all absolute orientations was 0.38 m, and was less than 0.5 m for all individual models. Three-dimensional models were displayed on-screen using the DVP photogrammetry suite and a PLANAR monitor system (DVP-GS, Québec, Canada).

Mapping the Dominant Vegetation

To estimate changes in the dominant vegetation cover between 1972 and 2004, shrub tundra and dwarf shrub tundra were mapped in all plots for both years. On-screen delineation of different vegetation types was completed while viewing stereomodels. Three-dimensional models were used so that differences in vegetation height and image tone and texture could all be used to distinguish among shrub tundra, dwarf shrub tundra, and unvegetated terrain. All vegetation patches larger than 2 m^2 were outlined and classified by a single photo interpreter. The absolute change in shrub tundra was calculated by subtracting shrub tundra cover in 1972 from the cover in 2004. The relative change in cover was calculated as: $(\%cover_{2004} - \%cover_{1972}) \div \%cover_{1972} * 100$.
To map 2004 shrub tundra cover in areas affected by tundra fire (1960–1968: Wein 1975), we used the same methods to map six burned plots. Because high-resolution air photos preceding each burn were not available, we estimated changes in cover by assuming that pre-fire shrub cover was similar to 1972 levels at nearby sites. A qualitative visual examination of coarse resolution (1:42,000) air photos from 1950 confirms that prior to burning these sites had shrub cover similar to unburned sites in the same area. Based on this assumption, we calculated change at burned sites as follows: $(\%cover_{2004} - \%cover_{1972:\ mean})$, where $cover_{1972:\ mean}$ is the average of sites in the southern portion of the study area (sites 6–11: Table 1). To compare our estimates of percent change on burned sites with the changes on unburned sites, we calculated annual rates by dividing by the number of years since each burn, and in the case of unburned sites, the number of years between photos.

Table 1. Shrub Tundra Cover Mapped at Sites in the Mackenzie Delta Uplands Using 1972 and 2004 Air Photos

Site #	Latitude	Longitude	1972 Cover (%)	2004 Cover (%)	Absolute Δ (%)	Relative Δ (%)
3	69.05	133.36	56.3	65.6	9.2	16.4
2	69.07	133.40	68.7	83.9	15.2	22.2
1	69.03	133.37	58.2	72.4	14.2	24.3
4	69.03	133.43	71.4	94.3	23.0	32.2
5	69.01	133.50	58.7	80.6	21.9	36.5
6	68.60	133.64	74.7	89.4	14.8	19.7
7	68.59	133.65	35.5	61.4	25.9	73.0
11	68.68	133.70	16.5	28.4	11.9	71.9
10	68.65	133.73	18.7	38.7	20.0	106.9
9	68.56	133.67	89.8	98.5	8.7	9.7
8	68.54	133.66	86.0	95.2	9.2	10.7
Regional mean			57.7	73.5	15.8	38.5

The area mapped at all sites was 25 ha. Also shown are the absolute and relative changes in shrub tundra cover between 1972 and 2004.

Green Alder Density

We also used stereomodels to count individual alders and estimate their density. Green alder stems typically radiate outwards from a central root crown creating circular growth form. Combined with alder's dark foliage, this growth form makes it possible to distinguish individual alders from the surrounding vegetation on fine-scale air photos (Figure 2). Ground surveys (Lantz and others 2010a, 2009) confirm that the vast majority of alder crowns visible on air photos consist of structurally single individuals. At the high alder densities characteristic of 30- to 50-year-old burns scars, where alders often form a continuous canopy, individuals could not be distinguished. Consequently, our estimates of alder density were confined to unburned portions of the study area. The absolute and relative changes in alder density were calculated using the rationale described in the previous section.

Map Validation

To validate the procedure used to create maps of alder cover and dominant vegetation, we randomly selected points in each cover type and year. These points were overlaid on the stereo images from both sample years (1972, 2004) and classified by a second observer. For maps of dominant vegetation,

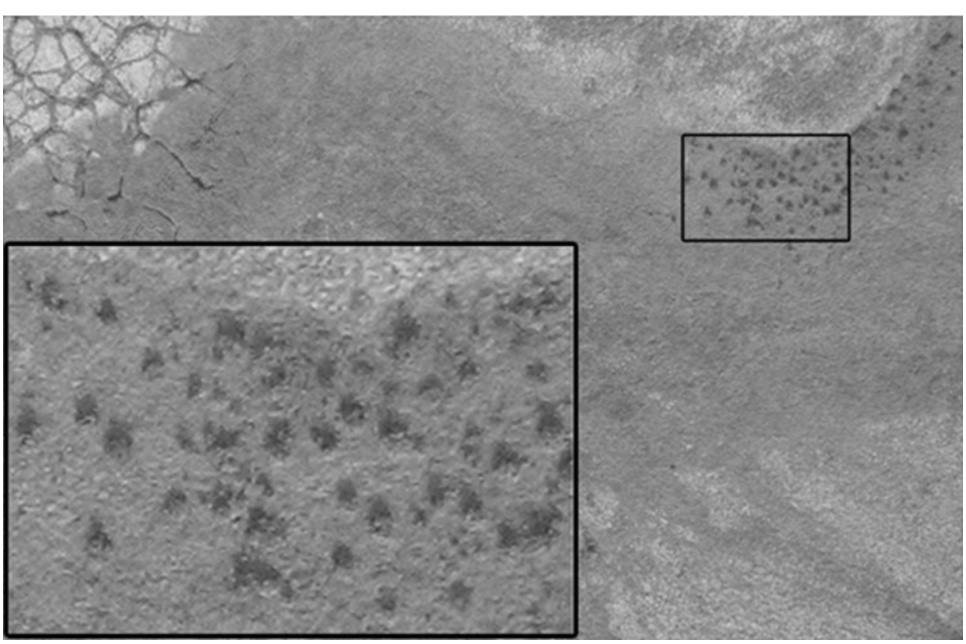

Figure 2. Area of the Mackenzie Delta uplands dominated by tall shrub tundra (*gray*) with smaller areas of dwarf shrub tundra (*white*). *Inset image* at the *bottom left* is an enlargement of the green alder patch at the *top right*. The *inset area* is ~60 × 45 m.

a total of 1,400 unique points (700 per time period) were examined and classified as either shrub tundra or dwarf shrub tundra. We used a similar approach to evaluate the alder maps. In each time period, we selected 125 points that were mapped as alder, and 125 that were not mapped as alder. These 500 points (250 per time period) were assigned a random order and overlaid on the stereomodels for the appropriate time period, then classified by an independent observer.

Statistical Analysis

To examine the difference in shrub tundra cover and alder density between 1972 and 2004, we used R to perform within-subject *t* tests (R Development Core Team 2012). To compare shrub tundra cover in 2004 on burned sites with cover at unburned sites in both time periods, we performed unpaired *t* tests that assumed unequal variance.

Microclimate

To examine differences in microclimate at sites with different shrub height and density, we selected three sites in the Trail Valley Creek (TVC) research watershed (Figure 1). These sites, described in greater detail by Marsh and others (2010) spanned the range of shrub densities across the study area (Lantz and others 2010b). They included: (1) a dwarf shrub tundra site where all vegetation was less than 40-cm high, (2) an open canopy shrub tundra site where tall shrubs ranged in height from 50- to 150-cm high (open shrub tundra), and (3) a tundra site that burned in about 1965 and is dominated by a dense canopy of tall shrubs, typically greater than 150-cm high (dense shrub tundra).

During the spring and summer of 2003, incoming and outgoing solar radiation was measured at a single location at each site above the highest vegetation, using a combination of calibrated Epply B&W and REBS PDS7.1 pyranometers. Albedo was determined using data from within 1 h of noon each day, and net solar radiation was determined at half hour intervals. Near-surface ground temperatures were measured during 2009/10 at each site using thermistors placed 10 cm below the ground surface. All radiation and soil temperature measurements were logged every 30 min using Campbell Scientific CR23x data loggers.

Prior to the start of snowmelt in 2003, 2004, and 2005, snow surveys were conducted at the three study sites following Pomeroy and others (1993). Snow depth was measured every 5 m using a snow depth probe. Bulk snow density (kg/m^3) was measured using an ESC-30 gravimetric snow density sampler. This technique has an accuracy of approximately ±5% (Berezovskaya 2007).

Results

Changes in the Dominant Vegetation

Between 1972 and 2004, the upland terrain east of the Mackenzie River delta has experienced significant increases in shrub tundra cover. Air photo analysis indicates that the average absolute increase in tall shrub cover was 15.8% (Figure 3; Table 1) and all photo pairs showed higher shrub tundra cover in 2004 (Table 1). Averaged over the 32-year interval between photos this represents an increase of 0.45% per year. The relative and absolute changes in individual plots ranged from 9.7 to 106.9% and 8.7 to 25.9%, respectively (Table 1) and the mean relative increase in shrub tundra cover was 38.5% (Table 1). Low altitude aerial photography and plot-based sampling indicate that these changes can be attributed to the increasing dominance of shrubs exceeding 40 cm in height (Lantz and others 2010a, b, 2009). Tall shrub cover is common in the study area and all of the observed changes occurred within close proximity to existing shrub patches (Figure 4). A within sample *t* test showed that the mean difference in shrub cover between 2004 and 1972 was significantly greater than zero ($t_{10} = 8.7091$, $p < 0.0001$).

The percent cover of shrub tundra on burned sites in 2004 was significantly greater than shrub tundra cover on unburned sites in both 1972 and 2004 ($t_{10} = 5.0$, $p < 0.001$; $t_{10} = 3.13$, $p < 0.01$). Our estimates of the percent change in shrub cover following fire suggest that shrub cover at these sites increased between 38.8 and 45.4%. The average

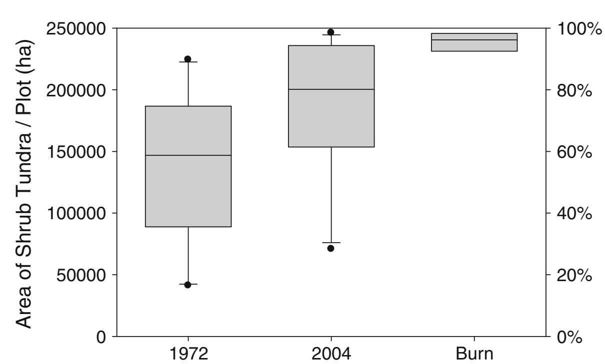

Figure 3. *Box* and *whisker plot* showing median shrub tundra cover in the Mackenzie Delta uplands in 1972 and 2004. Areas impacted by tundra fires were also mapped using 2004 images. *Whiskers* show the 10th and 90th percentiles, and the points show outliers.

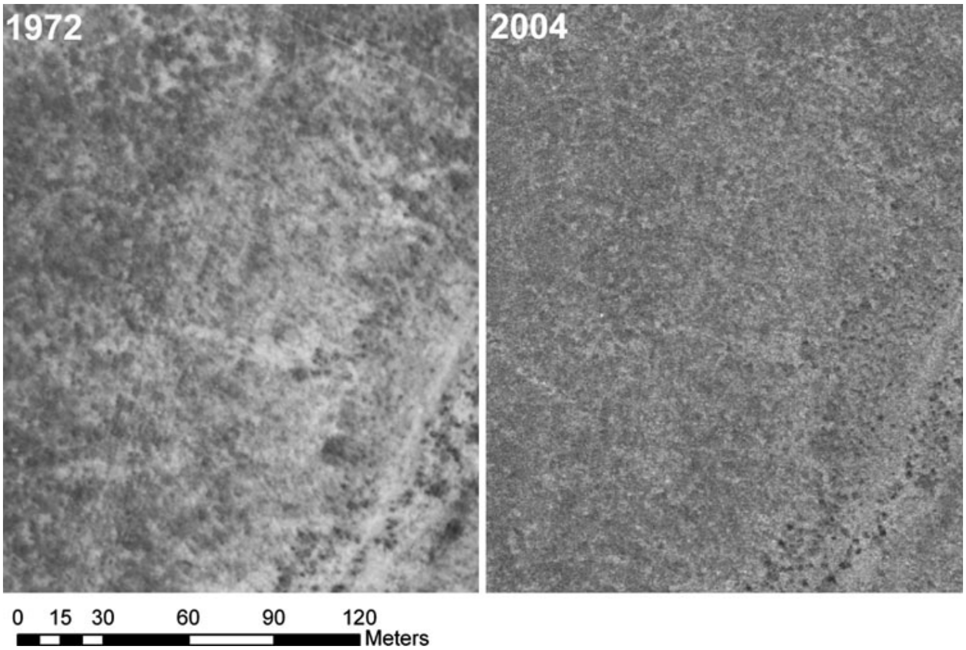

Figure 4. Area of upland tundra east of the Mackenzie Delta in 1972 and 2004 showing shrub tundra expansion typically encountered at undisturbed sites.

annual rate of change following fire was 1.1%, approximately double the annual rate of change observed on unburned sites. The difference between mean shrub tundra cover on burned sites in 2004 and mean cover on unburned sites in 1972 was also more than double the increase in cover on undisturbed sites over the same time period (Figure 3).

Map validations confirm that user error was small compared to the magnitude of the observed changes in vegetation. The percent agreement between different interpretations of the 1972 images was 94% for maps of the dominant vegetation and 96% for maps of alder density. The agreement between maps based on the 2004 images was 94% for maps of both dominant vegetation and alder density.

Changes in Green Alder Density

Like shrub tundra cover, the density of green alder in the study area has also increased during the last three decades. Between 1972 and 2004, mean alder density increased from 53,211 to 89,451 individuals/ha (Figure 5). Increases on individual plots ranged from 520 to 101,480 individuals/ha, with all individual photo pairs showing increases. The average relative increase was 68.1%, or about 1.6% per year (Table 2). Increases in alder density occurred primarily via the expansion of existing patches (Figure 6). A within sample *t* test showed that the mean difference in patch density between 2006 and 1972 was significantly greater than zero (t_{10} = 3.688, p = 0.003). Accuracy assessments confirm that classification error was small compared to the magnitude of the observed changes in alder density.

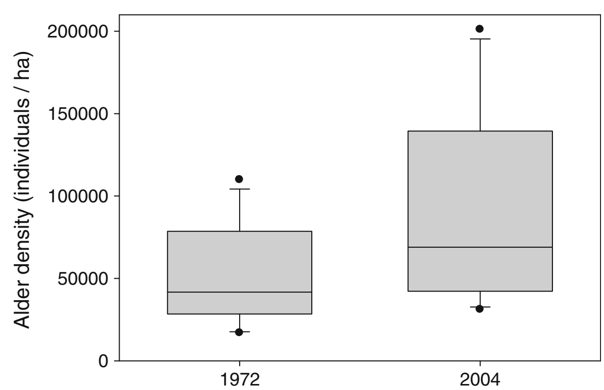

Figure 5. *Box* and *whisker plot* showing median green alder density in the Mackenzie Delta uplands in 1972 and 2004. *Whiskers* show the 10th and 90th percentiles, and the points show outliers.

Microclimate

To assess the potential impact of vegetation change on microclimatic parameters, we compared albedo, net solar radiation, near-surface ground temperatures, and end of winter snow conditions at: (1) a dwarf shrub tundra site, (2) an open canopy tall shrub tundra site, and (3) a dense canopy tall shrub tundra site. All three sites showed an abrupt decrease in albedo during the snow melt period (Figure 7A). The decrease in albedo occurred first at the dense shrub tundra site as tall shrubs bent over and buried by winter snow cover emerged at

Table 2. Green Alder Density (Individuals per Hectare) Mapped at Sites in the Mackenzie Delta Uplands Using 1972 and 2004 Air Photos

Site#	Latitude	Longitude	1972 (#/ha)	2004 (#/ha)	Absolute Δ (#/ha)	Relative Δ (%)
3	69.05	133.36	41,040	71,080	30,040	73.2
2	69.07	133.40	16,920	31,080	14,160	83.7
1	69.03	133.37	41,720	42,240	520	1.2
4	69.03	133.43	66,720	68,960	2,240	3.4
5	69.01	133.50	20,520	39,000	18,480	90.1
6	68.60	133.64	78,600	139,440	60,840	77.4
7	68.59	133.65	109,840	201,000	91,160	83.0
11	68.68	133.70	28,400	43,840	15,440	54.4
10	68.65	133.73	28,520	55,560	27,040	94.8
9	68.56	133.67	81,880	119,120	37,240	45.5
8	68.54	133.66	71,160	172,640	101,480	142.6
Regional mean			53,210.9	89,450.9	36,240.0	68.1

Also shown are the absolute and relative changes in alder density between 1972 and 2004.

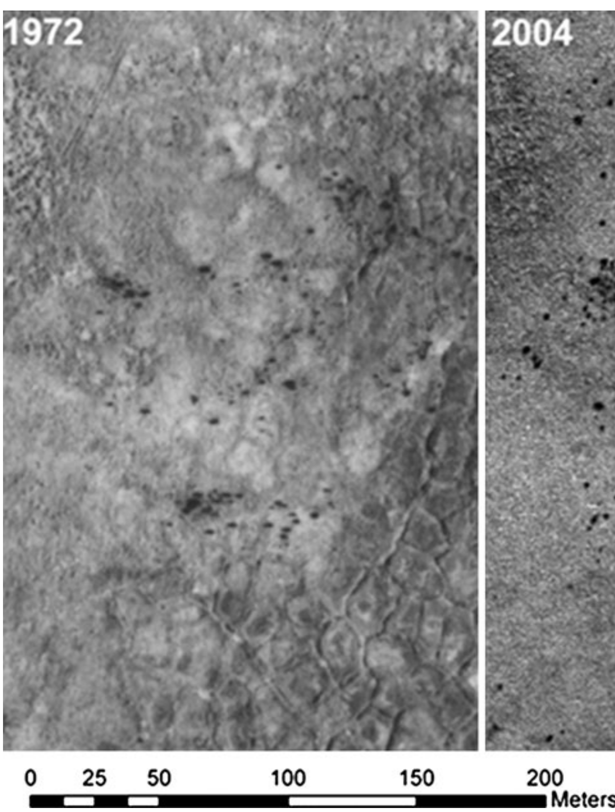

Figure 6. Extensive green alder proliferation in the Mackenzie Delta uplands. The number of individual alders in this image increased from 72 to 321 between 1972 and 2004. Increased abundance of alder generally occurred in the vicinity of existing shrubs.

the onset of snowmelt. Following snowmelt, albedo was highest in the dwarf shrub community, intermediate in the open shrub tundra site, and lowest in the dense shrub tundra (Figure 7A; Table 3). Net solar radiation showed the opposite pattern, with the highest net solar radiation at the dense shrub site, especially early in the melt period, intermediate in the open shrub site, and lowest in the dwarf shrub. This pattern was consistent throughout the growing season, but the magnitude of difference was smaller in the late summer (Figure 7B; Table 3).

Near-surface ground temperatures were consistently colder at the dwarf shrub site compared with both open and dense tall shrub tundra sites (Figure 8). Differences in ground temperature between dense and open shrub sites were more variable. In late summer and early winter, the dense shrub site was several degrees colder than the open shrub tundra site. Snow likely continued to accumulate

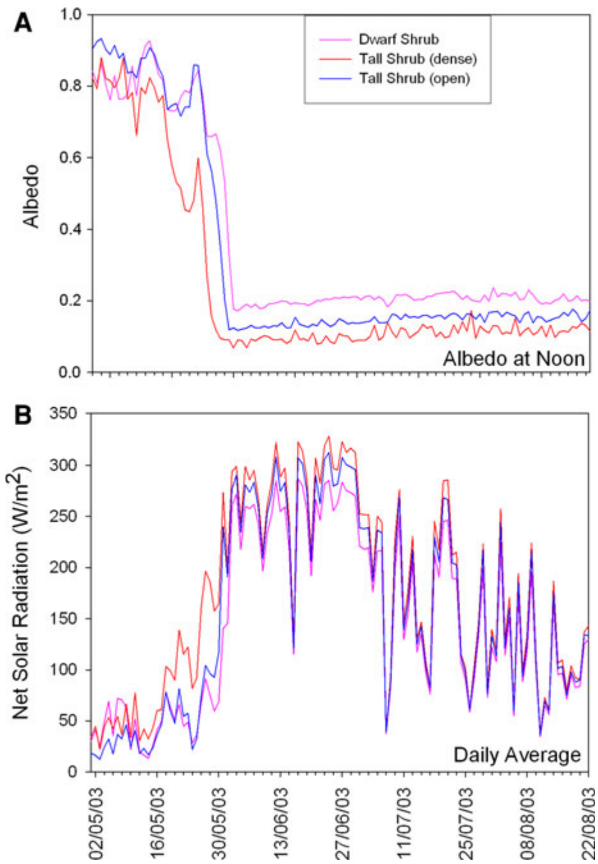

Figure 7. Microclimatic variables at shrub sites: **A** albedo at noon and **B** average daily net solar radiation.

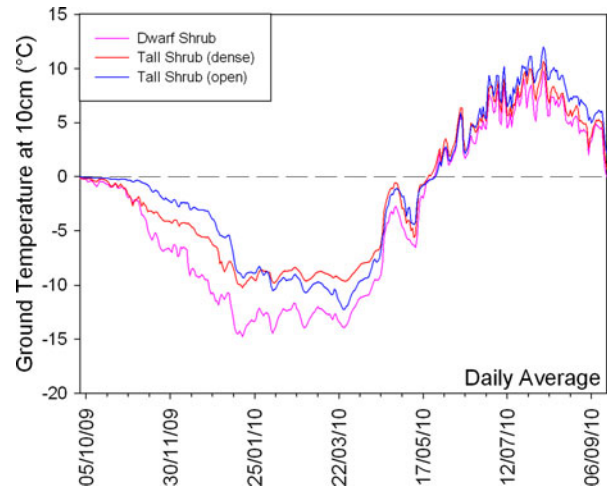

Figure 8. Near-surface ground temperatures (10 cm) at shrub microclimate sites. Data plotted are daily means.

via wind redistribution in the tall shrubs throughout the winter, dampening the late winter ground cooling in comparison with the dwarf shrub site. The lower snow cover promoted continued ground cooling at the open shrub site, resulting in temperatures several degrees colder than at the dense shrub site. Near-surface ground temperatures at the open shrub site remained colder than at the dense shrub tundra site until early July (Figure 8). Late winter snow pack depth and density were similar at the dwarf shrub and the open shrub tundra site, but were deeper at the dense shrub tundra site (Table 4).

Discussion

Vegetation Change

Fine-scale mapping of historical photographs shows that tall shrub cover and alder density in the tundra east of the Mackenzie Delta has increased significantly over the past three decades. These observations confirm anecdotal reports of shrub encroachment in several regions of the Arctic (Borderlands 2006, 2007; Mackay and Burn 2011; Thorpe and others 2002) and are consistent with existing quantitative studies (Tape and others 2006 Tremblay 2010). The dominant tall shrubs in our study area that are responsible for these changes

Table 3. Monthly Averages of Albedo and Net Solar Radiation at the Shrub Microclimate Sites

	Dwarf shrub	Tall shrub (open)	Tall shrub (dense)
Albedo at noon			
May	0.78 ± 0.03	0.78 ± 0.0061	0.61 ± 0.087
June	0.20 ± 0.010	0.13 ± 0.003	0.09 ± 0.004
July	0.21 ± 0.004	0.15 ± 0.003	0.11 ± 0.007
August	0.21 ± 0.004	0.16 ± 0.004	0.12 ± 0.005
Net solar radiation (W/m^2)			
May	52.1 ± 9.2	52.4 ± 15.9	89.0 ± 21.3
June	248.2 ± 15.5	268.9 ± 15.1	281.5 ± 16.1
July	157.9 ± 22.0	169.9 ± 24.2	178.4 ± 25.7
August	110.9 ± 18.3	117.8 ± 21.7	123.6 ± 23.0

Values are means and their 95% confidence intervals.

Table 4. End of Winter Snow Depth, Density, and Snow Water Equivalent at Microclimate Sites (Dwarf Shrub, Dense Shrub Tundra, and Open Shrub Tundra) in 2003, 2004, and 2005

Vegetation type	Year/mean	Snow depth (cm)	Snow density (kg/m^3)	Snow water equivalent (mm)
Dwarf shrub	2003	43.2	228	98
	2004	44.6	214	95
	2005	39.6	212	84
	Mean	42.5	218	92
Shrub tundra (open)	2003	43.1	242	104
	2004	50.0	244	122
	2005	37.1	236	88
	Mean	43.4	241	105
Shrub tundra (dense)	2003	55.6	186	103
	2004	69.4	218	151
	2005	72.7	221	160
	Mean	65.9	208	140

include green alder, dwarf birch (*B. glandulosa* Michx.), and willows (primarily *S. glauca* L. and *S. pulchra* Cham.). A similar suite of species have been implicated in shrub increases observed in Alaska (Tape and others 2006).

Increases in green alder stem density observed on air photos confirm that this species has contributed to regional shrub encroachment. These results are supported by ground-based investigations of alder population dynamics. Field sampling in 2004 and 2005 showed that alder populations in the mapped area exhibit high recruitment and are dominated by stems originating in the last two decades (Lantz and others 2010a). The increasing dominance of tall shrub cover (Figure 3) also suggests that recruitment is increasing in other deciduous shrubs (willow and dwarf birch) common in the region. Because these species cannot be enumerated using air photos, additional field investigations are required to confirm this.

Our observation of a 38% relative increase in tall shrub cover is similar to those obtained in two other studies using fine-scale air photos. Investigations (Tape and others 2006) using historic (1945–1953) and modern (1999–2002) oblique air photos indicated an average relative increase in tall shrub cover of 33% on upland slopes across Northern Alaska. Tremblay (2010), comparing vertical photographs from 1964 and 2003, reported a relative increase in continuous and discontinuous shrub cover of approximately 29% in the area surrounding the eastern Arctic community of Kangiqsualujjuaq. Taken together these observations confirm that shrub encroachment is a phenomenon that is occurring across the North American Arctic. Evidence of increased alder recruitment in the last few decades (Lantz and others 2010a), recent (1982 and 2008) increases in northern hemisphere NDVI (Bhatt and others 2010; Pouliot and others 2009) and increases in shrub cover of similar magnitude derived from air photos covering 30-, 40-, and 50 year intervals (Tape and others 2006; Tremblay 2010) raises the possibility that shrub encroachment has occurred primarily in the last three decades.

Causes of this Change

Regional Warming

There is a growing body of evidence suggesting that temperature has a strong influence on shrub growth and recruitment. A number of recently compiled shrub ring chronologies show significant correlations between ring width and air temperature (Forbes and others 2010; Blok and others 2011a). Field investigations of green alder suggest that recent recruitment in alder is the result of temperature-driven increases in seed viability (Lantz and others 2010a). Plot-based warming experiments from across the Arctic also confirm that deciduous shrubs respond to increases in air temperature on short-time scales (Elmendorf and others 2012; Walker and others 2006). Consequently, we expected the rate of shrub proliferation to decrease at the colder sites in the northern part of the study area. The observation that the magnitude of vegetation change was similar at all sites indicates that the difference in summer temperature (~1.6°C between 68.5°N and 69.1°N: Lantz and others 2010a) does not strongly limit shrub populations at these sites. However, it is possible that more northerly, Arctic populations are temperature limited. North of the area mapped in this study continued latitudinal decreases in summer temperature correspond with a decline in broad-scale tall shrub cover of 30% over approximately

100 km (Lantz and others 2010b). To test the hypothesis that this change in shrub cover is the product of temperature limitation of recruitment, additional change detection studies should be conducted in this area. If latitudinal changes in shrub cover are the product of temperature limitation of recruitment and survival (Lantz and others 2010a), the relative rate of shrub expansion should decline at higher latitudes, where warming has not yet exceeded critical thresholds.

Disturbance

Our mapping also demonstrates that shrub expansion can proceed extremely rapidly following tundra fire. Estimates show that the annual rate of shrub expansion at burned sites is more than double the rate of increase at unburned sites (Figure 3). These results are consistent with plot-scale studies that examined the impact of tundra fire on plant communities and shrub growth (Lantz and others 2010a; Racine and others 2004). Deciduous shrubs are well adapted to take advantage of the new seedbeds and favorable abiotic conditions created by fire (de Groot and Wein 2004; Gilbert and Payette 1982; Kokelj and Burn 2003; Racine and others 2004; Smithwick and others 2005; Zasada and others 1983). Rapid increases in shrub cover following fire likely occur because once established, deciduous shrubs are very responsive to both the direct and indirect effects of increasing temperatures (Bret-Harte and others 2002; Elmendorf and others 2012; Walker and others 2006). The percent cover of shrub tundra on the fire scars we mapped (92–98%) is significantly higher than on undisturbed sites across the shrub tundra ecotone (Lantz and others 2010b). This suggests that anticipated increases in the size and frequency of tundra fire (Jones and others 2009; Hu and others 2010) will drive a landscape transformation similar to the mid Holocene increases in shrub cover that were catalyzed by more frequent fire (Higuera and others 2008).

Plot-based investigations of vegetation development on thaw slumps, drained lakes, drilling mud sumps, and areas impacted by seismic exploration (Johnstone and Kokelj 2008; Kemper and Macdonald 2009a; Lantz and others 2010a, 2009; Mackay and Burn 2002) suggest that other forms of disturbance can also facilitate increased shrub dominance. Like fires, the increased nutrient availability and ameliorated soil microclimate associated with permafrost degradation favor the growth and establishment of tall shrubs (Johnstone and Kokelj 2008; Kemper and Macdonald 2009a; Lantz and others 2009). Because both anthropogenic and natural disturbances have increased in the Arctic in recent years (Lantz and Kokelj 2008; Forbes and others 2001), it is possible that a portion of the recent vegetation changes inferred from satellite imagery (Bhatt and others 2010; Pouliot and others 2009) has been driven by these perturbations. Additional research is required to estimate the contribution that tundra disturbance has had on recent Arctic vegetation change.

Implications for Microclimate and Permafrost Temperatures

Increases in shrub cover are widely anticipated to drive broad-scale decreases in albedo and increased regional heating (Chapin and others 2005; McGuire and others 2006). Our field observations of decreased albedo and increased radiative heat transfer at two shrub-dominated sites (Figure 7) are consistent with these predictions, but indicate that the magnitude of feedbacks between vegetation change and energy flux will depend on the density of expanding shrub populations. To date, estimates of the magnitude of microclimate feedbacks have treated shrub tundra as uniform (Blok and others 2011b; Lawrence and Swenson 2011; Loranty and others 2011; Sturm and others 2005). Our fieldwork showing intermediate values of albedo and net solar radiation at the open tall shrub tundra indicates that regional models of these parameters should account for differences in the structure of shrub tundra. This is consistent with the findings of Loranty and others (2011). Our field observations at three sites also demonstrate that fire and other disturbances, which can transform dwarf shrub tundra into dense stands of tall shrubs (Lantz and others 2010a, 2009), are likely to have a stronger influence on microclimatic parameters than smaller increases in shrub density at open shrub tundra sites.

Sturm and others (2001, 2005) predicted that deeper snow pack resulting from shrub expansion will increase ground temperatures. Our field observations of increased snowpack and ground temperatures at two shrub-dominated sites are consistent with this hypothesis, but emphasize that the magnitude and direction of the shrub-snow feedback can depend on the height and density of shrub cover. At our dense shrub tundra site, deep snow pack reduced winter cooling and kept winter ground temperatures higher than at the open shrub and dwarf shrub tundra sites. However, higher ground temperatures in summer and early winter at the open shrub versus dense shrub tundra site suggest that at high densities the positive feedback between shrub cover and ground temperatures can be offset by summer shading (Sturm and others 2005). This observation is also consistent with experimental removals of birch cover, which resulted in active layer deepening (Blok and others 2010). Additional research, replicated at multiple sites and focused on identifying density thresholds that result in large changes in abiotic parameters, is required to inform accurate models of Arctic ecosystem processes (Nelson and others 1997; Oechel and others 2000; Reeburgh and others 1998; Schneider and others 2009).

Conclusions

The vegetation in the upland tundra east of the Mackenzie Delta has changed dramatically in the last three decades with relative increases in tall shrub cover and alder density of 68.1 and 35%, respectively. These changes have important implications for regional climate (Chapin and others 2005; Epstein and others 2004a; McGuire and others 2006), hydrology (Endrizzi and Marsh 2010; Marsh and others 2010), permafrost, terrain, and infrastructure stability (Kokelj and others 2009, 2010; Palmer and others 2012), and wildlife habitat and abundance of traditional foods (Mansson and others 2007; Storeheier and others 2002; Walsh and others 1997). Fine-scale anecdotal observations and broad-scale investigations using NDVI suggest that changes in vegetation have been widespread (Bhatt and others 2010; Mackay and Burn 2011). However, additional investigations, at intermediate scales (4,000–40,000 km^2) and systematic plot-based monitoring are required to better characterize the rates and nature of changes in shrub cover across the Low Arctic. To improve our understanding of the causes of shrub proliferation, research exploring the relative impacts of increased temperature and more widespread tundra disturbances is also needed.

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