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Spatial Heterogeneity in the Shrub Tundra Ecotone in the Mackenzie Delta Region, Northwest Territories: Implications for Arctic Environmental Change

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ABSTRACT

Growing evidence suggests that plant communities in the Low Arctic are responding to recent increases in air temperature. Changes to vegetation, particularly shifts in the abundance of upright shrubs, can influence surface energy balance (albedo), sensible and latent heat flux (evapotranspiration), snow conditions, and the ground thermal regime. Understanding fine-scale variability in vegetation across the shrub tundra ecotone is therefore essential as a monitoring baseline. In this article, we use object-based classifications of airphotos to examine changes in vegetation characteristics (cover and patch size) across a latitudinal gradient in the Mackenzie Delta uplands. This area is frequently mapped as homogenous vegetation, but it exhibits fine-scale variability in cover and patch size. Our results show that the total area and size of individual patches of shrub tundra decrease with increasing latitude. The gradual nature of this transition and its correlation with latitudinal variation in temperature suggests that the position of the shrub ecotone will be sensitive to continued warming. The impacts of vegetation structure on ecological processes make improved understanding of this heterogeneity critical to biophysical models of Low Arctic ecosystems.

Key words: Low Arctic; object-oriented; object-based; climate change; airphotos; vegetation classification.

INTRODUCTION

The Arctic is often described as one of the major components in the Earth's cooling system. It plays a critical role in the global climate system by reflecting incoming solar radiation and by radiating energy gains transferred from the tropics (Chapin and others 2005; McGuire and others 2006). Northward temperature decreases across this biome are accompanied by changes in ecosystem properties including, community composition, vegetation structure, net primary productivity, heterotrophic respiration, carbon storage, albedo, and permafrost conditions (Chapin

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and others 2000; McGuire and others 2002; Thompson and others 2004; Euskirchen and others 2007; Burn and Kokelj 2009). Changes to Arctic vegetation such as increases in shrub abundance that may result from increasing temperature (Stafford and others 2000; Kaplan and others 2003; Hassol 2004; Johannessen and others 2004; Tape and others 2006; Notaro and others 2007) therefore have the potential to feedback to the global climate system (Chapin and others 2005; McGuire and others 2006).

Despite a range of classification schemes, broad-scale transitions in vegetation structure are similar throughout the Circum-Arctic (Bliss and Matveyeva 1992; Walker 2000; Epstein and others 2004a). The transition between the southernmost portion of the Low Arctic and the northern Boreal Forest is frequently referred to as the forest tundra (Payette and others 2001; Sirois 1992). This ecotone consists of a mosaic of forest and woodland interspersed with shrub tundra and wetlands. Moving northward, trees (typically *Picea*, *Larix*, *Pinus*, or *Betula*) give way to tundra dominated by shrubs that are 40–400-cm tall. This tall shrub zone is characterized by willows (*Salix*), alder (*Alnus*), dwarf birches (*Betula*), and a mix of ericaceous shrubs (*Ledum*, *Vaccinium*, and *Arctostaphylos*). Elsewhere, this zone has been referred to as the low shrub subzone (Walker and others 2002). At higher latitudes terrain dominated by tall shrubs is replaced by erect dwarf shrub tundra. Vegetation in this physiognomic unit is less than 40-cm tall and is characterized by dwarf shrubs (*Betula*, *Salix*, *Vaccinium*, *Ledum*, *Empetrum*, and *Dryas*) and sedges (*Carex* and *Eriophorum*). Further north erect dwarf shrubs are replaced by dwarf shrubs less than 10-cm tall. Shrubs and forbs in this prostrate dwarf shrub zone include: *Cassiope*, *Dryas*, *Salix*, *Draba*, *Saxifraga*, and *Carex*. In the northernmost portion of the Arctic biome landscapes typically have less than 5% vascular plant cover. Vegetation in this cushion-forb zone consists of scattered bryophytes, cyanobacteria, small forbs (*Draba*, *Papaver*, and *Saxifraga*), grasses (*Puccinellia* and *Alopecurus*), and lichens. This study focuses on the transition between the tall shrub zone and the erect dwarf shrub zone. For simplicity we refer to these zones throughout the manuscript as the shrub tundra (tall shrub tundra) and dwarf shrub tundra (erect dwarf shrub tundra).

At finer scales the transitions between Arctic vegetation zones exhibit considerable heterogeneity. For example, in the tall shrub–dwarf shrub tundra ecotone, changes in vegetation structure can occur across scales as fine as 1 m (Bliss and Matveyeva 1992; Walker and others 1994; Epstein and others 2004b). Because the response of vegetation in this ecotone to changes in climate will likely also occur at fine scales, it will be difficult to detect changes using land-cover classifications derived from broad-scale satellite imagery. Despite the importance of these fine-scale transitions, adequate baseline data and monitoring strategies are lacking in many areas (Bliss and Matveyeva 1992; Walker and others 1994; Epstein and others 2004b).

The anticipated expansion of tall shrub tundra, coupled with continued increases in air temperature are likely to have long-term impacts on permafrost temperatures and terrain stability across the Low Arctic (Sturm and others 2001a; Epstein and others 2004b; Chapin and others 2005; McGuire and others 2006). The accurate identification of the transition from tall shrub to dwarf shrub tundra is particularly critical to future predictions and tracking of northern environmental change because this ecotone corresponds to large differences in albedo, sensible heat flux, and duration and depth of snow pack (Pomeroy and others 1995; Epstein and others 2004a; Chapin and others 2005; Sturm and others 2005). It has also been proposed that feedbacks between vegetation, snow, ground heat flux, and nutrient availability will accelerate the rate of vegetation change in the Low Arctic (Sturm and others 2005), and potentially lead to the warming of permafrost. Because these feedbacks may be sensitive to threshold patch sizes (Pomeroy and others 1995; Sturm and others 2005) understanding variability in patch size across this transition is also important.

In the uplands north of Inuvik, Northwest Territories (NWT) there is a latitudinal shift from tundra communities dominated by shrubs more than 40-cm tall to those characterized by the abundance of dwarf shrubs and sedges less than 40 cm (Mackay 1963; Corns 1974; Forest Management Institute 1975). Recent evidence suggests that tall shrub tundra is encroaching into areas of dwarf shrub tundra across the entire circumpolar region (Silapaswan and others 2001; Sturm and others 2001b; Stow and others 2004; Tape and others 2006), but in the Mackenzie Delta Region, base-line data on this transition are lacking. In this article, we use object-based classification (Benz and others 2004) of airphotos to describe fine-scale changes in the proportion and patch sizes of shrub tundra and dwarf shrub tundra across the shrub tundra ecotone in the Mackenzie delta uplands.

METHODS

Study Area

Our study area in northwestern Canada is approximately 11,000 km^2 (Figure 1). This area

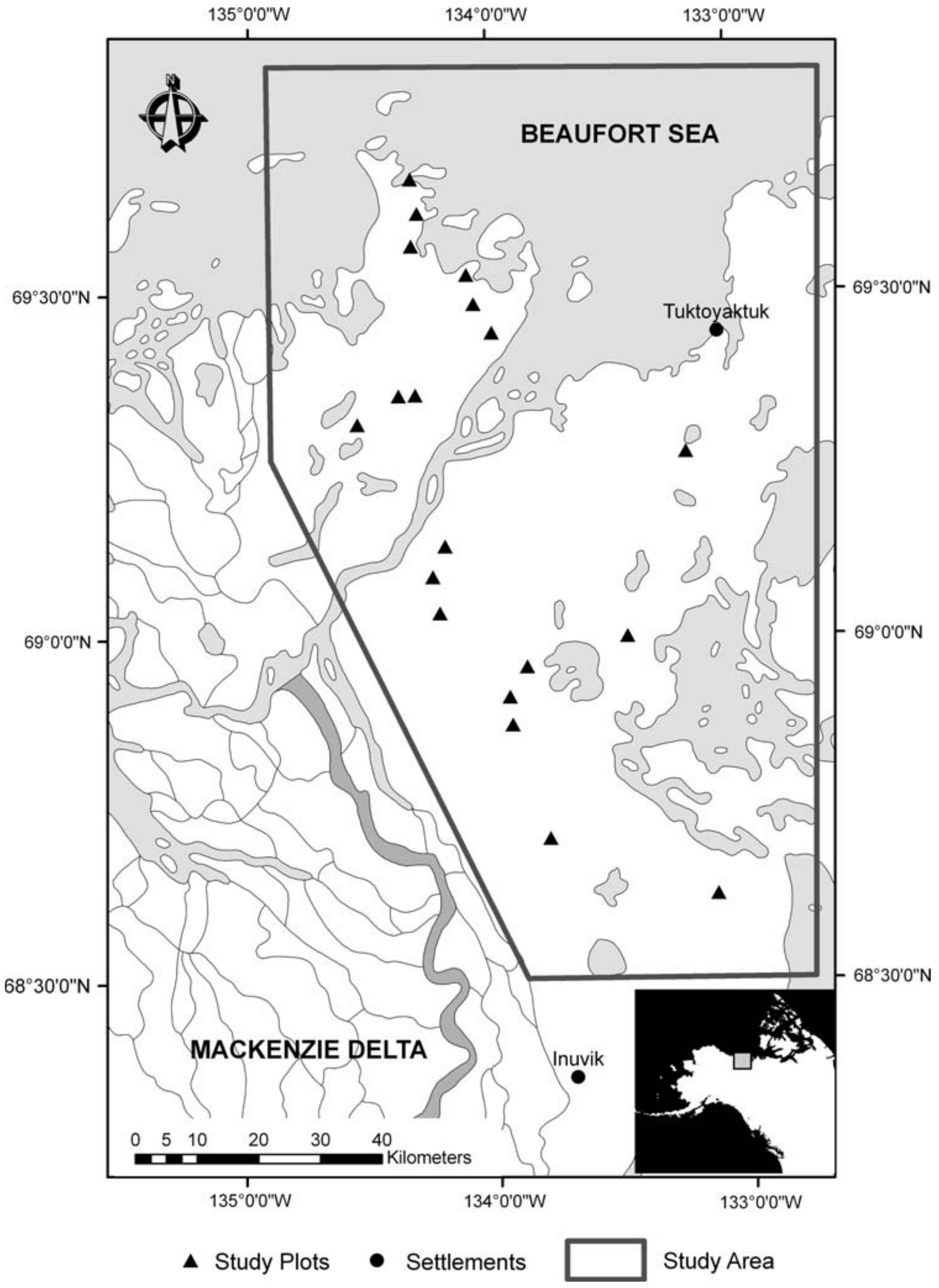

Figure 1. Map of the study region showing the study area, settlements, water (*light gray*), and airphoto study plots. *Inset* map at the *bottom right* shows the approximate position of the study area in North America.

east of the Mackenzie River delta is characterized by subtle topography and thousands of small lakes (Mackay 1963; Burn and Kokelj 2009). Quaternary surficial materials (primarily morainal deposits) and soils (predominantly silty clays) are relatively homogenous across the study area (Mackay 1963; Aylsworth and others 2000; Soil Landscapes of Canada Working Group 2007). From October through April mean air temperatures in the region are less than 0°C. During the short-growing season 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) (Burn 1997; Lantz and others 2009; Ritchie 1984). 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 melting ground ice (Lantz and Koklej 2008). The footprint 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 2009).

Airphoto Selection and Image Manipulation

To describe the vegetation structure across the uplands of the Mackenzie Delta region, we selected 18 air photos from a systematic survey of the Mackenzie Delta region completed in 2004 (http://www.gnwtgeomatics.nt.ca). We used a geodatabase of airphoto centers to randomly select 100 images between 68°26′ and 69°34′ (Figure 1). From these photos we chose 18 that spanned the study area, but had not been impacted by recent fires or seismic exploration. We rejected photos of areas with densities of seismic lines (areas where seismic exploration vehicles have been driven) exceeding 5 km/km^2, or within 1 km of known tundra fires. Each of the 18 images selected from this survey covered an area of approximately 49 km^2.

Negatives were scanned at 1814 dpi (1 pixel = 0.41 m) on a high-resolution photogrammetric quality scanner. Scanned airphotos were orthorectified using a 30-m DEM and Landsat 7 panchromatic orthoimagery (15-m pixel). Orthorectification was performed using a nearest neighbor algorithm (PCI Geomatics 2001) resulting in root mean square errors generally less than 3 orthophoto pixels. Each orthorectified image covered an area of approximately 49 km^2, but was clipped to a 36-km^2 area surrounding the principal point for classification and analysis. Images were also tested for, and did not exhibit, systematic bias in brightness (Lantz 2008).

Rationale for Object-Based Approach

To describe variability in vegetation structure and patch size across the study area we used the Definiens software package to perform object-based classifications of each image (Definiens 2006). An object-based approach to image classification differs from conventional pixel-based methods by assigning class membership to groups of pixels (objects) rather than individual pixels. It is essentially a two-step process that involves segmenting imagery into image objects (groups of pixels) followed by the classification of these objects. This approach enables the multi-scale description of patch structure and has been used successfully to map fine-scale pattern on air photos of shrub-dominated ecosystems (Laliberte and others 2004; Smith and others 2008). In the Definiens software package, segmentation is a bottom-up region merging algorithm that optimizes object creation by minimizing the heterogeneity (color) of pixels contained in each object, while creating objects that conform to user-defined shape criteria (Definiens 2006). The region merging process stops when the heterogeneity of an object exceeds a threshold defined by a unitless scale parameter. User modification of this threshold results in the creation of larger (higher heterogeneity), or smaller objects (lower heterogeneity) (Benz and others 2004). By iteratively modifying the heterogeneity threshold (by changing the scale parameter) users segment the image into objects that reflect the structure of the landscape (Blaschke and Hay 2001; Definiens 2006). In the Definiens software package, subsequent classification of image objects is accomplished using defined membership rules (for example, thresholds) or a nearest neighbor classification based on training data from the area of study (Laliberte and others 2004).

Object-Based Segmentation, Classification, and Accuracy Assessment

Segmentation

To minimize confusion between water- and dark-colored shrub tundra in this lake-rich region, we segmented each image at two scales. First, we segmented images into large heterogeneous objects whose borders corresponded to the boundary between water bodies and land (Figure 2). These coarse-scale objects were created by performing segmentation on the red, green, and blue bands, as well as two texture measures. Textural co-occurrence measures (contrast and entropy) were calculated using a grayscale band (ENVI 2006). Segmentation was performed using a scale parameter of 600, a color to shape ratio of 0.9, and compactness to smoothness ratio of 0.5 (Definiens 2006). Secondly, we performed a fine-scale segmentation using a scale parameter that yielded small homogenous objects that had shape and size similar to isolated patches of shrub tundra or dwarf shrub tundra (Figure 2). These fine-scale objects were created by performing segmentation of the red, green, and blue bands using a scale parameter of 25, a color to shape to ratio of 0.9, and compactness to smoothness of 0.5 (Definiens 2006).

Classification

After segmenting the images into objects, the objects were classified into areas representing: (1) shrub tundra [vegetation dominated by tall shrubs (*Alnus viridis*, tall *Salix* spp. and *Betula glandulosa*)], (2) dwarf shrub tundra [vegetation dominated by dwarf shrubs (*Ledum decumbens*, *Vaccinium vitis-idaea*, *Arctostaphylos*

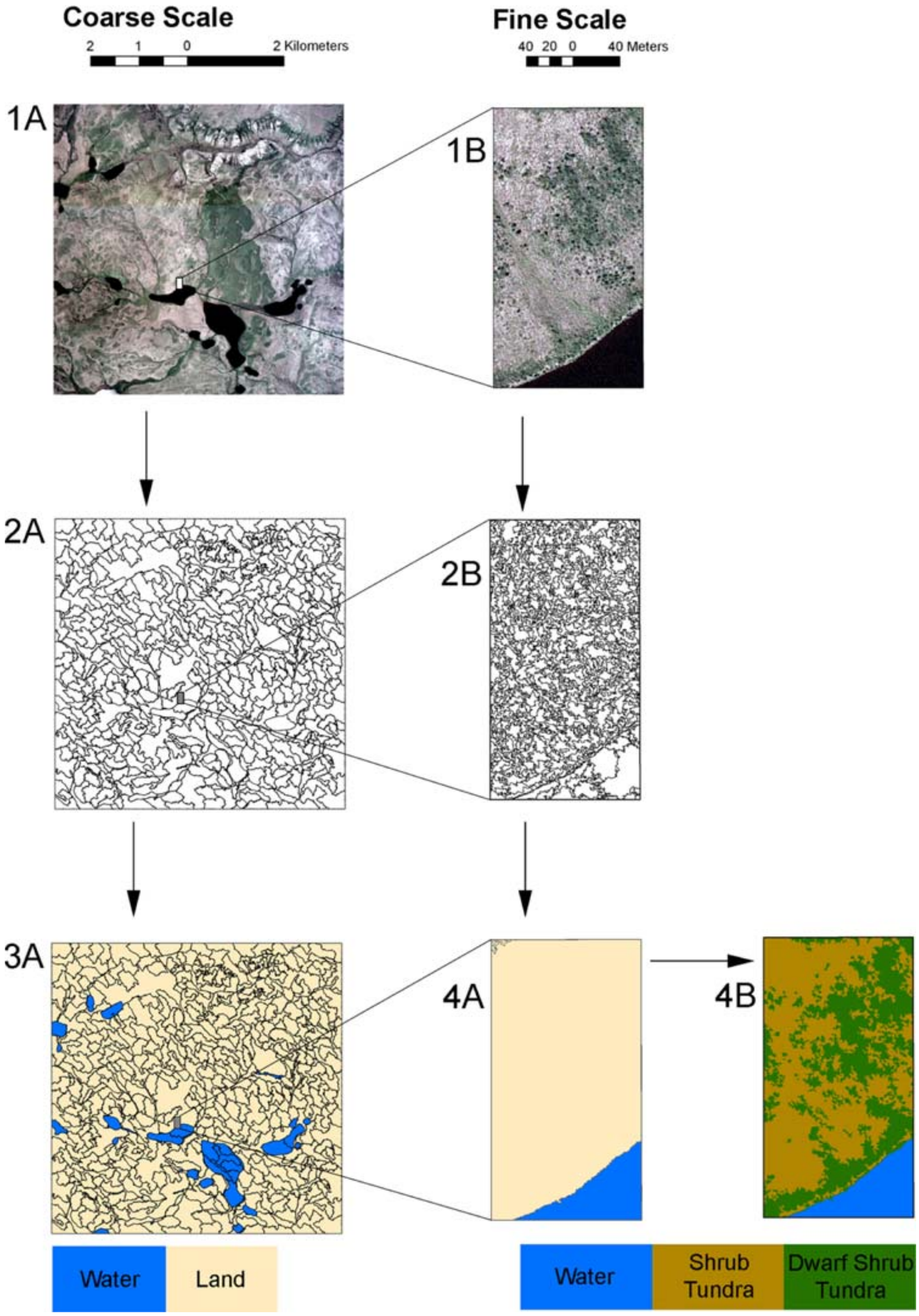

Figure 2. Diagram showing the sequence of operations in the object-based classification of air photo. *Panel 1* aerial photo of upland tundra plot at coarse (**1A**) and fine (**1B**) scales. *Panel 2* segmentation of the image at a coarse-scale (**2A**) is followed by segmentation at a fine-scale (**2B**). *Panel 3*. Coarse-scale objects are classified into land and water (**3A**) and fine-scale objects are classified as small water bodies, shrub tundra, and dwarf shrub tundra (**4B**), constrained by their membership in the coarse-scale classification (**4A**).

rubra, *Rubus chamaemorus*) and sedges (*Eriophorum vaginatum*, *Kobresia hyperborea*)], (3) water (lakes, rivers, ponds, and the Beaufort Sea), and (4) bare ground. We assigned fine-scale objects within the broader ‘‘land’’ class to shrub tundra, dwarf shrub tundra, smaller water bodies, or bare ground using a nearest neighbor classifier. Fine-scale objects contained within the broader ‘‘water’’ class were automatically classified as water. To perform each classification we used training data from high-resolution ground truth images. Training images were collected in the summer of 2006 using a Canon PowerShot S80 digital camera mounted on a helicopter. Photographs were captured at an altitude of approximately 450 m, had pixel sizes typically less than 0.25 m (Figure 3), and were georeferenced in ARCGIS using the 1:30,000 scale orthophotographs of each plot. When classifications were complete, we used Definiens to calculate the total area of each cover type and the proportion of shrub tundra in each

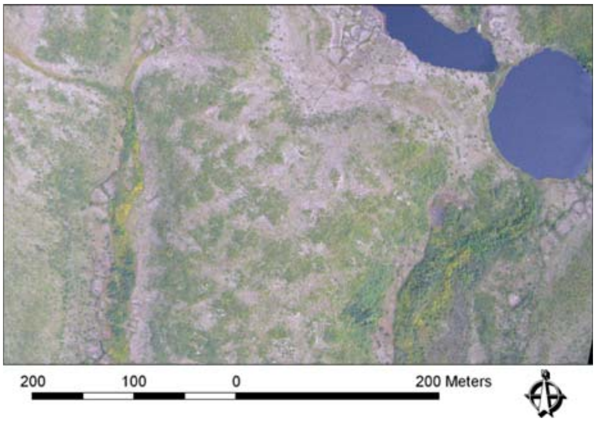

Figure 3. Example image from helicopter surveys used to train image classifiers and to conduct accuracy assessments. Image shows shrub tundra (dark gray [green and yellow]), dwarf shrub tundra (light gray [lavender-gray]), and two small lakes (black [blue]). (Color figure online)

photo. We also used Definiens to merge all contiguous objects of the same cover type and subsequently to determine the total number of patches and mean patch size for shrub tundra and dwarf shrub tundra classes.

Accuracy Assessment

To examine the accuracy of our object-based classifications, we constructed confusion matrices using two methods. In both the methods ground truth data were derived from independent manual classifications of five randomly selected images collected in the same manner as our training images. First, to conduct a standard pixel-based accuracy assessment, we compared 1,500 random points (300/ground truth image) from each cover type in our classifications with classified ground truth photos. To evaluate our estimates of patch sizes, we also conducted a polygon-based accuracy assessment (at the object level). To do this, we compared 1,500 randomly selected objects from each cover type with the ground-truth classification. Bare ground occupied less than 0.05% of the total area mapped and thus it was not feasible to include this cover type in accuracy assessments. We calculated overall accuracy, per class user's, and producer's accuracies and the kappa statistic (Lillesand and others 2003).

Statistical Analyses

To describe changes in the proportion and patch sizes of shrub tundra and dwarf shrub tundra with latitude we used regression analysis. We compared linear and non-linear models of proportion and patch size versus latitude by comparing Akaike's information criterion (AIC), AIC weights, and adjusted R^2 values (Anderson and others 2000; R Development Core Team 2006). We also examined residual plots to ensure that models met the assumptions of equal variance and normality. In plots that had available temperature data (Lantz and others 2009) we examined the Pearson correlations coefficient between the proportion of shrub tundra and mean summer (June–August) temperature.

RESULTS

Latitudinal Changes in the Proportion and Patch Sizes of Shrub Tundra and Dwarf Shrub Tundra

There was a northward decrease in the proportional area and mean patch size of shrub tundra across the study area (Figure 4). The northward decrease in the dominance of shrub tundra corresponded to an increase in the abundance and patch size of dwarf shrub tundra (Figure 5). All models showed strong evidence of non-linear relationships and non-linear models had improved fit and lower AIC's (Table 1). In all models the relationships between latitude and patch size and proportion of cover showed a steeper relationship north of 68.9°N. The Pearson correlation coefficient between the proportion of shrub tundra and mean summer temperatures was 0.95 and the latitude at which the proportion of shrub tundra declined below 50% corresponded approximately to the mean 10°C July isotherm in the region (Pelletier n.d.).

Accuracy Assessment

Pixel- and object-based estimates of overall classification accuracy were 85.8 and 78.1%, respectively. The kappa statistic, which ranges from 0 to 1 and provides an estimate of overall accuracy that accounts for the possibility that objects will be correctly classified by chance (Lillesand and others 2003), was 0.787 for the pixel-based method and 0.664 for the polygon-based method (Table 2). User accuracies (the percent of map units tested that were the same as the truth data) indicate that water bodies were extremely well classified (user accuracies 93.3–96.7%). Producer accuracies (the percent of truth points that were mapped correctly) were also high for the water class (94.0–97.6%). Conversely, shrub tundra and dwarf shrub tundra classes were prone to some classification error.

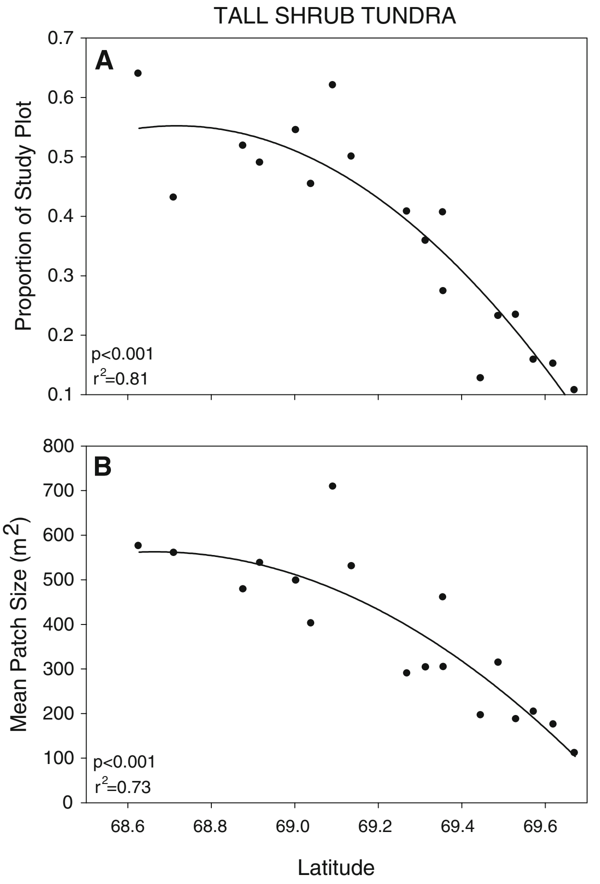

Figure 4. Least squares regressions of **A** proportion of shrub-tundra in the study plot versus latitude ($y = 73.3495x - 0.5336x^2 - 2519.9439$, $F_{2,15} = 38.25$, $P < 0.001$ adjusted $R^2 = 0.8142$) and **B** mean shrub tundra patch size versus latitude ($y = 63013x - 458.8x^2 - 2163009$, $F_{2,15} = 24.97$, $P < 0.001$ adjusted $R^2 = 0.7382$).

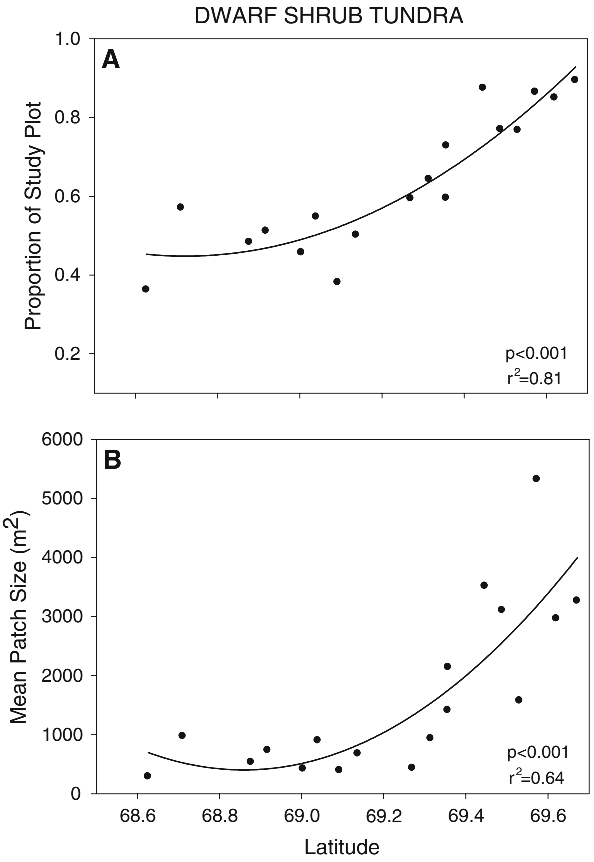

Figure 5. Least squares regressions of **A** proportion of dwarf shrub-tundra in the study plot versus latitude ($y = -73.3495x + 0.5336x^2 + 2520.9439$, $F_{2,15} = 38.25$, $P < 0.001$ adjusted $R^2 = 0.8142$) and **B** mean dwarf shrub patch size versus latitude ($y = -759116x + 5512x^2 + 26137774$, $F_{2,15} = 15.97$, $P < 0.001$ adjusted $R^2 = 0.6379$).

Specifically, user accuracies were from 76.9 to 75.3% for shrub tundra, and 83.8 to 69.2% for dwarf shrub tundra, for pixel- and object-based estimation methods, respectively (Table 2). Producer accuracies were 81.0 and 77.1% for shrub tundra and 79.1 and 66.6% for dwarf shrub tundra, for pixel- and object-based estimation methods, respectively (Table 2).

Discussion

Climate Change and the Position of the Shrub Ecotone

The strong correlation between summer temperatures and vegetation type suggests that increasing temperatures in the region (Lantz and Kokelj 2008) are likely to alter shrub abundance and shift the position of this ecotone. The vegetation transitions in the Arctic predicted to show rapid responses to warming are those with gradual rather than abrupt boundaries (Epstein and others 2004a). In the Mackenzie Delta region, the gradual transition between shrub and dwarf shrub (Figures 4, 5) suggests that this ecotone may be particularly sensitive to warming (Epstein and others 2004a). Studies of green alder population structure in the study area suggest that recent temperature increases may have already altered patterns of recruitment in this species (Lantz 2008). Increases in Normalized Difference Vegetation Index (NDVI) between 1986 and 2006 in the Mackenzie Valley just south of our study area are also consistent with increased productivity and changes in vegetation structure (Olthof and others 2008). In Alaska, where the shrub tundra ecotone is also coincident with the 10°C July isotherm (Muller and others 1999; Walker 2000; Epstein and others 2004a), increases in the abundance of tall shrubs have been attributed to the effects of regional temperature increases

Table 1. Comparison of Linear and Non-Linear Models Using Adjusted R^2, AIC, and AIC Weights

Dependant variable	Model	AIC	ΔAIC	Adjusted R^2	AIC weight
Proportion shrub tundra	Latitude	−85.82	4.97	0.740	0.071
	Latitude^2	−85.89	4.90	0.741	0.074
	Latitude + Latitude^2	**−90.78**	**0**	**0.811**	**0.855**
Proportion dwarf shrub tundra	Latitude	−85.48	5.12	0.740	0.067
	Latitude^2	−85.55	5.04	0.741	0.069
	Latitude + Latitude^2	**−90.60**	**0**	**0.813**	**0.864**
Shrub tundra patch size	Latitude	165.90	2.08	0.690	0.305
	Latitude^2	165.85	2.03	0.691	0.313
	Latitude + Latitude^2	**163.82**	**0**	**0.737**	**0.864**
Dwarf shrub tundra patch size	Latitude	249.79	3.87	0.530	0.125
	Latitude^2	249.74	3.83	0.532	0.127
	Latitude + Latitude^2	**245.92**	**0**	**0.639**	**0.864**

Best models (shown in bold) are plotted in Figures 4 and 5.

Table 2. Classification Accuracy Assessments

Classified data	Ground truth data			
	Water	Shrub tundra	Dwarf shrub tundra	User's accuracies (%)
Pixel-based				
Water	1451	31	18	96.7
Shrub tundra	31	1154	315	76.9
Dwarf shrub tundra	4	239	1257	83.8
Producers' accuracies (%)	97.6	81.0	79.1	
Overall accuracy (%)	85.8			
Kappa coefficient	0.787			
Object-based				
Water	850	27	34	93.3
Shrub tundra	44	1163	337	75.3
Dwarf shrub tundra	10	319	740	69.2
Producers' accuracies (%)	94.0	77.1	66.6	
Overall accuracy (%)	78.1			
Kappa coefficient	0.664			

Table shows raw tallies, producers and user's accuracies, overall accuracy, and the kappa coefficient.

(Tape and others 2006). Plot level manipulations of temperature and nutrient availability further support predictions that warming will increase shrub dominance in the Low Arctic (Parsons and others 1994; Chapin and others 1995; Bret-Harte and others 2001; Bret-Harte and others 2002; Dormann and Woodin 2002; Walker and others 2006).

Monitoring Shrub Encroachment

Accurate maps representing the shrub tundra transition are critical to monitoring the rate of shrub expansion in the Low Arctic. Our results are consistent with previous descriptions of vegetation transitions in the study area (Corns 1974; Forest Management Institute 1975; IEG 2002), but are a significant improvement to the accuracy of fine-scale mapping of regional tundra vegetation structure. Here, we mapped vegetation structure of the shrub–tundra transition in the Mackenzie Delta uplands with an overall accuracy of 86% and user's accuracies ranging from 69 to 84% for shrub classes. Previous classifications of the region had per class accuracies as low as 50% for shrub dominated terrain (IEG 2002). Estimates of the areal expansion of tall shrubs in the Western Arctic vary between approximately 1 and 6% per decade (Tape and others 2006; Lantz, unpublished data). Consequently, surveys repeated every 20–30 years using the methods implemented here will be capable of detecting rapid shrub expansion, but may not be suitable for tracking change in areas where tall shrub expansion is slow. Efforts to track broad-scale changes in tall shrubs using remote sensing should therefore be coupled with ground-based surveys.

Improvements in classification accuracy would make it possible to use this technique to detect finer-scale spatial and temporal changes in vegetation structure. For example, object-based classifications combining fine-scale airphotos and high-resolution multispectral imagery would likely improve accuracy. Additional contextual layers, including elevation and object texture, could also be used to further refine object-based classifications of these ecosystems (Dorren and others 2003; Bock and others 2005).

Implications

To date, there has been insufficient research describing and mapping the transition between shrub tundra and dwarf shrub tundra in the Mackenzie Delta uplands. Air and ground temperatures in this region are warming and the frequency of natural and anthropogenic disturbance is increasing (Lantz and Kokelj 2008; Burn and Kokelj 2009; Johnstone and Kokelj 2008; Kemper and Macdonald 2009). Disentangling and tracking the effects of multiple perturbations on the vegetation across this ecotone requires an accurate baseline. Although frequently mapped as a homogeneous cover type (Gould and others 2002; Walker and others 2002; Gould and others 2003) vegetation in this region shows significant non-linear changes in the relative abundance and patch size of shrub tundra and dwarf shrub tundra with increasing latitude. Strong correlations between this vegetation transition and regional temperature, coupled with evidence of increases in tall shrub tundra in other regions, suggest that further warming is likely to alter the structure of this ecotone.

The relations between vegetation structure, snow cover, and permafrost conditions (Burn and Kokelj 2009), highlight the importance of understanding vegetation change in this region. Large differences in the properties of tall shrub and dwarf shrub tundra, including snowpack, the duration of the snow-free season, albedo, methane flux, and active layer thickness (Pomeroy and others 1997; Epstein and others 2004a; Chapin and others 2005; Sturm and others 2005), suggest that changes in shrub abundance across this ecotone may alter ecosystem function (Epstein and others 2004a; Chapin and others 2005; Sturm and others 2005) and impact the ground thermal regime and terrain stability (Burn and Kokelj 2009; Kokelj and others 2009; Lantz and others 2009). Accurate maps of fine-scale differences in vegetation structure are therefore essential for establishing a baseline from which to track change, and for realistically parameterizing regional models of ecosystem processes (Nelson and others 1997; Reeburgh and others 1998; Oechel and others 2000; Chapin and others 2002; Schneider and others 2009).

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