Relationships of NDVI, Biomass, and Leaf Area Index (LAI) for six key plant species in Barrow, Alaska

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Abstract

Here we investigate relationships between NDVI, Biomass, and Leaf Area Index (LAI) for six key plant species near Barrow, Alaska. We explore how key plant species differ in biomass, leaf area index (LAI) and how vegetation spectral indices be used to estimate biomass and LAI for key plant species. A vegetation index (VI) or a spectral vegetation index (SVI) is a quantitative predictor of plant biomass or vegetative vigor, usually formed from combinations of several spectral bands, whose values are added, divided, or multiplied in order to yield a single value that indicates the amount or vigor of vegetation. For six key plant species, NDVI was strongly correlated with biomass ($R^2 = 0.83$) and LAI ($R^2 = 0.70$) but showed evidence of saturation above a biomass of 100 g/m$^2$ and an LAI of 2 m$^2$/m$^2$. Extrapolation of a biomass-plant cover model to a multi-decadal time series of plant cover observations suggested that Carex aquatilis and Eriophorum angustifolium decreased in biomass while Arctophila fulva and Dupontia fisheri increased 1972-2008.

Introduction

High latitude arctic ecosystems are undergoing dramatic changes in response to climate change (Post et al., 2009, Hinzman et al., 2005, Smith et al., 2005) IPCC 2007, ACIA 2005. Arctic vegetation is particularly sensitive to climate change (Walker et al., 2005, Epstein et al., 2008, Myneni et al., 1997). A slight change in summer air temperatures, for example, has the capacity to cause major changes in plant growth (Arndal et al., 2009), vegetation structure (Riedel et al., 2005), phytomass (Epstein et al., 2008), species diversity, and shifts in altitudinal and zonal vegetation boundaries (Walker et al., 2005, Jia et al., 2003). Changes in vegetation biomass have important consequences for many components of the Arctic System including surface energy budgets (Chapin et al.,
2005), permafrost (Shiklomanov et al., 2010) and hydrological cycles (Vorosmarty et al. 2008). Changes in plant growth also have important feedbacks to the Climate System through changes in ecosystem carbon balance (Schuur et al., 2009, McGuire et al., 2006). Therefore, understanding how vegetation biomass changes across different arctic ecosystems is key to understanding the future state of ecosystem structure and function in the Arctic.

Optical remote sensing is a valuable tool capable of assessing changes in plant biomass and other ecosystem properties and processes in response to climate change at multiple spatial scales panning leaf to ecosystem to global scales (Huemmrich et al., 2010b, Sitch et al., 2007, Riedel et al., 2005, Boelman et al., 2003). Remote sensing, apart from being the only suitable tool for repeated assessment of vegetation properties such as phenology and biomass at regional to continental scales, is particularly well suited to monitoring changes in arctic ecosystems because of the logistical difficulties in accessing these vast and mostly unpopulated areas. Satellite based sensors such as AVHRR, MODIS, Landsat have either daily coverage and/or accessible historical time series data of the Arctic, which provides opportunities for monitoring long term change (Bhatt et al., 2010, Olthof et al., 2008, Myneni et al., 1997) in factors such as biomass and leaf area index (LAI) (Riedel et al., 2005, Riedel et al. 2005, Walker et al. 2003, Hansen 1991). Large scale studies in the Arctic have used optical remote sensing indices (i.e. NDVI) using data from satellite platforms to study long-term changes in vegetation greenness (Bhatt et al., 2010, Olthof et al., 2008, Myneni et al., 1997). For a majority of these studies, ground-based data suitable for calibrating and validating remote sensing products are lacking.

Even though ground based validation of satellite-derived indices of biomass is well explored in other ecosystems (Soenen et al., 2010, Gamon et al., 1995) Pontailer et al. 2003 only a few studies have related plot level spectral reflectance indices to aboveground biomass or land-atmosphere CO$_2$ fluxes in the Arctic (Arndal et al., 2009, Epstein et al., 2008, Boelman et al., 2003). Some studies have related spectral reflectance to CO$_2$ fluxes to demonstrate the usefulness of NDVI in arctic landscape (Huemmrich et al., 2010a, La Puma et al., 2007, McMichael et al., 1999), while other studies have demonstrated the usefulness of spectral indices in estimating aboveground biomass (Epstein et al., 2008), and biomass and landscape age (Walker et al. 1995). However, total live plant biomass and net primary productivity is highly variable among arctic plant communities (Riedel et al., 2005, Shaver et al., 1996). More studies are required, therefore, to explore and establish fundamental relationships between optical measurements and ecosystem properties and processes in the Arctic.

In this study we explore the relationship between above-ground biomass, LAI and NDVI for six vascular plant species common in tundra near Barrow, Alaska (Johnson et al., 2011, Hollister et al., 2006) Webber et al. 1978. To extrapolate these relationships to the landscape level and over decadal time scales in order to assess how ecosystem structure and function may have altered, we used plant community data from an International Polar Year Back to the Future (BTF) study (Callaghan et al. 2011, Villarreal et al. Accepted), which revisited sites established in Barrow during International Biome Program (IBP, Brown et al. 1980, Webber et al. 1978).
Method

Site Description

Data for this study were collected on or near the Barrow Environmental Observatory (BEO), Alaska, 71°17'01” N, 156°35'48” W. The site is situated on the northern-most point of the Alaskan Arctic Coastal Plain and has a low relief and an average elevation of 4 meters (Aguirre et al. 2008). Seventy two percent of the landscape near Barrow contains oriented lakes, drained thaw lake basins and small ponds (Hinkel et al., 2003). The region is underlain by continuous permafrost and includes thermokarst terrain typical of the Alaskan Arctic Coastal Plain (Brown et al. 1980), such as thaw lakes, high and low-centered polygons, shallow ponds and lakes. Active layer is generally less than 50 centimeters (Shiklomanov et al., 2010). Soils of the area have been described by (Bockheim et al., 1999) and include cryoturbated gelisols, specifically Typic Aquorthels with high soil moisture content, Histoturbels, and Aquaturbels. The upper layer of this soil consists of carbon rich peat (ca. 50 kg/C/m$^3$) (Bockheim et al., 1999). Soils are generally moisture rich due to shallow drainage gradients, relatively low rates of evapotranspiration, and impeded drainage caused by ice-rich continuous permafrost (Liljedahl et al., 2011, Bockheim et al., 1999) Miller et al. 1998.

Biomass Harvest

Plant species selected for the study included Arctophila fulva, Carex aquatilis, Dupontia fisheri, Eriophorum angustifolium, Eriophorum scheuchzeri and Petasites frigidus. These six species are among the eight most common vascular plant species in the Barrow area (Hollister et al., 2006, Johnson et al., 2011) (Webber et al. 1978. Fifteen plots were selected for harvesting of above ground biomass (Table 1). The selected plots had dense mono-specific plant cover for a respective key plant species, which was considered to equate to 100% cover of the respective species. All plots were chosen so that there was no standing water present. Green fractions of the above ground plant biomass were harvested using a circular ring 23.3 cm in diameter. Green biomass within the plots was harvested and stored in zip-lock bags and kept cool. Harvested biomass was sorted within a few hours for any impurities then weighed using an Explorer Ohaus balance with accuracy of 0.0001g. Samples were then oven dried and weighed several times until no further loss in weight was recorded. The mean biomass for each species was calculated by averaging values for all plots of the same species.

Biomass for each of the plots was also calculated as follows:

\[ \text{Biomass} = (\text{Dry Weight}) \times 0.054 \text{ gm/m}^2 \]  
Equation (1)

Here 0.54 m$^2$ is the area for each of the harvest plots.

Spectral Data Collection

Spectral reflectance data for all the vegetation plots were collected before the plots were harvested using a dual-detector field portable spectrometer (Unispec DC, PP Systems, Amesbury, MA, USA), which collects radiance (radiation from the target) and irradiance.
(radiation from the sky) simultaneously, thereby permitting correction of surface reflectance under varying sky conditions (Gammon et al., 2006). The two detectors were cross-calibrated using a white panel with 99% reflectance (Spectralon, Labsphere, North Sutton, NH, USA) several times during spectral measurements. The Unispec-DC had a nominal range of operation between 303 and 1148 nm in 256 contiguous bands with a spectral resolution of approximately 3 nm and a full-width-half maximum of approximately 10 nm. The usable range of this detector (range with reasonable signal-to-noise) is approximately 400-1000 nm. The downward looking sensor has a field of view of 20 degrees and therefore to cover a plot size of diameter 23.3 cm, spectral scans were taken at a height of 78 cm above the plots. Measurements were taken around mid-day.

For each plot sampled, the normalized difference vegetation index (NDVI) (Sims and Gamon, 2003) was derived from the hyperspectral reflectance data (Equation 2). NDVI is indicative of the abundance of photosynthetically active vegetation (Rouse et al. 1974).

\[ \text{NDVI} = \frac{(R_{800} - R_{680})}{(R_{800} + R_{680})} \]  \hspace{1cm} \text{Equation (2)}

Here R680 and R800 are reflectance values at 680nm, 800nm wavelengths respectively. Average NDVI for each species were calculated by averaging NDVI values for all plots in which each key plant species was found.

**Calculation of Leaf Area Index (LAI)**

Digital photos of the vegetation plots were taken before the plots were harvested using a Nikon Coolpix 5400 digital camera. The photos were taken with an automatic exposure looking vertically down at the plots to capture a rectangular area of roughly 50cm by 50cm. The color images were recorded in JPEG format and downloaded for further processing. LAI was derived from the digital images using GreenCropTracker v.1.0 software (Liu and Pattey, 2010) developed by Agriculture and Agri-Food Canada. This software is provided free of cost and uses the IDL (Interactive Data Language) virtual machine freely available from ITT Corporation, USA and calculates vegetation green cover fraction and LAI from color digital images. The software applies a simple transformation to generate a feature representing greenness from three color channels i.e. Red (R), Green (G), and Blue (B):

\[ \text{Greenness} = 2G – B – R \]

Here, R, G and B represent the intensity levels recorded for each color by the digital camera. The transformation uses the high contrast between the reflected intensity of green leaves and other background color associated with features like dead material, soil etc. A sequential threshold approach based on histogram analysis is used to calculate canopy vertical green fraction. LAI is estimated from the vertical gap fraction as follows Equation (3):

\[ LAI = -2\ln(Po(0)) \]  \hspace{1cm} \text{Liu and Pattey, 2010)} \hspace{1cm} \text{Equation (3)}
In Equation (3) Po(0) refers to the gap fraction at a solar zenith angle zero. For a detailed derivation of this equation, refer to Liu and Pattey (2010). Average LAI values for each species were calculated by averaging all the plots for each species.

Data Analysis

To investigate statistical differences in NDVI, LAI and biomass among different species, one-factor ANOVA were performed using JMP v 7.0. Average values for each of the above mentioned parameters for each of the species were calculated and plotted as bar graphs using Excel 2007. Error bars indicating one standard deviation were added to each data series. To explore how NDVI and LAI relate to biomass, linear regression analyses were performed for all species combined and for only the graminoids using data from all plots and all species. Biomass regression models were developed with NDVI, LAI as individual inputs.

To investigate decadal time scale change, biomass was modeled for five species i.e. *Arctophila fulva*, *Carex aquatilis*, *Dupontia fisheri*, *Eriophorum angustifolium*, *Eriophorum scheuchzeri*, using mean percent cover data available for these species for 1972 and 2008 in the Barrow IBP study sites. Using biomass data measured for these species for the hundred percent species cover harvest plots, biomass were estimated for these particular species for 1972 and 2008 were calculates using the percent cover data available for the Barrow IBP study sites. This helped us to investigate if we could use our method to model biomass in decadal time scale using existing data which could potentially be helpful in understanding how arctic plant communities have changed over decadal time scales in response to climatic and other change is imperative (Finzi et al. 2011).

Results

Plots that were selected for this study were free from standing water and were deemed to have hundred percent vegetation cover for the respective species of interest. *Dupontia fisheri* had the highest NDVI (0.87) closely followed by *Arctophila fulva* (0.82) and *Petasites frigidus* (0.77). *Eriophorum scheuchzeri* had the lowest NDVI values (0.50). *Arctophila fulva* had the highest LAI (3.53) followed by *Dupontia fisheri* (2.49), *Carex aquatilis* (1.88), *Petasites frigidus* (1.74), and *Eriophorum scheuchzeri* had the lowest LAI (0.56). *Arctophila fulva* had the highest aboveground biomass (136.81 g/m²) followed by *Dupontia fisheri* (43.48 g/m²), *Carex aquatilis* (40.09 g/m²) and *Eriophorum angustifolium* (36.66 g/m²). *Eriophorum scheuchzeri* had the lowest biomass among all the species studied (11.66 g/m²) (Table 4.1 and Fig. 4.1).

NDVI showed strong exponential relationships with both LAI (Figs. 4.2a, 4.2b) and aboveground biomass (Figs. 4.2c, 4.2d). The relationship between NDVI and LAI for graminoids was slightly stronger with $R^2 = 0.85$ compared to that for all species combined while correlations between NDVI and biomass for graminoids was stronger ($R^2 = 0.82$) compared to that for all species combined ($R^2 = 0.70$). All the relationships between NDVI, LAI and biomass showed strong exponential relationships with $R^2\geq0.7$, indicating that NDVI saturates at higher biomass and LAI values. The relationship between LAI and
biomass was slightly stronger for graminoids ($R^2 = 0.88$) compared to the relationships for all species combined ($R^2 = 0.86$) (Fig. 4.3).

Analysis of the species percent cover change for the IBP plots for 1972 and 2008 showed that *Carex aquatilis* and *Eriophorum angustifolium* decreased in cover between 1972 and 2008 while *Arctophila fulva* and *Dupontia fisheri* increased in cover (Fig. 4.4a). Similarly, modeling of biomass showed that *Carex aquatilis* and *Eriophorum angustifolium* had a predicted decreased biomass in 2008 compared to 1972 while *Arctophila fulva* and *Dupontia fisheri* had increased predicted biomass cover in 2008 compared to 1972 (Fig. 4.4b). A 2.8% increase in percent cover for *Arctophila fulva* showed a 124% increase in biomass while a 3.4% increase in percent cover for *Dupontia fisheri* showed a 14.93% increase in biomass between 1972 and 2008. The 13.36% decrease in percent cover for *Carex aquatilis* suggested a 33.92% decrease in of biomass whereas a 1.59% decrease in percent cover for *Eriophorum angustifolium* showed a 14.65% decrease in biomass. As *Eriophorum scheuchzeri* had very low percent cover and biomass, it was not included in this analysis.

**Discussion**

In the Arctic, ecosystem properties such as standing plant biomass appears to be sensitive to phenomenon associated with climate change such as warming (Bhatt et al. 2010, Hollister et al. 2006, Walker et al. 2005, Epstein et al. 2000). Changes in vegetation biomass have important consequences for many components of the Arctic system including surface energy balance and permafrost (Euskirchen et al. 2007, Chapin et al. 2005), hydrology (Post et al. 2009, Hinzman et al. 2005) and wildlife. Optical remote sensing is the only feasible tool for regional scale monitoring and assessment of change in vegetation properties such as biomass and LAI (Stow et al. 2004), which is essential for understanding processes such as land-atmosphere carbon balance (Merbold et al. 2009, Wolf et al. 2008), and therefore, the future state of the Arctic and Earth Systems as they respond to climate change (IPCC 2007, ACIA 2005). Establishing sound spatio-temporal relationships between remote sensing products and ground based measurements underpins capacities of being able to extrapolate ecosystem properties and processed from the plot level to landscape and global scales (Boelman et al. 2003). This study aimed to develop such relationships between above ground biomass, LAI and NDVI for six common plant species found in tundra near Barrow, Alaska using ground based plot level measurements. To explore the potential of scaling these relationships over decadal time scales, data from a historic plant community resampling effort associated with the International Polar Year Back to the Future (BTF) study (Callaghan et al. 2011) were used that resampled sites formerly associated with the IBP field site near Barrow (Villarreal et al. Accepted).

The results showed that the NDVI values for the six species studied varied within a range of ~ 0.3 with corresponding change in values in LAI and biomass. The strong relationships between NDVI and biomass and LAI for the species studied support the use of NDVI as a spectral index for indirectly measuring plant community structure. The strong relationship between NDVI and biomass found in this study is similar to studies conducted in other tundra ecosystems including tussock tundra (Boelman et al. 2003), shrub and high
arctic tundra (Walker et al. 2003). While Boelman et al. (2003) reported a linear relationship between NDVI and biomass, Walker et al. (2003) reported an exponential relationship between NDVI and biomass, similar to our finding. Further investigation of these relationships throughout the growing season could be helpful to strengthen these relationships.

The strong exponential relationships between NDVI and biomass and NDVI and LAI suggest that NDVI saturates for higher values of biomass ($>100 \text{ g/m}^2$) and LAI ($>2 \text{ m}^2/\text{m}^2$). On the other hand, the strong linear relationship between LAI and biomass suggests that there is no saturation in the measurement of biomass from LAI. The saturation of NDVI for higher biomass and LAI is well reported for non-arctic studies (Santin-jain et al. 2009, Huete et al. 2002) whereas these relationships are reported to be both linear (Boelman et al. 2003) and exponential (Walker et al. 2003) in the Arctic. Our vegetation plots were chosen to have 100 percent species cover without any standing water and minimal litter and standing dead matter. This probably resulted in an unusually high LAI and biomass, suggesting the linearity of the relationship between LAI and biomass requires more extensive exploration in the Arctic.

It is important to understand how arctic plant communities have changed over decadal time scales in response to climatic and other changes to understand the potential impact on biodiversity and ecosystem functional processes such as those associated with land-atmosphere carbon exchange (Finzi et al. 2011). Findings from the decadal extrapolation of plant cover values to biomass, for the former IBP plots suggest that three species had increased biomass while three species had decreased biomass from 1972 to 2008. This finding shows that the rate of change of biomass for some species can be different which might cause non-linear trends in greening in different tundra ecosystems as species respond differently to change. Our finding is similar to the findings of Lara et al. (Accepted) who reported that ecosystem function in different plant communities within a tundra landscape have changed at different rates over decadal time scales. To better understand the non-linear change observed for specific species in our study, more studies similar to this are needed in tundra ecosystems in Barrow as well as in other tundra ecosystems to assess which species could act drivers of such non-linear changes.

Conclusions

This study found strong plot level correlations between NDVI and biomass and LAI for six key plant species that are relatively common in tundra near Barrow, Alaska. These findings are similar to other published studies focusing on other tundra ecosystems elsewhere in the Arctic (Epstein et al. 2008, Riedel et al. 2005, Boelman et al. 2003). However, NDVI was found to saturate at an approximate biomass of 100 g/m$^2$ and an LAI of 2 m$^2$/m$^2$, which suggests that greening of tundra could be linked to a relatively small change in species cover. LAI was not found to saturate with an increase in biomass. Extrapolating results over multiple decades to hypothesize trajectories of change in biomass, LAI and NDVI, highlight the potential importance of species level change, which has the potential to cause non-linear change in various metrics of ecosystem structure and function. Overall, results reaffirm the applicability of NDVI for large scale assessment of vegetation change in the Arctic and highlight the need for additional species specific and
multi-scale studies, which are likely to facilitate interpretation of drivers and mechanisms of change derived at large spatial scales using remote sensing approaches.

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The strong exponential relationships between NDVI and biomass and NDVI and LAI suggest that NDVI saturates for higher values of biomass ( > 100 g/m²²) and LAI ( > 2 m²/m²²). On the other hand, the strong linear relationship between LAI and biomass suggests that there is no saturation in the measurement of biomass from LAI. The saturation of NDVI for higher biomass and LAI is well reported for non-arctic studies (Santin-janin et al. 2009, Huete et al. 2002) whereas these relationships are reported to be both linear (Boelman et al. 2003) and exponential (Walker et al. 2003) in the Arctic. Our vegetation plots were chosen to have 100 percent species cover without any standing water and minimal litter and standing dead matter. This probably resulted in an unusually high LAI and biomass, suggesting the linearity of the relationship between LAI and biomass requires more extensive exploration in the Arctic.

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Estimating aboveground forest biomass from canopy reflectance model inversion in

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Table 4.1. Summary of NDVI, LAI, and biomass measurements for the six key plant species.

<table>
<thead>
<tr>
<th>Species</th>
<th>No. of Plots</th>
<th>Avg. NDVI</th>
<th>Avg. LAI</th>
<th>Avg. Biomass (g/m²)</th>
<th>Graminoid (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Species</td>
<td>Count</td>
<td>NDVI Mean ± SE</td>
<td>Biomass Mean ± SE</td>
<td>LAI Mean ± SE</td>
<td>Key Status</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-------</td>
<td>----------------</td>
<td>-------------------</td>
<td>---------------</td>
<td>------------</td>
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<tr>
<td>Arctophila fulva</td>
<td>4</td>
<td>0.82 ± 0.08</td>
<td>3.53 ± 1.03</td>
<td>136.81 ± 45.54</td>
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<tr>
<td>Carex aquatilis</td>
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<td>0.68 ± 0.10</td>
<td>1.88 ± 0.86</td>
<td>40.09 ± 15.87</td>
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</tr>
<tr>
<td>Dupontia fisheri</td>
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<td>Eriophorum angustifolium</td>
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<td>1.49</td>
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<td>Eriophorum scheuchzeri</td>
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<tr>
<td>Petasites frigidus</td>
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<td>1.74 ± 0.80</td>
<td>30.66 ± 17.55</td>
<td>No</td>
</tr>
</tbody>
</table>

Figure 4.1. Average values of NDVI, Biomass and LAI for each of the key plant species. Error bars represent ± one standard error.
Figure 4.2. Correlations between NDVI and LAI and Biomass for all species combined (left figures) and for graminoids only (right figures). All the relationships showed strong exponential relationships with $R^2 \geq 0.7$, indicating that NDVI saturates at higher biomass and LAI values.
Figure 4.3. Correlations between LAI and Biomass for all species combined (left figures) and for graminoids only (right figures). Biomass showed a strong linear relationships with LAI for both correlations ($R^2 = 0.86$ all species, $R^2 = 0.88$ graminoids).

Figure 4.4. Measured decadal change in percent cover and modeled biomass for key species in the Barrow IBP study area. The greatest percent and magnitude of increase in cover was recorded for *Arctophila fulva* and decrease for *Carex aquatilis*. The greatest percent and magnitude of increase in biomass was modeled for *Arctophila fulva* and decrease for *Carex aquatilis*. 