Does NDVI reflect variation in the structural attributes associated with increasing shrub dominance in arctic tundra?

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Abstract
This study explores relationships between the normalized difference vegetation index (NDVI) and structural characteristics associated with deciduous shrub dominance in arctic tundra. Our structural measures of shrub dominance are stature, branch abundance, aerial per cent woody stem cover (deciduous and evergreen species), and per cent deciduous shrub canopy cover. All measurements were taken across a suite of transects that together represent a gradient of deciduous shrub height. The transects include tussock tundra shrub and riparian shrub tundra communities located in the northern foothills of the Brooks Range, in northern Alaska. Plot-level NDVI measurements were made in 2010 during the snow-free period prior to deciduous shrub leaf-out (early June, NDVI_{pre−leaf}), at the point in the growing season when canopy NDVI has reached half of its maximum growing season value (mid-June, NDVI_{demi−leaf}) and during the period of maximum leaf-out (late July, NDVI_{peak−leaf}). We found that:
(1) NDVI_{pre−leaf} is best suited to capturing variation in the per cent woody stem cover, maximum shrub height, and branch abundance, particularly between 10 and 50 cm height in the canopy; (2) NDVI_{peak−leaf} is best suited to capturing variation in deciduous canopy cover; and (3) NDVI_{demi−leaf} does not capture variability in any of our measures of shrub dominance. These findings suggest that in situ NDVI measurements made prior to deciduous canopy leaf-out could be used to identify small differences in maximum shrub height, woody stem cover, and branch abundance (particularly between 10 and 50 cm height in the canopy). Because shrubs are increasing in size and regional extent in several regions of the Arctic, investigation into spectrally based tools for monitoring these changes are worthwhile as they provide a first step towards development of remotely sensed techniques for quantifying associated changes in regional carbon cycling, albedo, radiative energy balance, and wildlife habitat.

Keywords: Arctic tundra, normalized difference vegetation index, shrub dominance, vegetation structure
1. Introduction

1.1. Increasing shrub dominance in Alaskan tundra

Evidence accumulating from many disciplines shows that the Arctic is currently undergoing a warming trend, and multiple models predict this warming will continue (ACIA 2004). Paleo-ecologic evidence suggests that previous warm periods have been correlated with greater birch and alder abundance in the pollen record (e.g., Brubaker et al 1995, Hu et al 1995, Higuera et al 2008) and with greater willow growth from an annual growth ring study (Forbes et al 2010). Recently, tundra ecosystems in this region have responded to warming with increased ‘greenness’ as detected through satellite imagery (e.g., Myneni et al 1997, Bunn et al 2007, Goetz et al 2005). Over the past decade, the greening of northern Alaska has been attributed to increases in the size, abundance and range of deciduous shrubs (alder, willow and birch, Sturm et al 2001). Tape et al (2006) found strong evidence that deciduous shrub expansion is a pan-Arctic phenomenon including Canada, Scandinavia, and possibly Russia and Siberia. There is clear evidence that the above is happening in valley bottoms and riparian areas in Alaskan arctic tundra (Sturm et al 2001, 2005, Tape et al 2006), but there is also mounting evidence that upland tundra is likely to respond strongly to warming by shifting towards increasing deciduous shrub dominance (e.g. Forbes et al 2010). At the landscape scale, shrub abundance is greater at the warmer end of a latitudinal gradient (Bliss and Matveyeva 1992). Many plot-level warming experiments show increased deciduous shrub abundance (Bret-Harte et al 2001, Chapin et al 1995, Chapin and Shaver 1996, Hobbie and Chapin 1998, Boelman et al 2005, Jia et al 2006, Dormann and Woodin 2002, van Wijk et al 2003). Walker et al (2006) found that in response to experimental warming, the height of deciduous shrubs increased more than their per cent canopy cover. Birch and willow grew taller over an eight-year period in natural vegetation in the vicinity of Toolik Lake, Alaska (Wahren et al 2005). Because these small shrubs are already abundant and have a more flexible growth strategy compared to other shrub species (Bret-Harte et al 2001, 2002), deciduous shrubs, particularly dwarf birch (Hobbie and Chapin 1998), are predicted to expand their range very rapidly (Epstein et al 2004).

1.2. Impacts of increasing shrub dominance on the tundra

Apart from the obvious changes in plant species composition, the increase in canopy height that occurs with increasing shrub dominance (Walker et al 2006) has been associated with several important secondary effects (Wookey et al 2009) that have both regional and potentially global consequences. Several studies have shown that snow depth is increased by even small increases in canopy height (McFadden et al 2001), primarily because shrubs trap blowing snow (Evans et al 1989, Kane et al 1991, Schaefer and Messier 1995, Jonasson 1981) and cause lower snow sublimation rates (McFadden et al 2001). This leads to changes in the spatial pattern, magnitude and timing of the landscape’s energy balance (McFadden et al 2001, Loranty et al 2011) and run-off rates (Sturm et al 2005). In addition, Shaver and Chapin (1995) found that increased snow depth leads to warmer winter ground temperatures (3–10°C higher) under tall shrubs than under shrub-free vegetation, resulting in a 25% greater annual rate of nitrogen mineralization. Increasing shrub dominance has also been shown to decrease landscape albedo during the snow-free period because taller shrubs have higher canopy leaf area index values compared to other plant functional types, and during the winter months because tall shrubs, which have thick, stiff stems, protrude through the snowpack (Sturm et al 2005). There is some debate as to how increasing shrub dominance will ultimately alter carbon dynamics of the tundra (Loya and Grogan 2004, Weintraub and Schimel 2005). On one hand, Mack et al (2004) found higher soil respiration rates in shrub-dominated communities compared to graminoid-dominated communities, and suggest that this is will likely overwhelm the carbon sequestering effect of enhanced aboveground carbon storage. On the other hand, because woody tissues have high C:N ratios (Hobbie 1996, Shaver et al 2001) and decompose very slowly relative to annually produced roots and leaves, increasing shrub extent and size could enhance long-term carbon storage on the tundra (Sturm et al 2005). For example, Bret-Harte et al (2001) found that the amount of aboveground biomass stored by dwarf birch almost doubled with a doubling in canopy height after six years of experimental warming. In addition, the increase in woody stem material would increase the tundra’s susceptibility to wildfire (Higuera et al 2008).

In addition to these relatively well-studied ecological effects of increasing shrub extent and size, food and shelter quality and availability for local fauna are likely to be impacted in yet undetermined ways. There is a large body of literature that illustrates the importance of biophysical habitat structure on the distribution of various faunal species (i.e. Macarthur and Macarthur 1961, Boelman et al 2007, Goetz et al 2010, Vierling et al 2011). Since increasing shrub cover and stature in response to experimental warming and fertilization has been associated with decreasing plant species diversity in tundra (Bret-Harte et al 2001, Walker et al 2006), increasing shrub dominance is likely to reduce the variety of plant-based food resources. This would presumably reduce forage quality for some faunal species (Batzli and Lesieutre 1991), increasing competition for the resources available and potentially causing populations of specialist species to suffer. Conversely, increases in shrub canopy cover, stature and branch abundance may benefit some faunal species by increasing shelter availability and nesting sites for shrub-nesting birds (Wingfield et al 2004).

1.3. NDVI and increasing shrub dominance

Because the impacts of increasing shrub dominance are likely to be significant, it is necessary that we are able to detect and quantify the change across tundra landscapes. Since the tundra ecosystem is both vast and relatively remote, remote sensing techniques that can accomplish this over large areas are highly desirable. Previous field-and space-based studies have compared NDVI values among the tundra’s main vegetation types. These studies have consistently found that...
during the peak of maximum aboveground biomass (late July), deciduous shrub-dominated tussock communities have higher NDVI values than other tussock types because deciduous shrubs have higher canopy leaf areas compared to the other plant species (Street et al. 2007, Jia et al. 2006, Stow et al. 2004, Riedel et al. 2005, Hope et al. 1993, Shippert et al. 1995, Walker et al. 2003, Raynolds et al. 2006, Steltzer and Welker 2006). Muller et al. (1999) produced a map of northern Alaska in which low-stature shrub and shrubland tussock were distinguished from other tussock communities using Landsat MSS imagery, but variation within shrub communities was not quantified. A recent landscape-level study by Selkowitz (2010) conducted on the North Slope of Alaska shows that space-based multi-spectral remote sensing can be used to map the per cent cover of deciduous shrub canopy in late July. Although highly valuable, this study does not explicitly explore relationships between NDVI and variation in structural characteristics, such as canopy height or branching, both of which are associated with increasing shrub dominance (Walker et al. 2006). We suggest that it is both complementary and equally important to be able to remotely quantify expected changes in the structural characteristics of existing shrubs as it is to map their per cent canopy cover, because the ecological responses and potential feedbacks to increasing shrub dominance are largely attributed to changes in canopy structure that accompany increasing shrub dominance. In addition, the Selkowitz (2010) study focused on mapping the per cent aerial cover of deciduous shrub canopy for shrubs greater than 0.5 m tall. In Alaskan tussock, shrubs of this stature are mostly associated with riparian communities and are rare within upland tussock. Although Beck et al. (2011) have developed and employed a method for mapping areas of tall (>1 m in stature) and lower-stature shrub presence using a combination of IKONOS, SPOT, and Landsat TM imagery, the method does not enable mapping variation in shrub stature beyond these two groupings. Given that shrubs in upland tussock tend to be less than 0.5 m in stature, and it is in this vegetation type that shrubs are predicted to become increasingly dominant (Bret-Harte et al. 2001, Epstein et al. 2004) we suggest that it is also important to quantify variation in the degree of shrub dominance among upland tussock communities. To the best of our knowledge, the only remote sensing-based study that has explored differences in biophysical structure among tussock tussock communities was conducted by Vierling et al. (1997). Although Vierling et al. (1997) found that bidirectional NDVI measurements permit good discrimination between non-woody and woody tussock tussock communities, no empirical relationships were established between bidirectional NDVI and shrub stature or dominance.

1.4. Study objectives

The main objective of this study is to establish empirical relationships between high spatial resolution field-based NDVI and structural characteristics of deciduous shrub dominance across a gradient of increasing canopy height, including both deciduous shrub-dominated water-track communities (with shrubs ranging from <10 to 50 cm in stature) and riparian shrub tussock communities (>50 cm in stature). Our structural measures of deciduous shrub dominance are stature, branch abundance, and per cent woody stem cover. We also explore the relationship between NDVI and per cent deciduous canopy cover. We explore whether or not NDVI measured at various stages during the growing season (prior to deciduous leaf-out (early June), half way to peak leaf-out (mid-June) and during peak leaf-out (late July)) will each correlate with variation in shrub stature, branch abundance, per cent woody stem cover, and per cent of deciduous canopy cover, and determine if the strength of these relationships differs depending on which NDVI measurements are being considered. This will contribute to our understanding of how structural characteristics associated with the gradual increase in shrub dominance can be monitored via spectral reflectance properties.

2. Methods

2.1. Transect/field site layout

In May 2010 we established six transects (n = 6, two at each of three field site locations) which together made up a gradient of increasing canopy height in the northern foothills of the Brooks Range, Alaska (figure 1). Two of the six transects (Tussock tussock (TT) 1 and 2) were located in tussock tussock water-track communities dominated by low-stature shrubs (<0.5 m), while Tussock tussock 3 and 4 were located in non-water-track tussock tussock communities dominated by low-stature shrubs (<0.5 m), and the other two transects (Riparian (Rip) 1 and 2) were located in riparian shrub tussock communities (>0.5 m) (figure 2(a)). Transects were 100 m in length. Ten quadrats (1 m × 1 m each) were established at 10 m intervals along each transect (ten quadrats per transect).

2.2. Transect descriptions

The tussock tussock tussock sites were deglaciated ∼65 000 (TT3 and TT4) and ∼120 000 (TT1 and TT2) years before present, following the Itkillik I and Sagavanirktok River glaciations, respectively (Hamilton 2003). The riparian shrub transects (Rip1 and Rip2) were also deglaciated following the Itkillik I glaciation. The vegetation at the tussock tussock shrub transects (TT1, TT2, TT3 and TT4) is made up of a mix of low-stature (10–30 cm) rhizomatous sedges (10–20% of aerial cover; mainly Carex bigelowii), deciduous dwarf shrubs (<5–50 cm, 22–35%; mainly Betula nana, Salix pulchra and Vaccinium uliginosum), dwarf evergreens (6–13%; mainly Vaccinium vitis-idaea and Ledum palustre), perennial herbs (10–18%; mainly Polygonum bistorta and Rubus chamaemorus) and mosses. The vegetation at the riparian shrub transects (Rip1 and Rip2) is made up of deciduous shrubs of various statures (ranging from 30 to 105 cm, 43–56%; mainly Betula nana and Salix spp.), with scattered forbs, graminoids, and evergreens.

In early June, deciduous shrub stems are leafless; the background understory and ground cover is highly exposed and is made up of a mix of green evergreen shrubs and mosses, lichen, and standing litter. In mid-June, deciduous
Figure 1. Map of Alaska (inset) and map of the North Slope of Alaska showing the location of the six transects used in this study.

Figure 2. (a) Transect means for maximum shrub height. (b) Transect means for NDVI_{pre-leaf}, NDVI_{dem-leaf}, and NDVI_{peak-leaf}. (c) Transect means for the index of branch abundance in each of four canopy height increments. (d) Transect means for per cent cover of woody stem material and per cent deciduous canopy cover. X-axis labels are transect labels, where TT1 through TT4 correspond to tussock tundra shrub transects and Rip1 and Rip2 correspond to riparian shrub tundra transects. Error bars represent 1 SEM. Means shown above with the same letter are not statistically different at the $P < 0.05$ level of significance. Significance for the 0–10 cm increment are indicated in lower case letters, and the 10–50 cm increment in capital letters. In (b), letters should be compared within each NDVI variable and not between NDVI variables.
shrubs have leafed out and, to varying degrees depending on their abundance and stature, are obscuring the background understory and ground cover. By late July, deciduous shrubs have reached their maximum canopy leaf area and are obscuring the background understory and ground cover to the maximum possible extent.

2.3. Measurement of vegetation cover, shrub height and branch abundance

Aerial per cent cover was estimated in each 1 m$^2$ quadrat in late July (period of maximum leaf area) of 2010. A 1 m$^2$ frame outlining 20 cm × 20 cm sub-quadrats was placed over each quadrat. Within this 1 m$^2$ the per cent aerial cover of mosses, lichens, canopy for all vascular plant species, all visible woody stem and branch material (evergreen and deciduous), and litter was visually estimated. Per cent cover was calculated by dividing the cover of the individual species or tissue type in each quadrat by the quadrat ground area (1 m$^2$). Per cent deciduous canopy cover included foliage cover for *Betula nana* and all *Salix* species. Maximum shrub height was determined by measuring the height of the tallest deciduous shrub (*Betula nana* or *Salix* species only) in each quadrat. Deciduous shrub (*Betula nana* or *Salix* species only) branch abundance in various vertical increments within the canopy was determined using a modified point frame technique. A metre stick was placed on the ground along the inside edge of each vegetation quadrat and a graduated dowel was inserted vertically into the vegetation every 10 cm along the metre stick. The number of *Betula nana* and *Salix* spp. branches touching the dowel within each of four height increments: 0–10, 10–50, 50–100, 100+ cm was recorded. Our index of branch abundance, which does not relate to ground surface area, is the mean number of woody stem touches per quadrat, averaged across the 10 dowel insertions.

2.4. Measurements of spectral reflectance and NDVI

Quadrat-level spectral radiance measurements were made with a field portable spectroradiometer (FieldSpec3, Analytical Spectral Devices, Boulder, CO, USA) at three times during the growing season of 2010: (1) during the snow-free period prior to deciduous shrub leaf-out (early June); (2) at the point in the growing season when canopy NDVI had reached half of its maximum growing season value (mid-June); and (3) during the period of maximum leaf-out (late July). The spectroradiometer has a 25° full angle cone of acceptance field-of-view (FOV) fibre optic with a spectral range of from 350 to 1050 nm. The spectral sampling interval of the spectroradiometer is 1.4 nm. Radiance measurements were preceded by a calibration scan of a 99% reflectance white standard (Spectralon, LabSphere, North Sutton, NH, USA) to normalize for changes in light conditions between measurements. The foreoptic was held approximately 1 m above the top of the canopy, so that each measurement’s circular footprint was approximately 0.15 m$^2$. Spectral measurements were made in the 1 m$^2$ quadrats along each of the six transects described above. Five measurements were collected within each 1 m$^2$ quadrat in order to ensure that the spatial heterogeneity of each quadrat was captured, which resulted in 50 spectra for each transect. All spectral measurements were converted to reflectance values, and were interpolated to 1 nm intervals.

We employ the normalized difference vegetation index (NDVI), which is indicative of the abundance of photosynthetically active vegetation (Rouse et al. 1974). It has proven highly sensitive to variation in aboveground biomass of vegetation (Boelman et al. 2003, Boelman et al. 2005), to leaf area index and gross primary production (Street et al. 2007), as well as to ecosystem CO$_2$ flux (Boelman et al. 2003, La Puma et al. 2007) in tundra landscapes. In the present study, NDVI was determined from canopy reflectance values according to the following red and near-infrared (NIR) band definitions:

$$\text{NDVI} = \frac{(\text{NIR} - R)}{(\text{NIR} + R)} \quad (1)$$

where NIR indicates mean reflectance between 750 and 850 nm (near-infrared wavelengths), and $R$ indicates mean reflectance between 650 and 690 nm (visible red wavelengths). The five NDVI values associated with each quadrat were averaged to give a mean quadrat NDVI value. In this study, we calculated NDVI from spectral measurements collected at three times during the growing season: early June (NDVI$_{pre}$–leaf), mid-June (NDVI$_{demi}$–leaf) and late July (NDVI$_{peak}$–leaf).

NDVI ranges from $-1$ to $1$, where values below zero usually correspond to water or dark surface materials containing no vegetation, and highly vegetated areas generally range between 0.4 and 1.0. A threshold level of vegetation abundance, at which NDVI values no longer correlate well to actual vegetation abundance, typically occurs at LAI values between 2 and 6, depending on the type of vegetation being measured (Hatfield et al. 1985). In deciduous shrub-dominated tussock tundra and riparian shrub tundra communities, LAI values are typically <1 and ≤2, respectively (Williams and Rastetter 1999).

2.5. Statistical analysis

One-way analysis of variance (ANOVA) was used to test for overall differences among transects for NDVI, shrub height, index of branch abundance, and per cent cover values. Differences were considered significant at $P \leq 0.05$. If the ANOVA showed an overall significant effect, individual pairs of means were compared using Tukey’s honestly significant difference (Tukey’s HSD) criterion (Zar 1999). Linear regressions were used to determine relationships between selected pairs of measured variables.

3. Results

3.1. NDVI and measures of shrub dominance

NDVI$_{pre}$–leaf was higher in the tussock tundra shrub transects, with the Rip2 transect having significantly lower NDVI$_{pre}$–leaf than several of the tussock tundra shrub transects (figure 2(b)). In contrast, NDVI$_{peak}$–leaf showed the opposite pattern with increasing shrub height, with both Rip1 and Rip2 having significantly higher NDVI$_{peak}$–leaf values than several of the tussock tundra transects (figure 2(b)).
showed no significant pattern as a function of shrub height (figure 2(b)).

Branch abundance was lowest in the lowest-stature shrub transects and higher in the taller shrub transects (figure 2(c)). Across all transects, branch abundance in the 0–10 cm increment was relatively similar (figure 2(c)). With greater canopy height, the 10–50 cm increment contained significantly more branches, showing that the shrubs in the riparian shrub transects in particular, have greater branch abundance higher in the canopy (figure 2(c)). Branch abundance was null or very low in both the 50–100 cm and 100 cm+ increments for all transects (figure 2(c)). Per cent woody stem cover followed the trend in canopy height, with Rip2 having significantly higher woody stem cover than all of the tussock tundra transects. In comparison, per cent deciduous canopy cover varied among some transects, but not as closely with shrub height (figure 2(d)).

### 3.2. Relationships among measures of shrub dominance

Maximum shrub height was strongly correlated with per cent woody stem cover, per cent deciduous canopy cover, total branch abundance, and branch abundance in the 10–50 cm and 100 cm+ increments, and moderately correlated with branch abundance in the 50–100 cm increment (table 1). It is important to note that woody stem cover, deciduous canopy cover, total branch abundance, and branch abundance in the 10–50 cm increment, each increased linearly with the gradual increase in maximum shrub height among our transects (figure 3(a)); the accompanying increases in branch abundance at increments above 50 cm within the canopy were not incremental (data not shown). Instead, the strength of these relationships is due to two distinct clusters of data points (tussock tundra shrub versus riparian shrub transects). Similarly, although correlation coefficients suggest that the relationship between branch abundance and each of per cent woody stem cover and deciduous canopy cover were strong (table 1), the exemplary relationships shown in figure 3(b) show that they resulted only from major differences between the tussock tundra and riparian transects (figure 3(b)). The strong relationship between per cent woody stem cover and deciduous canopy cover (table 1) cover was also driven by the same two clusters of data points.

### 3.3. Spectral reflectance of woody stems and early season ground cover

Spectral reflectance properties during the pre-leaf-out period (early June) differed substantially between quadrats with minimal woody stem cover and those with dominantly woody stem cover (figure 4(a)). Quadrats with little woody stem cover show a steep increase in reflectance from the red to the NIR wavelengths (large red edge), and thus higher NDVI values, while dominantly woody-stem-covered quadrats show a distinct but much smaller increase in reflectance in this region (small red edge), with substantially lower NIR reflectance values and thus lower NDVI values (figure 4). Examination of digital pictures of each quad suggests that quadrats with minimal woody stem cover have high exposure (aerial cover per cent) of green moss and prostrate evergreen cover, while this green ground cover is partially to entirely obscured by woody stem material in quadrats with high woody stem cover (compare figures 4(b) and (c)).

### 3.4. Relationships between NDVI and measures of shrub dominance

As illustrated by the relationships shown in figure 5, NDVI_{pre-leaf} was consistently negatively correlated with our measures of shrub dominance across transects (figures 5(a) and (b)), while NDVI_{peak-leaf} was consistently positively correlated with them (figure 5(c)). Because the trends in NDVI_{pre-leaf} and NDVI_{peak-leaf} across transects were consistent for all NDVI–shrub dominance relationships, we do not show each one. Instead, we show the relationships in figure 5 as representative selections, and report the strength of all NDVI–dominance relationships in table 2.

Correlation coefficients suggest that NDVI_{pre-leaf} is strongly correlated with maximum shrub height, woody stem cover, total branch abundance, and branch abundance in the 10–50 cm increment (table 2), and it is important to note that NDVI_{pre-leaf} decreases in step with increases in each of these variables among our transects (figures 5(a) and (b)). On the other hand, although correlation coefficients suggest that NDVI_{pre-leaf} is well correlated with variation in deciduous canopy cover (table 2), the relationship is driven...
Table 1. Correlation coefficients among measures of shrub dominance. All correlations are significant at $p < 0.05$, except where there is a $^*$ indicating that the relationship is significant at $p < 0.1$. Linear equations are reported for all relationships shown in figure 3.

|                           | % woody stem cover | % deciduous canopy cover | Index of branch abundance (total) | Index of branch abundance (0–10 cm) | Index of branch abundance (10–50 cm) | Index of branch abundance (50–100 cm) | Index of branch abundance (100 cm+) |
|---------------------------|--------------------|--------------------------|-----------------------------------|-------------------------------------|--------------------------------------|----------------------------------------|-------------------------------------|
| Maximum shrub height      | 0.95               | 0.85                     | 0.94                              | No relationship                     | 0.97                                 | 0.7*                                   | 0.91                                |
|                           | $y = 0.26x + 2.75$  | $y = 0.37x + 16.47$      |                                   |                                     | $y = 0.27x - 3.94$                    |                                        |                                     |
| % woody stem cover        | $x$                | 0.84                     | 0.83                              | No relationship                     | 0.91                                 | No relationship                        | 0.87                                |
|                           |                    |                          | $y = 0.62x + 4.57$                |                                     |                                      |                                        |                                     |
| % deciduous canopy cover  | $x$                | $x$                      | 0.88                              | No relationship                     | 0.91                                 | 0.92                                   | No relationship                      |
|                           |                    |                          | $y = 1.02x + 16.27$               |                                     |                                      |                                        |                                     |
Figure 4. (a) Representative spectral reflectance properties collected in early June (pre-deciduous shrub leaf-out) for two different quadrats with high woody stem cover (black spectra) and two different quadrats with low woody stem cover (grey spectra). Each spectra represents the average of five spectra taken for a single quadrat. Numbers indicate the NDVI value for each quadrat spectrum shown below. Photographs at right show representative low woody-stem-covered quadrats (b) and high woody-stem-covered quadrats (c) quadrats. The photos were taken in early June (pre-deciduous shrub leaf-out).

Figure 5. (a) Relationships between NDVI<sub>pre-leaf</sub> and each of maximum shrub height (black diamonds) and branch abundance in the 10–50 cm canopy height increment (open circles). (b) Relationships between NDVI<sub>pre-leaf</sub> and each of per cent deciduous canopy cover (grey triangles) and per cent woody stem cover (black squares). (c) Relationships between NDVI<sub>pre-leaf</sub> and each of per cent deciduous canopy cover (grey triangles) and branch abundance in the 10–50 cm canopy height increment (open circles).

by two distinct clusters of data points (tussock tundra shrub versus riparian shrub transects) (figure 5(b)), revealing that NDVI<sub>pre-leaf</sub> was not sensitive to small variation in either deciduous canopy cover. The strong relationship between NDVI<sub>pre-leaf</sub> and branch abundance above 50 cm within the canopy can only be driven by the same two distinct clusters of
Correlation coefficients between NDVI and measures of shrub dominance. All correlations are significant at $p < 0.05$, except where there is a * indicating that the relationship is significant at $p < 0.1$. Linear equations are reported for all relationships shown in figure 5.

|                         | NDVI_{pre-leaf} | NDVI_{demi-leaf} | NDVI_{peak-leaf} |
|-------------------------|-----------------|------------------|-----------------|
| Maximum shrub height    | −0.96           | No relationship  | 0.81            |
|                         | $y = -0.001x + 0.45$ | No relationship  | 0.81            |
| % woody stem cover      | −0.93           | No relationship  | 0.99            |
|                         | $y = -0.005x + 0.46$ | No relationship  | 0.88            |
| % deciduous canopy cover| −0.88           | No relationship  | 0.95            |
|                         | $y = 0.003x + 0.62$ | No relationship  | 0.69            |
| Index of branch abundance (total) | −0.95          | No relationship  | 0.90            |
| Index of branch abundance (0–10 cm) | No relationship | No relationship | No relationship |
| Index of branch abundance (10–50 cm) | −0.99          | No relationship  | 0.95            |
|                         | $y = -0.005x + 0.43$ | No relationship  | 0.95            |
| Index of branch abundance (50–100 cm) | −0.86          | No relationship  | 0.95            |
| Index of branch abundance (100 cm+) | −0.76*         | No relationship  | No relationship |

4. Discussion

4.1. What does NDVI_{pre-leaf} reflect?

The inverse relationships between NDVI_{pre-leaf} and each of our structural variables (maximum shrub height, branch abundance, and woody stem cover) can be attributed to the fact that in early June, leafless deciduous shrub stems make up the overstory, obscuring the green, vegetated ground layer. The ground layer in our tussock tundra and riparian shrub tundra communities are characterized by substantial moss and/or prostrate evergreen shrub cover (see section 2.2) which is green in early June (see sample quadrat photos in figures 4(b) and (c)). Since woody stem material exhibits very little difference in red compared to NIR reflectance, while moss and evergreen cover exhibit a larger difference, quadrats with more overstory woody stem material are associated with lower NDVI_{pre-leaf} values compared to those with less woody stem overstory cover (figure 4(a)).

Woody stem cover is a function of both shrub height and total branch abundance, and since taller deciduous shrubs have more extensive branching (see figure 3) (Bret-Harte et al. 2002), NDVI_{pre-leaf} was well correlated with all three variables. Among all height increments, NDVI_{pre-leaf} was most highly correlated with branch abundance in the 10–50 cm increment because branch abundance within this class varied most among transsects, and all transsects had shrubs that were at least 10–50 cm in stature. We also found that while NDVI_{pre-leaf} was sensitive to both the small differences (among tussock tundra shrub transsects) and large differences (tussock tundra shrubs versus riparian transsects) in maximum shrub height, woody stem cover, and branch abundance among our transsects, it was only sensitive to the large differences (tussock tundra shrubs versus riparian transsects) in deciduous canopy cover. This is not surprising, given that NDVI_{pre-leaf} directly senses variation in aerial cover of woody stem material, which did not differ predictably among transsects with small differences in deciduous canopy cover. These findings suggest that in situ NDVI measurements made prior to deciduous canopy leaf-out could be used to identify small differences in maximum shrub height, woody stem cover, and branch abundance (particularly between 10 and 50 cm height in the canopy) within and among both tussock tundra shrub and riparian tundra communities, as well as to monitor and verify the gradual changes in these measures of biophysical structure that are expected in these tundra communities as warming continues.

4.2. What does NDVI_{peak-leaf} reflect?

Compared to NDVI_{pre-leaf}, NDVI_{peak-leaf} more closely tracked small and large differences in deciduous canopy cover among all of our transsects. It is not surprising that NDVI_{peak-leaf} was more sensitive to differences in deciduous canopy cover compared to NDVI_{pre-leaf} since: (1) both deciduous canopy cover and NDVI_{peak-leaf} were measured during the period of peak leaf-out, (2) taller shrubs exhibited more extensive branching than low-stature shrubs along our transect, and branch abundance has been shown to exhibit significant control over canopy leaf area among deciduous shrub species (Bret-Harte et al. 2002); and (3) NDVI is known to be sensitive to variation in canopy leaf area across tundra landscapes (Bret-Harte et al. 2001, Street et al. 2007, Steltzer and Welker 2006). On the other hand, NDVI_{peak-leaf} did not track variation in our biophysical measures of shrub dominance as well as NDVI_{pre-leaf}, because most of the structural woody material was obscured by green canopy cover when NDVI_{peak-leaf} was measured. These findings suggest that in situ NDVI measurements made during the period of peak leaf-out can be
used to identify differences in deciduous canopy cover within and among both tussock tundra shrub and riparian tundra communities in tundra landscapes, and to monitor and verify the gradual increase in deciduous canopy cover that is expected within these communities as warming continues.

4.3. What does NDVIdemi−leaf reflect?

We found no significant relationships between NDVIdemi−leaf and any of our measures of shrub dominance, because there were no significant differences in NDVIdemi−leaf among our transects. Because NDVIdemi−leaf was collected at the midpoint in canopy development, this is most likely due to stronger nonlinear spectral mixing of non-photosynthetic and photosynthetic plant material (Asner 1998) compared to pre-leaf-out or peak-leaf-out periods when one of either woody stem cover or canopy leaf area strongly dominates the spectral reflectance characteristics of the canopy.

5. Conclusions and implications

This study demonstrates that plot-level NDVI measurements made during the period prior to deciduous shrub leaf-out (early June) may be well suited to capturing variation in measures of shrub dominance that characterize the biophysical structure of the canopy: per cent woody stem cover, deciduous shrub height, and branch abundance, particularly between 10 and 50 cm height in the canopy. In contrast, NDVI measurements made during the period of peak leaf-out (late July) are better suited to capturing variation in per cent deciduous canopy cover, and are not as sensitive to variation in biophysical structure. This study suggests that NDVI measurements made at different times during the tundra’s growing season provide complementary information which, together, may have the potential to provide comprehensive characterization (biophysical structure and canopy cover per cent) of the degree of deciduous shrub dominance. This would be useful to those interested in quantifying and monitoring changes in regional carbon cycling, albedo, radiative energy balance, and wildlife habitat on the tundra.

Our finding that pre-leaf-out NDVI is related to variation in biophysical structure may prove particularly useful because, although high resolution light detection and ranging (LiDaR) is an excellent remote technique for quantifying variation in three-dimensional canopy structure in several ecosystems (LeFsky et al 2002, Asner et al 2007, Boelman et al 2007, Goetz et al 2010, Vierling et al 2011), detection of spatial and temporal variation in canopy height in inherently low-stature landscapes (Riaño et al 2007), including the majority of tundra vegetation communities, is not yet possible.

However, future work is required to test the applicability of our findings across a wider variety of tundra vegetation communities and landscapes than is included in the current study. Perhaps the most obvious difficulty in applying the inverse relationship found between pre-leaf-out NDVI and our measures of biophysical structure, will arise from the fact that low pre-leaf-out NDVI values are also likely to be associated not only with areas of high woody stem cover, but also with those of low woody stem cover, such as windblown ridgetops that area characterized by rocky outcrops and lichen. In order for our findings to be effectively applied to spectral data collected by airborne and space-based sensors, it is likely that they will need to be combined with other remotely sensed datasets, or a priori spatial information on ground or vegetation community cover. Additional challenges to applying our pre-leaf-out NDVI relationships to image-based analyses will include the notoriously persistent cloud cover over the North Slope of Alaska and the rapid pace of canopy phenology. Together these characteristics are likely to result in few suitable pre-leaf-out images in a given growing season. This may render MODIS, a moderate resolution sensor with frequent revisit times, the most realistic space-based sensor option. However, because biophysical structure does not change measurably from one year to the next, a cloud-free image acquired during the period of pre-leaf-out within any of three consecutive growing seasons should provide the same information on shrub height, branch abundance, and woody stem cover.

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