

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 can 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 $2 \text{ m}^2/\text{m}^2$. 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.,

42 2005), permafrost (Shiklomanov et al., 2010) and hydrological cycles (Vorosmarty et al.
43 2008). Changes in plant growth also have important feedbacks to the Climate System
44 through changes in ecosystem carbon balance (Schuur et al., 2009, McGuire et al., 2006).
45 Therefore, understanding how vegetation biomass changes across different arctic
46 ecosystems is key to understanding the future state of ecosystem structure and function in
47 the Arctic.

48 Optical remote sensing is a valuable tool capable of assessing changes in plant
49 biomass and other ecosystem properties and processes in response to climate change at
50 multiple spatial scales panning leaf to ecosystem to global scales (Huemmrich et al., 2010b,
51 Sitch et al., 2007, Riedel et al., 2005, Boelman et al., 2003). Remote sensing, apart from
52 being the only suitable tool for repeated assessment of vegetation properties such as
53 phenology and biomass at regional to continental scales, is particularly well suited to
54 monitoring changes in arctic ecosystems because of the logistical difficulties in accessing
55 these vast and mostly unpopulated areas. Satellite based sensors such as AVHRR, MODIS,
56 Landsat have either daily coverage and/or accessible historical time series data of the
57 Arctic, which provides opportunities for monitoring long term change (Bhatt et al., 2010,
58 Olthof et al., 2008, Myneni et al., 1997) in factors such as biomass and leaf area index
59 (LAI) (Riedel et al., 2005)(Riedel et al. 2005, Walker et al. 2003, Hansen 1991). Large
60 scale studies in the Arctic have used optical remote sensing indices (i.e. NDVI) using data
61 from satellite platforms to study long-term changes in vegetation greenness (Bhatt et al.,
62 2010, Olthof et al., 2008, Myneni et al., 1997). For a majority of these studies, ground-
63 based data suitable for calibrating and validating remote sensing products are lacking.

64 Even though ground based validation of satellite-derived indices of biomass is well
65 explored in other ecosystems (Soenen et al., 2010, Gamon et al., 1995) Pontailer et al. 2003
66 only a few studies have related plot level spectral reflectance indices to aboveground
67 biomass or land-atmosphere CO₂ fluxes in the Arctic (Arndal et al., 2009, Epstein et al.,
68 2008, Boelman et al., 2003). Some studies have related spectral reflectance to CO₂ fluxes to
69 demonstrate the usefulness of NDVI in arctic landscape (Huemmrich et al., 2010a, La
70 Puma et al., 2007, McMichael et al., 1999), while other studies have demonstrated the
71 usefulness of spectral indices in estimating aboveground biomass (Epstein et al., 2008), and
72 biomass and landscape age (Walker et al. 1995). However, total live plant biomass and net
73 primary productivity is highly variable among arctic plant communities (Riedel et al., 2005,
74 Shaver et al., 1996). More studies are required, therefore, to explore and establish
75 fundamental relationships between optical measurements and ecosystem properties and
76 processes in the Arctic.

77 In this study we explore the relationship between above-ground biomass, LAI and
78 NDVI for six vascular plant species common in tundra near Barrow, Alaska (Johnson et al.,
79 2011, Hollister et al., 2006) Webber et al. 1978. To extrapolate these relationships to the
80 landscape level and over decadal time scales in order to assess how ecosystem structure and
81 function may have altered, we used plant community data from an International Polar Year
82 Back to the Future (BTF) study (Callaghan et al. 2011, Villarreal et al. Accepted), which
83 revisited sites established in Barrow during International Biome Program (IBP, Brown et al.
84 1980, Webber et al. 1978).

85

86 **Method**

87 **Site Description**

88 Data for this study were collected on or near the Barrow Environmental
89 Observatory (BEO), Alaska, 71°17'01" N, 156°35'48" W. The site is situated on the
90 northern-most point of the Alaskan Arctic Coastal Plain and has a low relief and an average
91 elevation of 4 meters (Aguirre et al. 2008). Seventy two percent of the landscape near
92 Barrow contains oriented lakes, drained thaw lake basins and small ponds (Hinkel et al.,
93 2003). The region is underlain by continuous permafrost and includes thermokarst terrain
94 typical of the Alaskan Arctic Coastal Plain (Brown et al. 1980), such as thaw lakes, high
95 and low-centered polygons, shallow ponds and lakes. Active layer is generally less than 50
96 centimeters (Shiklomanov et al., 2010). Soils of the area have been described by
97 (Bockheim et al., 1999) and include cryoturbated gelsols, specifically Typic Aquorthels
98 with high soil moisture content, Histoturbels, and Aquaturbels. The upper layer of this soil
99 consists of carbon rich peat (ca. 50 kg/C/m³) (Bockheim et al., 1999). Soils are generally
100 moisture rich due to shallow drainage gradients, relatively low rates of evapotranspiration,
101 and impeded drainage caused by ice-rich continuous permafrost (Liljedahl et al., 2011,
102 Bockheim et al., 1999) Miller et al. 1998.

103 **Biomass Harvest**

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

118
119
120 Biomass for each of the plots was also calculated as follows:

$$121 \text{Biomass} = (\text{Dry Weight}) * 0.054 \text{ gm/m}^2 \text{ ----- Equation (1)}$$

122
123
124 Here 0.54 m² is the area for each of the harvest plots.

125 **Spectral Data Collection**

126 Spectral reflectance data for all the vegetation plots were collected before the plots
127 were harvested using a dual-detector field portable spectrometer (Unispec DC, PP Systems,
128 Amesbury, MA, USA), which collects radiance (radiation from the target) and irradiance
129

130 (radiation from the sky) simultaneously, thereby permitting correction of surface
 131 reflectance under varying sky conditions (Gamon et al., 2006). The two detectors were
 132 cross-calibrated using a white panel with 99% reflectance (Spectralon, Labsphere, North
 133 Sutton, NH, USA) several times during spectral measurements. The Unispec-DC had a
 134 nominal range of operation between 303 and 1148 nm in 256 contiguous bands with a
 135 spectral resolution of approximately 3 nm and a full-width-half maximum of approximately
 136 10 nm. The usable range of this detector (range with reasonable signal-to-noise) is
 137 approximately 400-1000 nm. The downward looking sensor has a field of view of 20
 138 degrees and therefore to cover a plot size of diameter 23.3 cm, spectral scans were taken at
 139 a height of 78 cm above the plots. Measurements were taken around mid-day.

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

143

$$144 \quad \text{NDVI} = (R_{800} - R_{680}) / (R_{800} + R_{680}) \text{ ----- Equation (2)}$$

145

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

149

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

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

162

$$163 \quad \text{Greenness} = 2G - B - R$$

164

165 Here, R, G and B represent the intensity levels recorded for each color by the digital
 166 camera. The transformation uses the high contrast between the reflected intensity of green
 167 leaves and other background color associated with features like dead material, soil etc. A
 168 sequential threshold approach based on histogram analysis is used to calculate canopy
 169 vertical green fraction. LAI is estimated from the vertical gap fraction as follows Equation
 170 (3):

171

$$172 \quad \text{LAI} = -2\ln(P_o(0)) \text{ (Liu and Pattey, 2010)..... Equation (3)}$$

173

174 In Equation (3) $P_0(0)$ refers to the gap fraction at a solar zenith angle zero. For a detailed
175 derivation of this equation, refer to Liu and Pattey (2010). Average LAI values for each
176 species were calculated by averaging all the plots for each species.

177

178 Data Analysis

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

187 To investigate decadal time scale change, biomass was modeled for five species i.e.
188 *Arctophila fulva*, *Carex aquatilis*, *Dupontia fisheri*, *Eriophorum angustifolium*, *Eriophorum*
189 *scheuchzeri*, using mean percent cover data available for these species for 1972 and 2008 in
190 the Barrow IBP study sites. Using biomass data measured for these species for the hundred
191 percent species cover harvest plots, biomass were estimated for these particular species for
192 1972 and 2008 were calculates using the percent cover data available for the Barrow IBP
193 study sites. This helped us to investigate if we could use our method to model biomass in
194 decadal time scale using existing data which could potentially be helpful in understanding
195 how arctic plant communities have changed over decadal time scales in response to
196 climatic and other change is imperative (Finzi et al. 2011).

197

198 Results

199 Plots that were selected for this study were free from standing water and were
200 deemed to have hundred percent vegetation cover for the respective species of interest.
201 *Dupontia fisheri* had the highest NDVI (0.87) closely followed by *Arctophila fulva* (0.82)
202 and *Petasites frigidus* (0.77). *Eriophorum scheuchzeri* had the lowest NDVI values (0.50).
203 *Arctophila fulva* had the highest LAI (3.53) followed by *Dupontia fisheri* (2.49), *Carex*
204 *aquatilis* (1.88), *Petasites frigidus* (1.74), and *Eriophorum scheuchzeri* had the lowest LAI
205 (0.56). *Arctophila fulva* had the highest aboveground biomass (136.81 g/m²) followed by
206 *Dupontia fisheri* (43.48 g/m²), *Carex aquatilis* (40.09 g/m²) and *Eriophorum angustifolium*
207 (36.66 g/m²). *Eriophorum scheuchzeri* had the lowest biomass among all the species
208 studied (11.66 g/m²) (Table 4.1 and Fig. 4.1).

209

210 NDVI showed strong exponential relationships with both LAI (Figs. 4.2a, 4.2b) and
211 aboveground biomass (Figs. 4.2c, 4.2d). The relationship between NDVI and LAI for
212 graminoids was slightly stronger with $R^2 = 0.85$ compared to that for all species combined
213 while correlations between NDVI and biomass for graminoids was stronger ($R^2 = 0.82$)
214 compared to that for all species combined ($R^2 = 0.70$). All the relationships between NDVI,
215 LAI and biomass showed strong exponential relationships with $R^2 \geq 0.7$, indicating that
216 NDVI saturates at higher biomass and LAI values. The relationship between LAI and

217 biomass was slightly stronger for graminoids ($R^2 = 0.88$) compared to the relationships for
218 all species combined ($R^2 = 0.86$) (Fig. 4.3).

219

220 Analysis of the species percent cover change for the IBP plots for 1972 and 2008
221 showed that *Carex aquatilis* and *Eriophorum angustifolium* decreased in cover between
222 1972 and 2008 while *Arctophila fulva* and *Dupontia fisheri* increased in cover (Fig. 4.4a).
223 Similarly, modeling of biomass showed that *Carex aquatilis* and *Eriophorum angustifolium*
224 had a predicted decreased biomass in 2008 compared to 1972 while *Arctophila fulva* and
225 *Dupontia fisheri* had increased predicted biomass cover in 2008 compared to 1972 (Fig.
226 4.4b). A 2.8% increase in percent cover for *Arctophila fulva* showed a 124% increase in
227 biomass while a 3.4% increase in percent cover for *Dupontia fisheri* showed a 14.93%
228 increase in biomass between 1972 and 2008. The 13.36% decrease in percent cover for
229 *Carex aquatilis* suggested a 33.92% decrease in of biomass whereas a 1.59% decrease in
230 percent cover for *Eriophorum angustifolium* showed a 14.65% decrease in biomass. As
231 *Eriophorum scheuchzeri* had very low percent cover and biomass, it was not included in
232 this analysis.

233

234 Discussion

235 In the Arctic, ecosystem properties such as standing plant biomass appears to be
236 sensitive to phenomenon associated with climate change such as warming (Bhatt et al.
237 2010, Hollister et al. 2006, Walker et al. 2005, Epstein et al. 2000). Changes in vegetation
238 biomass have important consequences for many components of the Arctic system including
239 surface energy balance and permafrost (Euskirchen et al. 2007, Chapin et al. 2005),
240 hydrology (Post et al. 2009, Hinzman et al. 2005) and wildlife. Optical remote sensing is
241 the only feasible tool for regional scale monitoring and assessment of change in vegetation
242 properties such as biomass and LAI (Stow et al. 2004), which is essential for understanding
243 processes such as land-atmosphere carbon balance (Merbold et al. 2009, Wolf et al. 2008),
244 and therefore, the future state of the Arctic and Earth Systems as they respond to climate
245 change (IPCC 2007, ACIA 2005). Establishing sound spatio-temporal relationships
246 between remote sensing products and ground based measurements underpins capacities of
247 being able to extrapolate ecosystem properties and processed from the plot level to
248 landscape and global scales (Boelman et al. 2003). This study aimed to develop such
249 relationships between above ground biomass, LAI and NDVI for six common plant species
250 found in tundra near Barrow, Alaska using ground based plot level measurements. To
251 explore the potential of scaling these relationships over decadal time scales, data from a
252 historic plant community resampling effort associated with the International Polar Year
253 Back to the Future (BTF) study (Callaghan et al. 2011) were used that resampled sites
254 formerly associated with the IBP field site near Barrow (Villarreal et al. Accepted).

255 The results showed that the NDVI values for the six species studied varied within a
256 range of ~ 0.3 with corresponding change in values in LAI and biomass. The strong
257 relationships between NDVI and biomass and LAI for the species studied support the use of
258 NDVI as a spectral index for indirectly measuring plant community structure. The strong
259 relationship between NDVI and biomass found in this study is similar to studies conducted
260 in other tundra ecosystems including tussock tundra (Boelman et al. 2003), shrub and high

261 arctic tundra (Walker et al. 2003). While Boelman et al. (2003) reported a linear
262 relationship between NDVI and biomass, Walker et al. (2003) reported an exponential
263 relationship between NDVI and biomass, similar to our finding. Further investigation of
264 these relationships throughout the growing season could be helpful to strengthen these
265 relationships.

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

277 It is important to understand how arctic plant communities have changed over
278 decadal time scales in response to climatic and other changes to understand the potential
279 impact on biodiversity and ecosystem functional processes such as those associated with
280 land-atmosphere carbon exchange (Finzi et al. 2011). Findings from the decadal
281 extrapolation of plant cover values to biomass, for the former IBP plots suggest that three
282 species had increased biomass while three species had decreased biomass from 1972 to
283 2008. This finding shows that the rate of change of biomass for some species can be
284 different which might cause non-linear trends in greening in different tundra ecosystems as
285 species respond differently to change. Our finding is similar to the findings of Lara et al.
286 (Accepted) who reported that ecosystem function in different plant communities within a
287 tundra landscape have changed at different rates over decadal time scales. To better
288 understand the non-linear change observed for specific species in our study, more studies
289 similar to this are needed in tundra ecosystems in Barrow as well as in other tundra
290 ecosystems to assess which species could act drivers of such non linear changes.

291

292 **Conclusions**

293 This study found strong plot level correlations between NDVI and biomass and LAI
294 for six key plant species that are relatively common in tundra near Barrow, Alaska. These
295 findings are similar to other published studies focusing on other tundra ecosystems
296 elsewhere in the Arctic (Epstein et al. 2008, Riedel et al. 2005, Boelman et al. 2003).
297 However, NDVI was found to saturate at an approximate biomass of 100 g/m^2 and an LAI
298 of $2 \text{ m}^2/\text{m}^2$, which suggests that greening of tundra could be linked to a relatively small
299 change in species cover. LAI was not found to saturate with an increase in biomass.
300 Extrapolating results over multiple decades to hypothesize trajectories of change in
301 biomass, LAI and NDVI, highlight the potential importance of species level change, which
302 has the potential to cause non-linear change in various metrics of ecosystem structure and
303 function. Overall, results reaffirm the applicability of NDVI for large scale assessment of
304 vegetation change in the Arctic and highlight the need for additional species specific and

305 multi-scale studies, which are likely to facilitate interpretation of drivers and mechanisms
306 of change derived at large spatial scales using remote sensing approaches.

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

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

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

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

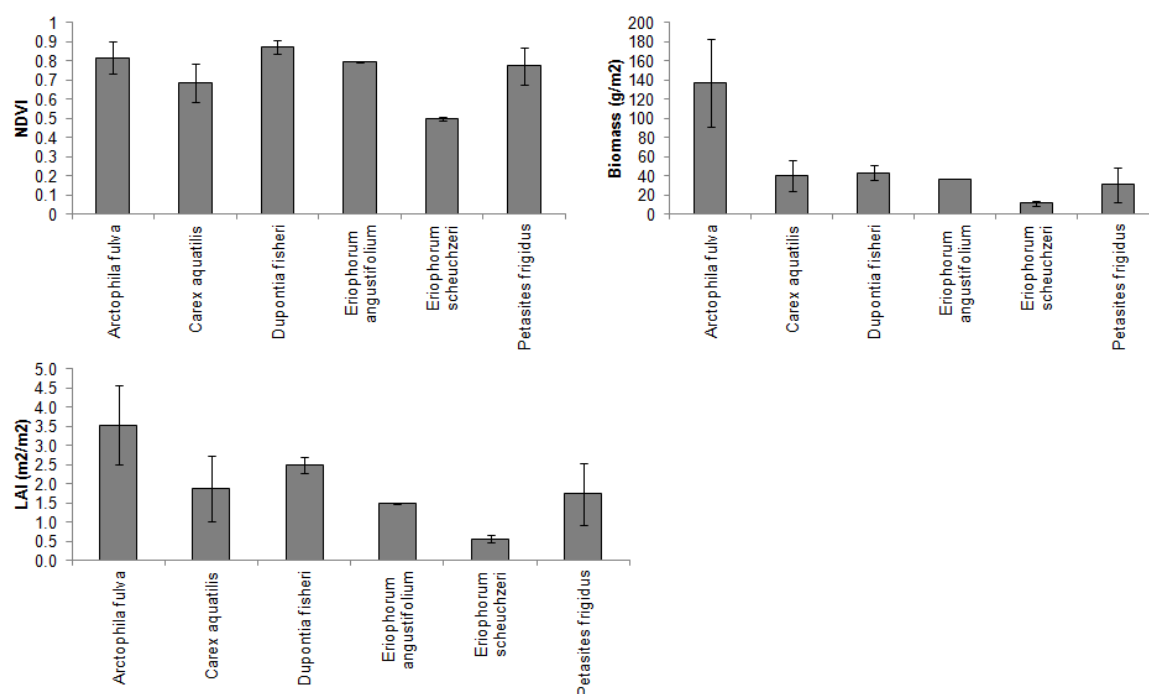
Species	No. of Plots	Avg. NDVI	Avg. LAI	Avg. Biomass (g/m ²)	Graminoid (Yes/No)
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<i>Arctophila fulva</i>	4	0.82 ± 0.08	3.53 ± 1.03	136.81 ± 45.54	Yes
<i>Carex aquatilis</i>	3	0.68 ± 0.10	1.88 ± 0.86	40.09 ± 15.87	Yes
<i>Dupontia fisheri</i>	2	0.87 ± 0.04	2.49 ± 0.22	43.48 ± 7.53	Yes
<i>Eriophorum angustifolium</i>	1	0.79	1.49	36.66	Yes
<i>Eriophorum scheuchzeri</i>	2	0.50 ± 0.01	0.56 ± 0.10	11.66 ± 2.83	Yes
<i>Petasites frigidus</i>	3	0.77 ± 0.09	1.74 ± 0.80	30.66 ± 17.55	No

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525 Figure 4.1. Average values of NDVI, Biomass and LAI for each of the key plant species.

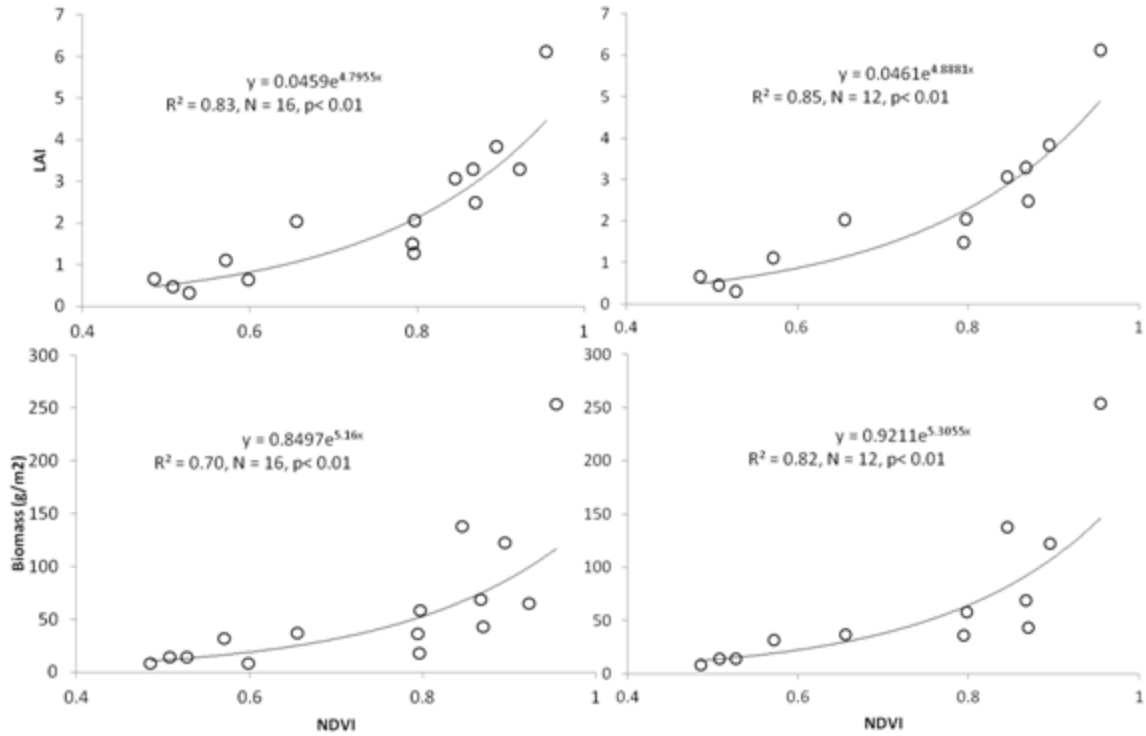
526 Error bars represent ± one standard error.

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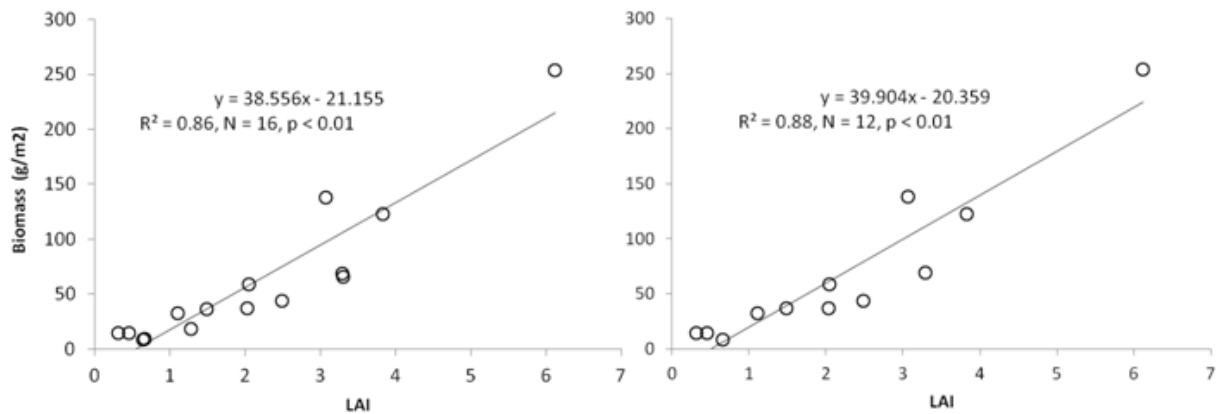
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532 Figure 4.2. Correlations between NDVI and LAI and Biomass for all species combined (left
533 figures) and for graminoids only (right figures). All the relationships showed strong
534 exponential relationships with $R^2 \geq 0.7$, indicating that NDVI saturates at higher biomass
535 and LAI values.

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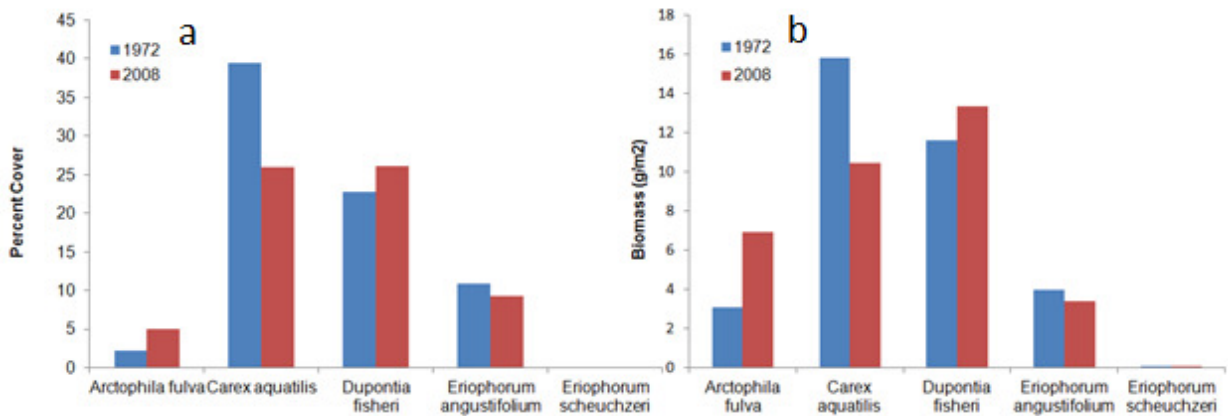


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538 Figure 4.3. Correlations between LAI and Biomass for all species combined (left figures)
 539 and for graminoids only (right figures). Biomass showed a strong linear relationships with
 540 LAI for both correlations ($R^2 = 0.86$ all species, $R^2 = 0.88$ graminoids).
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545 Figure 4.4. Measured decadal change in percent cover and modeled biomass for key species
 546 in the Barrow IBP study area. The greatest percent and magnitude of increase in cover was
 547 recorded for *Arctophila fulva* and decrease for *Carex aquatilis*. The greatest percent and
 548 magnitude of increase in biomass was modeled for *Arctophila fulva* and decrease for *Carex*
 549 *aquatilis*.
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