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Biotic controls over spectral reflectance of arctic tundra vegetation

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In this study, seasonal field measurements of the normalized difference vegetation index (NDVI), using a field spectroradiometer, and leaf area index (LAI), using a LI-COR LAI-2000 Plant Canopy Analyzer, were compared with above-ground phytomass data to investigate relationships between vegetation properties and spectral indices for four distinct tundra vegetation types at Ivotuk, Alaska (68.49° N, 155.74° W). NDVI, LAI and above-ground phytomass data were collected biweekly from four 100 m × 100 m grids, each representative of a different vegetation type, during the 1999 growing season. Shrub phytomass, especially the live foliar deciduous shrub phytomass, was the major factor controlling NDVI across all vegetation types. LAI showed the strongest relationship with the overstorey component (total above-ground excluding moss and lichen) of phytomass and also showed a significant relationship with NDVI. The results from this study illustrated that time of the growing season in which sampling is conducted, non-linearity of relationships, and plant composition are important factors to consider when using relationships between NDVI, LAI and phytomass to parameterize or validate ecological models. The relationships established in this study also suggest that NDVI is useful for estimating levels of total live above-ground phytomass and LAI in tundra vegetation.

1. Introduction

The dynamics of tundra vegetation have become an important topic of research due to recent studies indicating that arctic systems are potentially sensitive to climate change and that long term consequences are complex in nature (Oechel *et al.* 1993, 1994, Chapin *et al.* 1995, Myneni *et al.* 1997, Arft *et al.* 1999, Epstein *et al.* 2000). To examine tundra vegetation at large spatial scales or over long time periods the use of remotely sensed data has become a desirable option (Shippert *et al.* 1995, Walker *et al.* 1995, Myneni *et al.* 1997, Jia *et al.* 2002). The key step in using remotely sensed data is correlating ecological properties of interest occurring on the ground to spectral reflectance data measured from satellites; this process has been fairly successful in temperate regions (Aase and Siddoway 1981, Tucker *et al.* 1981, Asrar *et al.* 1985, Park and Deering 1982).

Recently, studies conducted in the tundra have focused on correlating differences in phytomass among vegetation types to variations in normalized difference vegetation index (NDVI) (Hope *et al.* 1993, Stow *et al.* 1993, Shippert *et al.* 1995, Walker *et al.*

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1995). NDVI was found to be greater in water track and moist hill-slope acidic tundra communities compared to moist non-acidic tundra communities, due to a greater abundance of deciduous shrubs (Walker *et al.* 1995). Several studies have examined the difference between NDVI in moist acidic tundra and moist non-acidic tundra on regional scales and found generally higher values of NDVI in the moist acidic tundra (Jia *et al.* 2002, Walker *et al.* 2003). Relationships have also been examined within plant community types. Hope *et al.* (1993) found that approximately 50% of the variance in NDVI could be explained by the amount of photosynthetic phytomass within several tundra vegetation types.

Modelling of carbon dynamics or plant productivity is often accomplished by making estimates from a simple set of vegetation properties which often includes above-ground phytomass and/or leaf area index (LAI) (Williams and Rastetter 1999, Williams *et al.* 2000). Obtaining actual values of above-ground phytomass and LAI is not always logistically feasible particularly over coarse spatial scales. Therefore it is beneficial to be able to derive these variables from measures that can be obtained remotely, such as NDVI. Comparing field measurements of NDVI and LAI with detailed phytomass data is important not only for estimating ecological variables to use in modelling studies, but also provides information regarding the structure of vegetation that corresponds to a certain measure of a vegetation index. While several studies have successfully investigated relationships between NDVI and vegetation properties in the Arctic (Hope *et al.* 1993, Stow *et al.* 1993, Shippert *et al.* 1995, Walker *et al.* 1995), the relationship between LAI and phytomass has not been investigated. Additionally, the relationships between NDVI, LAI, and phytomass have not been examined in detail for this set of common tundra vegetation types.

The primary objective of our study was to examine relationships between phytomass, and LAI and NDVI to determine what specific components of phytomass are controlling the variance in these vegetation indices. Past research has demonstrated that LAI can be useful in estimating above-ground primary production and foliar N levels in vascular plants in the Arctic (Williams and Rastetter 1999). Therefore, relationships between NDVI and LAI were investigated to assist in modelling efforts that use LAI as a driving vegetation variable. Collecting phytomass and LAI data simultaneously with field spectral data enabled us to avoid confounding effects of the atmosphere, and also provided the ability to target distinct local vegetation types (Hope *et al.* 1993).

It is thought that relationships between spectral measures and vegetation properties vary across the growing season (Hope *et al.* 1993); we intended to capture these variations throughout the entire growing season. Therefore, a secondary objective of this study was to examine how relationships between spectral indices and phytomass change over the growing season. Conducting field measurements across several vegetation types for an entire field season allowed for the examination of these relationships at a high level of detail. The real utility and the overall goal of establishing relationships between spectral indices, such as NDVI, and vegetation properties, such as LAI or above-ground phytomass, was to provide information that is representative of landscape-scale distinctions of tundra vegetation, which can then be extrapolated to coarser scales or monitored over time through the use of satellite sensor data.

2. Methods

Ivotuk, Alaska (68.49° N, 155.74° W), located on the North Slope of the Brooks Mountain Range, is characterized by a growing season of approximately 110 days and a mean July maximum daily temperature of 12°C. Ivotuk is a key sampling location for the National Science Foundation (NSF) Arctic Transitions in the Land–Atmosphere System study as part of the western North Slope transect from Point Barrow to the Seward Peninsula. Ivotuk was chosen as a research site because it has one of the few airstrips in all of north-western Alaska, and it is comparable to Toolik Lake, a NSF Long-Term Ecological Research site (Van Cleve and Martin 1991) found to the east. Additionally, the study site was chosen because four tundra vegetation types, moist acidic tundra (MAT), moist non-acidic tundra (MNT), mossy tussock tundra (MT), and shrub tundra (ST) exist within a 2 km^2 area (see figure 1 for plant community composition of the vegetation types).

The vegetation at the MAT site consists of *Eriophorum vaginatum* (cotton grass; sedge), *Sphagnum* mosses, and prostrate and erect shrubs. The MNT site, found on neutral pH soils, has a vegetative community dominated by *Carex bigelowii* (sedge) and *Dryas integrifolia* (prostrate evergreen shrub), as well as non-*Sphagnum* mosses. The MT site consists mostly of *Sphagnum* mosses, *Betula nana* (dwarf birch), and lichens. The ST site, found in a well drained riparian region, is dominated by *Salix pulchra* (willow) and *Betula nana*.

NDVI, LAI and above-ground phytomass samples were collected bi-weekly from four 100 m × 100 m grids, each representative of a different vegetation type, during the 1999 growing season. Field measurements were divided into seven sampling periods beginning 5 June and ending 27 August. LAI and NDVI measurements were taken at 20 random points within each grid; the same 20 points were used throughout the growing season. NDVI was measured using an Analytical Spectral

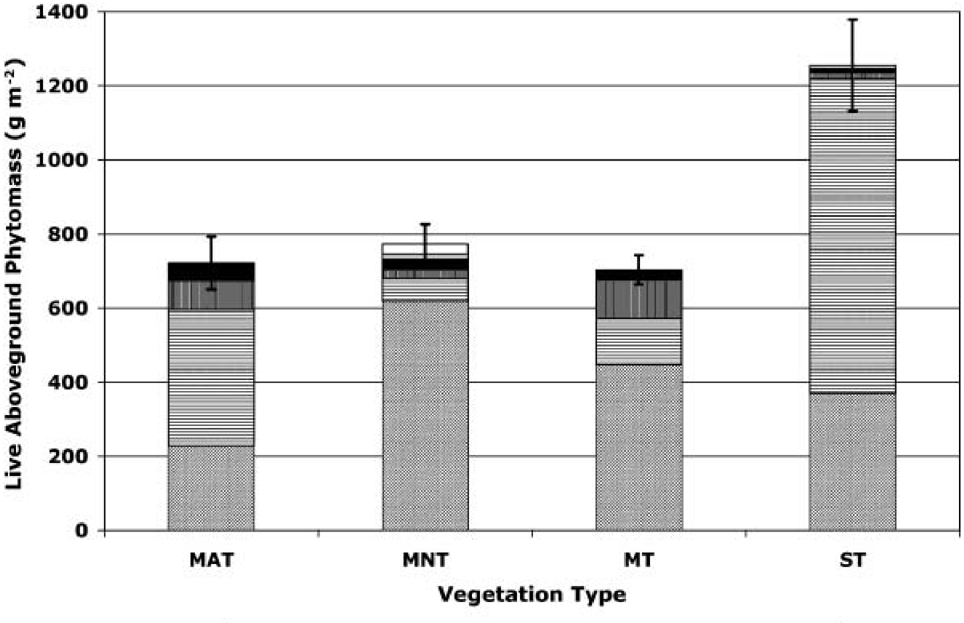

Figure 1. Live above-ground phytomass composition (g m^{-2}) of the four vegetation types at Ivotuk, Alaska.

Devices FieldSpec spectroradiometer (Analytical Spectral Devices 1998). The reflectance data for the pertinent wavelength intervals were used to calculate NDVI from the formula:

$$\mathrm{NDVI}=\frac{(\mathrm{NIR}-\mathrm{Red})}{(\mathrm{NIR}+\mathrm{Red})} \tag{1}$$

where NIR is the near-infrared reflectance (725–1060 nm), and Red is the red reflectance (580–680 nm) of the vegetation. Four replicate measurements were taken 1 m north, east, south, and west of each grid point and averaged to give a mean NDVI value. The fibre-optic sensor of the FieldSpec spectroradiometer was held approximately 1.5 m above the surface of the vegetation, providing a 0.35 m^2 footprint using a 25° field of view.

LAI, which is simply the total leaf area per unit ground surface area ($m^2 m^{-2}$), is commonly measured optically, as it was in this study, using a LI-COR LAI-2000 Plant Canopy Analyzer (Lincoln, Nebraska, USA). Above- and below-canopy radiation measurements are made with a 'fish eye' optical sensor with a five-ring 148° angle of view. Below-canopy measurements were made just above the moss layer. LAI is calculated using a model of radiative transfer in vegetation canopies and then stored in the unit data logger. At each of the 20 grid points, one above-canopy reading was taken, and four below-canopy readings were taken (1 m north, east, south and west of the grid point) to yield a single LAI value.

Above-ground phytomass was collected from 10 randomly selected 20 cm × 50 cm plots within each grid, for a total of 1 m^2 per vegetation type for each of the first six sample periods. Phytomass sampling occurred near, but not within, the footprints of LAI and NDVI measurements. On the fourth sample period (15–26 July), the number of phytomass plots harvested was doubled for MAT and MT. On the fifth sample period (27 July to 7 August), the number of phytomass plots harvested was doubled for MNT and ST. Vascular plants were clipped at the top of the moss surface; mosses were clipped at the base of the green layer. Phytomass samples were sorted into six main categories (horsetails, other forbs, graminoids, lichens, mosses, and shrubs). The graminoid and shrub samples were sorted further into subcategories. Graminoid phytomass was divided into live and dead material. Shrub phytomass was divided into evergreen and deciduous, which were then separated into woody, foliar live, and foliar dead components. Dead material was combined into a single pool, referred to as *standing dead*. Therefore when we refer to specific components of phytomass or total phytomass, we are referring only to the above-ground live fraction.

Statistical analyses were performed on several levels of data aggregation. First, data were grouped by each of four vegetation types and six sample periods (individual grid point measurements for each vegetation type were averaged for each sample period), to investigate relationships across all vegetation types (n=24; four vegetation types × six sample periods) and within vegetation types (n=6; six sample periods). Second, individual grid point measurements were compared to investigate how relationships varied throughout the growing season (n=80 for NDVI vs LAI, n=40 for NDVI or LAI vs phytomass). Regression analyses were performed using SPSS 8.0 to establish relationships between vegetation indices (such as NDVI and LAI) and total live phytomass, between vegetation indices and specific components of phytomass, and between NDVI and LAI.

3. Results

3.1 *Correlation of NDVI to vegetation properties*

When the data were grouped by vegetation type and sample period ($n=24$), mean NDVI was significantly related to mean total live phytomass ($r^2=0.42$, $p<0.05$), as well as several components of phytomass (table 1). Aside from the forb component, all the phytomass components that exhibited significant relationships with NDVI consisted, either completely or partially, of subsets of shrub phytomass. The photosynthetic component of total phytomass (all live phytomass excluding woody material) surprisingly showed no significant relationship with mean NDVI. The phytomass component that showed the strongest correlation to mean NDVI was the live foliar deciduous shrub phytomass. A power curve provided the best fit for this relationship ($\mathrm{NDVI}=0.5987\times\mathrm{FolDecShrub}^{0.0559}$, $r^2=0.77$, $n=24$, $p<0.05$, where foliar deciduous shrub phytomass (FolDecShrub) is in units of $\mathrm{g\,m^{-2}}$ and its coefficient has the appropriate units for producing a unitless NDVI value) (figure 2(*a*)).

When examining the data within individual tundra vegetation types ($n=6$), mean NDVI was not significantly related to mean total live phytomass. Mean NDVI showed the strongest relationship to the mean live foliar deciduous shrub component of phytomass for MAT ($r^2=0.93$, $p<0.05$) and ST ($r^2=0.87$, $p<0.05$) (figure 2(*b*)). However, for MNT and MT the strongest relationship observed was

Table 1. Significance level of linear regressions and coefficient of determination values (r^2) of relationships between specific phytomass components and NDVI across all vegetation types for data grouped by vegetation type and sampling period ($n=24$). Components in bold are significantly related to NDVI ($p<0.05$).

Phytomass component	*p* value	r^2
Live graminoid	0.469	0.024
Dead graminoid	0.837	0.002
Total graminoid	0.941	0.000
Moss	0.804	0.003
Lichen	0.721	0.006
Horsetail	0.407	0.031
Forb	**0.009**	**0.275**
Woody deciduous shrub	**0.007**	**0.288**
Live foliar deciduous shrub	**0.000**	**0.662***
Dead foliar deciduous shrub	0.425	0.029
Total foliar deciduous shrub	**0.001**	**0.399**
Woody evergreen shrub	0.773	0.004
Live foliar evergreen shrub	0.765	0.004
Dead foliar evergreen shrub	0.065	0.146
Total live foliar shrub	**0.002**	**0.357**
Total foliar shrub	**0.000**	**0.506**
Total live shrub	**0.001**	**0.422**
Total dead shrub	0.663	0.009
Total shrub	**0.002**	**0.370**
Photosynthetic biomass	0.297	0.049
Total live biomass	**0.001**	**0.417**
Total dead biomass	0.662	0.009
Total biomass	**0.001**	**0.421**

*Strongest relationship.

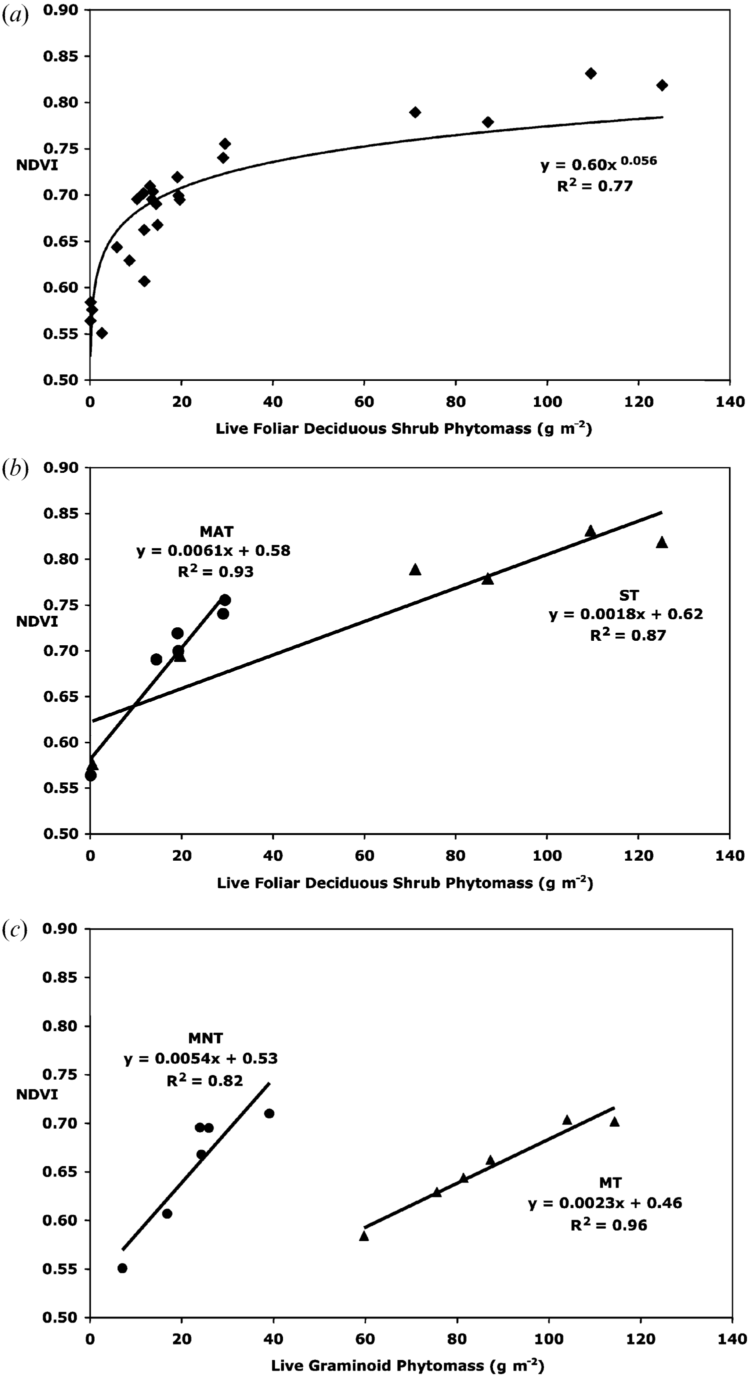

Figure 2. (*a*) The relationship between mean live foliar deciduous phytomass and mean NDVI for data grouped by vegetation type and sampling period. (*b*) The relationship between mean live foliar deciduous phytomass and mean NDVI for moist acidic tundra (MAT) and shrub tundra (ST) for data grouped by sampling period. (*c*) The relationship between mean live graminoid phytomass and mean NDVI for moist non-acidic tundra (MNT) and mossy tussock tundra (MT) for data grouped by sampling period.

between mean NDVI and mean live graminoid phytomass ($r^2=0.82$, 0.96, respectively; $p<0.05$) (figure 2(*c*)).

Analysis of data grouped by vegetation type and sample period revealed a significant linear relationship between mean NDVI and mean LAI ($\mathrm{NDVI}=0.0487\times\mathrm{LAI}+0.6001$, $r^2=0.23$, $p<0.05$). No significant relationships between NDVI and LAI existed within vegetation types.

3.2 *Correlation of LAI to phytomass*

The best relationship between LAI and phytomass was observed between mean LAI and the mean overstorey (total phytomass excluding moss and lichen) component of phytomass ($r^2=0.66$, $p<0.05$) (figure 3). Mean LAI was significantly related to mean total live phytomass ($r^2=0.47$, $p<0.05$), as well as several components of phytomass (table 2). The phytomass components that exhibited significant positive relationships consisted of either or both the woody and foliar deciduous shrub components of phytomass.

3.3 *Seasonal patterns of relationships*

Comparison of relationships at different times of the growing season indicated the strongest correlations occurred during mid to late growing season in all three vegetation property comparisons (NDVI vs phytomass, LAI vs phytomass, and NDVI vs LAI). This analysis was accomplished by using each of the individual grid point samples within each sampling period. For relationships between NDVI or LAI and phytomass several of the key phytomass components demonstrated a peak in coefficient of determination values (r^2) during mid growing season. The strongest relationships between NDVI and the deciduous live foliar ($r^2=0.69$) and total live ($r^2=0.59$) components of phytomass occurred during the sample period from

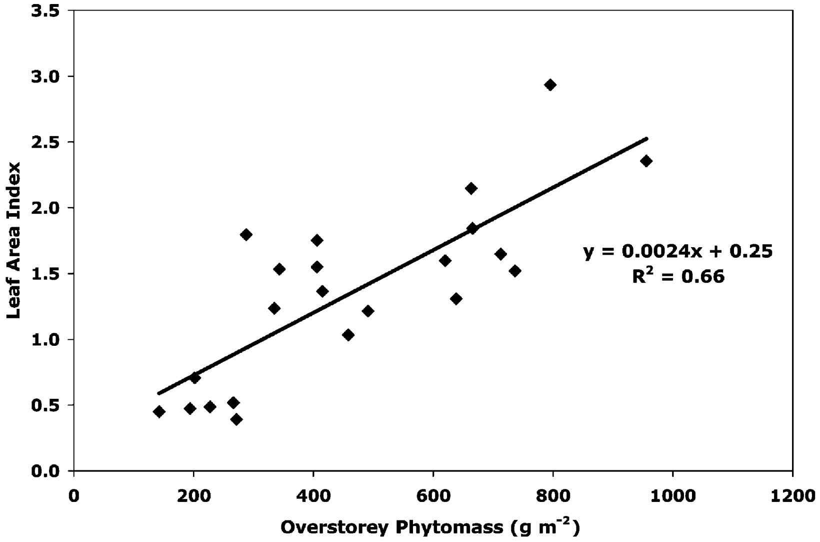

Figure 3. The relationship between mean overstorey phytomass and mean LAI for data grouped by vegetation type and sample period ($n=24$).

Table 2. Significance level of linear regressions and coefficient of determination values (r^2) of relationships between specific phytomass components and LAI across all vegetation types for data grouped by vegetation type and sampling period (n=24). Components in bold are significantly related to LAI (p<0.05).

Phytomass component	p value	r^2
Live graminoid	0.313	0.048
Dead graminoid	0.361	0.040
Total graminoid	0.330	0.045
Moss	**0.036**	**0.193**
Lichen	0.515	0.020
Horsetail	**0.000**	**0.530**
Forb	0.643	0.010
Woody deciduous shrub	**0.001**	**0.393**
Live foliar deciduous shrub	**0.003**	**0.343**
Dead foliar deciduous shrub	0.124	0.109
Total foliar deciduous shrub	**0.003**	**0.343**
Woody evergreen shrub	0.278	0.056
Live foliar evergreen shrub	0.876	0.001
Dead foliar evergreen shrub	**0.024**	**0.219**
Total live foliar shrub	**0.020**	**0.233**
Total foliar shrub	**0.008**	**0.287**
Total live shrub	**0.000**	**0.533**
Total dead shrub	0.998	0.000
Total shrub	**0.000**	**0.486**
Overstorey biomass	**0.000**	**0.663***
Total live biomass	**0.022**	**0.225**
Total dead biomass	0.275	0.057
Total biomass	**0.005**	**0.323**

*Strongest relationship

2 to 10 July (figure 4(*a*)). The strongest relationship between NDVI and the live shrub component of phytomass (r^2=0.72) occurred during the sample period from 15 to 25 July. The strongest relationships between LAI and the deciduous woody (r^2=0.41), live shrub (r^2=0.50), overstorey (r^2=0.50), and total live (r^2=0.25) components of phytomass occurred during the sample period from 15 to 26 July (figure 4(*b*)).

The relationship between NDVI and LAI became stronger as the growing season progressed (figure 4(*c*)), with a peak correlation for sampling conducted from 13 to 20 August ($\mathrm{NDVI}=0.6647\times(\mathrm{LAI})^{0.0534}$, $r^2=0.59$, $p<0.05$) (figure 5) with a slight drop at the end of the season. The relationships were generally best described by simple linear functions, except for the last two sample periods in which a power relationship demonstrated the best fit for the data.

3.4 *Reanalysis of relationships considering seasonal patterns*

Due to the presence of seasonal patterns in the relationships, regression analyses were performed on data grouped by vegetation type and by sample period using only mid or late season data. The relationship between mean NDVI and mean total live phytomass was improved when only mid-season data were included in the regression. This relationship was best described by a linear function ($\mathrm{NDVI}=0.002\times\mathrm{TotLive}+0.59$, $r^2=0.66$, $n=12$, $p<0.05$, where total live phytomass (TotLive) has units of $\mathrm{g\,m^{-2}}$ and its coefficient has units of $\mathrm{m^2\,g^{-1}}$)

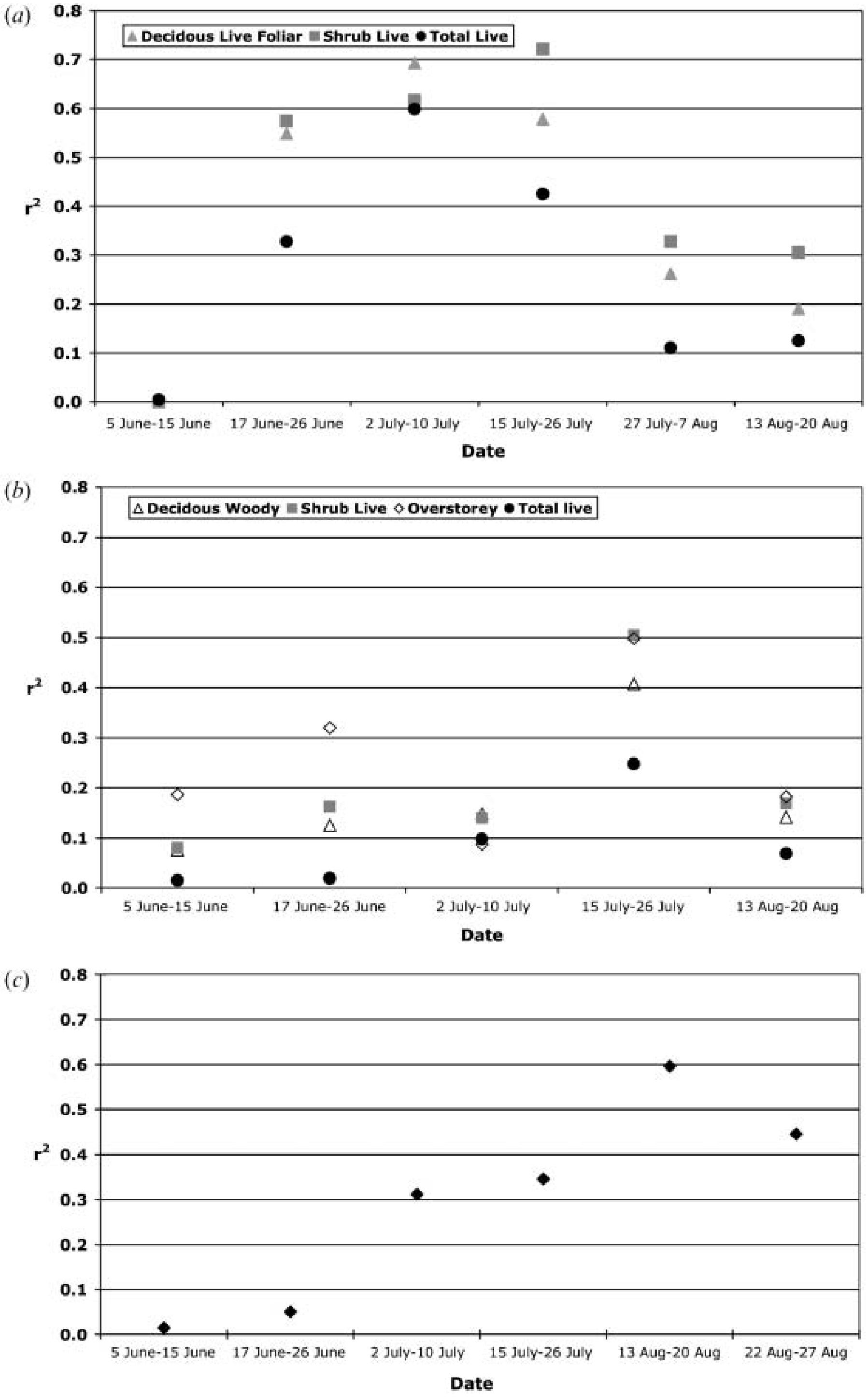

Figure 4. (*a*) Coefficient of determination values (r^2) for relationships between three phytomass components and NDVI over the 1999 growing season. (*b*) r^2 values for relationships between four phytomass components and LAI over the 1999 growing season. (*c*) r^2 values for relationships between NDVI and LAI over the 1999 growing season.

(figure 6) for data collected in periods 2–4 (17 June to 26 July). The relationships between mean LAI and mean total live phytomass or mean overstorey phytomass did not become significantly stronger when using only mid season data. The relationship between mean NDVI and mean LAI became only slightly stronger when early season data were excluded from the analysis and was similar to the relationship observed when analysing the data for only sample period 6 (13–20 August) (figure 5).

4. Discussion

As suggested by the findings of Hope *et al.* (1993), the photosynthetic component of phytomass was expected to have a significant influence on the spatial and temporal variance of NDVI. However, our results surprisingly did not reveal a significant relationship between NDVI and the total photosynthetic component of phytomass. Rather a subset of photosynthetic phytomass, the live foliar deciduous shrub component of phytomass, exerted the greatest control on NDVI. This is true when all vegetation types are combined and for two of the four vegetation types individually, moist acidic tundra (MAT) and shrub tundra (ST). For the moist non-acidic (MNT) and mossy tussock tundra (MT) live graminoid phytomass had the greatest control on NDVI. The discrepancy as to which phytomass component exhibits the greatest control on NDVI within a vegetation type can most likely be attributed to the absence or presence of substantial shrub phytomass. In the MNT and MT the live shrub phytomass makes up only 11% and 19% of total live phytomass, respectively, which is substantially lower than in the MAT and ST (51% and 63%, respectively). The relatively low quantity of shrub phytomass found in the MNT and MT means that variations in other phytomass components, such as graminoids, could have a greater effect on NDVI. The fact that

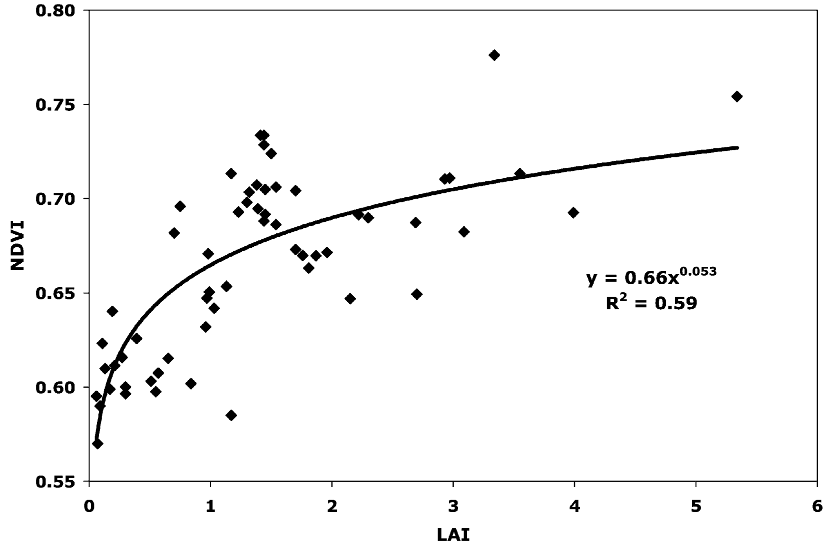

Figure 5. The relationship between LAI and NDVI using individual grid point data taken during sample period 6 (13–20 August).

the absence or presence of substantial quantities of shrub phytomass determines the relationships between NDVI and phytomass components within a vegetation type supports the conclusion that quantities of shrub phytomass are the most important factor controlling levels of NDVI across all vegetation types. This was demonstrated by the relationship observed in this study (figure 2(*a*)) and is consistent with previous studies conducted on tundra vegetation (Hope *et al.* 1993, Walker *et al.* 1995).

The results from this study suggest that the quantity of overstorey phytomass has the strongest influence on LAI. In examining which phytomass components were significantly related to LAI, it is evident that deciduous foliar shrub material had a strong impact on LAI when examining across vegetation types. Obviously foliar phytomass was expected to control values of LAI, but the fact that woody material had such a significant influence on LAI is most likely due in part to the method of measurement (attenuation of solar radiation) and in part to the fact that woody phytomass and foliar material are covariates. Although strong relationships were observed between LAI and several phytomass components across all vegetation types, when examining within individual vegetation types no significant relationships were found.

The high variability of NDVI and LAI observed within a vegetation type also resulted in the absence of a strong correlation between NDVI and LAI within any of the individual vegetation types. While a significant relationship was observed across all vegetation types, the strongest correlation occurred when comparing individual grid point data taken late in the growing season. The relationship between NDVI and LAI became stronger as the growing season progressed, until peaking at the second to last sampling period (13–20 August). This seasonal trend suggests that the relative abundances of material, that are contributing differently to values of either LAI or NDVI, may not be in balance early in the growing season and fluctuate across the growing season. For example, early in the growing season the relative amount of woody material is greater than at peak season, which would influence values of LAI (with this methodology) while having minimal effect on NDVI. Additionally, late in the growing season the relationship between NDVI and LAI becomes non-linear (13–27 August). The non-linear nature of relationships of NDVI to vegetation properties could be explained by the fact that as vegetation density increases late in the growing season, the ability for chlorophyll to absorb more incident red light saturates with respect to increased phytomass or LAI (Shippert *et al.* 1995). Therefore, patches or sites with dense phytomass reach a point where the NDVI is no longer sensitive to increases of phytomass or LAI.

Similar to the relationships between NDVI and LAI, the strength of the relationships changed substantially over the course of the growing season when comparing both NDVI and LAI to phytomass. The strongest relationships were observed in July, during mid growing season, when plant growth had reached sufficient levels to influence spectral indices, yet before there was substantial plant tissue senescence.

4.1 *Implications for modelling*

The results from this study illustrated that the period of the growing season in which sampling is conducted, non-linearity of relationships, and plant composition are important factors to consider when using relationships between NDVI, LAI and

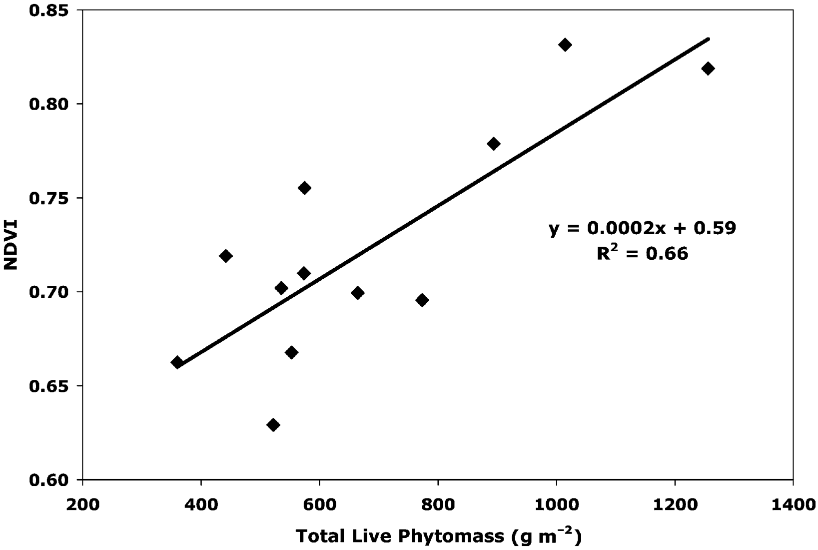

Figure 6. The relationship between mean total live phytomass and mean NDVI for data grouped by vegetation type and sampling period. The data are for sampling conducted from 17 June to 26 July (n=12).

phytomass to parameterize or validate ecological models. The fact that the relationships are not constant over the growing season (Hope *et al.* 1993) suggests that when estimating phytomass or LAI from spectral data it is best to do so during mid to late growing season. For example, estimating phytomass from the relationships found in this study using NDVI values obtained at times other than mid growing season would reduce accuracy.

The power relationships observed in our results are consistent with past researchers who have found non-linear relationships between NDVI and vegetation properties, such as LAI and phytomass (Hope *et al.* 1993, Shippert *et al.* 1995). When there is substantial landscape-scale spatially heterogeneity, non-linear relationships further complicate the process of upscaling (Friedel *et al.* 1995, Harvey 2000) and could lead to inconsistencies when using spectral indices to infer phytomass or LAI at coarser scales. With non-linear relationships, at high levels of NDVI there is relatively greater variability in LAI or phytomass thus decreasing the predictability of these ecological variables. Small errors in NDVI can lead to large errors in the variable being predicted. Harvey (2000) identified two key steps that are necessary for upscaling when non-linear relationships are involved. First, the level and extent of the spatial heterogeneity must be correctly identified. This study and several past studies in the tundra have focused on establishing relationships at a detailed spatial scale and consequently address this issue (Hope *et al.* 1993, Stow *et al.* 1993, Shippert *et al.* 1995, Walker *et al.* 1995, Jia *et al.* 2002). Second, an appropriate method must be used to integrate or aggregate the spatial heterogeneity found at small spatial scales into estimates at coarser scales. Several suggested solutions to this challenge in upscaling include using a deterministically distributed model, a statistically distributed model, or by explicit spatial integration (King 1991, Harvey 2000).

However, another approach is to disregard the non-linearity. This method may be valid when the relationship is nearly linear and thus scaling errors introduced by spatially averaging would be minor or may cancel (Friedl *et al.* 1995, Harvey 2000). In the relationship between NDVI and LAI (figure 5), less than 10% of the observations were found in the range of LAI (>3) in which NDVI begins to saturate and subsequently the consequences of the non-linearity may be minor. Due to the low values of LAI in tundra vegetation the saturation of NDVI with respect to LAI may not be as large a problem as in other systems.

Shrub phytomass, especially the live foliar deciduous shrub phytomass, was the major factor affecting NDVI across all vegetation types. The live foliar deciduous shrub component represented less than 10% of the total live phytomass but explained almost 80% of the variance of NDVI. However, quantities of live foliar shrub phytomass were strongly correlated to quantities of total live shrub phytomass. When considering that a substantial portion of the total live phytomass consists of live shrub phytomass (42%), it is not surprising that approximately 66% of the variance of peak season NDVI was explained by total live phytomass (figure 6). Therefore, the results from this study suggest that NDVI is useful in estimating levels of total live phytomass even though it is significantly affected by the presence of shrub foliar phytomass.

LAI is a valuable vegetation index to be able to estimate due to its relation to several important ecosystem processes (such as photosynthesis, transpiration, foliar N, and above-ground net primary productivity (ANPP)). Estimating total live above-ground phytomass is useful in describing carbon storage and other ecosystem functions. The ability to predict these variables from remotely sensed data is essential for modelling vegetation and is dependent on relationships established from field studies conducted at a high level of detail. While there are several complications, made evident in this study, in deriving vegetation properties from NDVI, our results provide a means for predicting these important ecological variables for use in modelling studies or to monitor changes in community structure over time.

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