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Trends in NDVI and Tundra Community Composition in the Arctic of NE Alaska Between 1984 and 2009

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Abstract

As Arctic ecosystems experience increases in surface air temperatures, plot-level analyses of tundra vegetation composition suggest that there are important changes occurring in tundra communities that are typified by increases in shrubs and declines in non-vascular species. At the same time analyses of NDVI indicate that the Arctic tundra is greening. Few studies have combined plot-level trends in species composition and cover with remote sensing measurements to understand the linkages between tundra vegetation dynamics and NDVI over time. This study reports on trends in species composition for field plots in the Arctic National Wildlife Refuge in NE Alaska from 1984 to 2009 and links these trends to the trends in NDVI at fine and coarse scales. Over this time frame there were few changes in plant community composition. None of the five tundra types that were measured had increases in total vegetative cover, and deciduous shrub cover did not show the large increases reported elsewhere. Surface-(plot) measured NDVI was positively correlated to deciduous and evergreen shrub composition suggesting that these functional groups had a strong influence on NDVI values. Modeled values of NDVI, derived from measures of deciduous and evergreen shrub composition over time, decreased slightly for tussock tundra but did not change for other tundra types. This result suggests that surface NDVI did not change over time on these tundra types. Fine-scale (30-m pixels) Landsat NDVI also did not show any changes for the pixels located at the permanent plots (1992–2009). However, coarse-scale (8-km pixels) AVHRR NDVI across the study area did increase (1988–2007). Furthermore, aggregate values of Landsat pixels matching the same area as AVHRR pixels also did not show significant changes over time. Although Landsat NDVI was consistent with surface-measured NDVI, AVHRR NDVI was not. AVHRR NDVI values showed increases that were in neither the field nor Landsat data. This result suggests that AVHRR may be demonstrating increasing trends in NDVI that are not occurring on the ground in some Arctic tundra ecosystems. These results highlight the need to combine remote sensing with on-the-ground measurements of plant community composition and NDVI in the analysis of the responses of Arctic tundra ecosystems to climate change.

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Introduction

Arctic tundra ecosystems are experiencing some of the greatest increases in surface air temperature globally (Kattsov and others 2005; McBean 2005; Anisimov and others 2007). Understanding how these ecosystems are responding to climate changes is of critical importance to the people and wildlife that depend on these ecosystems for subsistence (Post and others 2009) and to understanding and predicting feedbacks to global carbon cycles (McGuire and others 2009). A recent meta-analysis of the trends in plot-level studies of tundra vegetation change from 46 locations across the globe found increases in the height of tundra canopy, litter, and shrubs, along with decreases in mosses and bare ground (Elmendorf and others 2012a). However, these trends were not consistent across all sites. Another meta-analysis of the impacts of experimental warming of tundra that included 61 studies found that increased temperature led to increases in deciduous shrubs and dead plant material and to decreases in mosses and lichens (Elmendorf and others 2012b). Other studies confined to single or multiple sites have found that experimental warming of Arctic tundra leads to increases in deciduous shrubs (Chapin and others 1995; Hobbie and Chapin 1998; Wahren and others 2005), graminoids (Arft and others 1999; Hollister and others 2005; Wahren and others 2005), and shrubs and graminoids (Walker and others 2006). Increased shrub growth has been associated with warmer summers (Forbes and others 2010; Blok and others 2011b). Experimental increases in temperature have also resulted in decreases in non-vascular species (Hollister and others 2005; Wahren and others 2005; Walker and others 2006; Elmendorf and others 2012b) and to decreases in species richness and/or diversity (Chapin and others 1995; Hollister and others 2005; Walker and others 2006). Fertilization studies designed to simulate potential increases in N mineralization that could occur under warmer conditions have found increases in deciduous shrubs such as *Betula nana* (Chapin and others 1995; Wahren and others 2005; Gough and others 2002; van Wijk and others 2004) and graminoids (van Wijk and others 2004) and decreases in mosses and lichens (van Wijk and others 2004).

Warming temperatures in Arctic tundra ecosystems of North America appear to be driving increases in both growing season length and peak photosynthetic activity (Goetz and others 2005). Another index of the changes occurring in the Alaskan Arctic and across the Pan Arctic is the observed increases in normalized difference vegetation index (NDVI) as seen in coarse-scale (1–12 km resolution) satellite imagery (Jia and others 2003; Verbyla 2008; Pouliot and others 2009; Bhatt and others 2010; Beck and Goetz 2011). Increases in maximum NDVI have been attributed in large part to increases in shrubs, particularly in riparian areas (Tape and others 2006; Raynolds and others 2008; Forbes and others 2010; Tape and others 2012), as well as to a generalized greening of the tundra (Goetz and others 2005; Myneni and others 1997; Bhatt and others 2010). Variation in NDVI at the surface is strongly linked to shrub cover (Jia and others 2003; Riedel and others 2005; Blok and others 2011a) such that relatively small differences in shrub cover can result in large impacts on plot NDVI.

The insights from remote sensing studies (Goetz and others 2005; Jia and others 2003; Verbyla 2008; Bhatt and others 2010; Pouliot and others 2009; Beck and Goetz 2011) are often limited by a lack of simultaneous repeated measurements of plant community composition. Repeated photography studies (Sturm and others 2001; Tape and others 2006) have depicted in many cases shrub abundance increases but do not address changes in less prominent growth forms (for example, lichens). Conversely, plot-level changes in plant community composition (Arft and others 1999; Walker and others 2006; Elmendorf and others 2012a, b) are often not directly linked to remote sensing measures. Approaches that combine remote sensing on repeatedly measured field plots may provide important insights into Arctic tundra changes that are not apparent with either approach alone. Furthermore, studies that examine surface NDVI and its association to plant community composition can provide important insights into trends not detected with satellite measures of NDVI (Gamon and others 2013).

In this study, we examine the changes in plant community composition and satellite-derived NDVI from 1984 to 2009 from a set of Arctic tundra field plots in the Arctic National Wildlife Refuge (Arctic NWR). We also examined the relationship between surface-measured NDVI and tundra community composition. The Arctic NWR is a part of the North Slope of Alaska that has seen summer temperature increases of 4°C and an increase in maximum NDVI of 16% from 1982 to 2008 (Bhatt and others 2010). The field plots are some of the longest continuously monitored plots in the Arctic and are unique in that they include measurements in riparian shrublands as well as upland tundra. The size of the field plots (4 × 30 m) and the long-term duration of repeated measurements (25 years) allowed us to examine the relationship between trends in satellite-derived values of NDVI and tundra community composition. The principal question addressed with this study is: how do plot measurements of vegetation in the Arctic NWR over the past 25 years correspond to coarse- and fine-scale changes in NDVI measured by satellites?

Methods

Plots used in this study were originally part of a study to monitor the response of tundra communities to oil exploration activities (Jorgenson and others 2010) (Figure 1). Twenty-seven pairs (undisturbed and disturbed) of field plots were chosen along vehicular exploration tracks in 1984 and 1985 after track formation in the winter of the previous years. Disturbed plots were chosen to represent different levels of disturbance in a range of vegetation types (see Jorgenson and others 2010 for details of plot selection). Undisturbed plots were 2–10 m away from disturbed plots.

Plot Composition

Plant community composition of plots was initially measured in the first 2 years after disturbance (1984 and 1985, or 1985 and 1986) and in 1988, 1991, 2002, and 2009. In 2009 only undisturbed plots were measured. Surface NDVI measures (see below) were made in 2009. This study focused on trends in 27 undisturbed plots. Percent cover of plant species was quantified with point sampling (Kent and Coker 1992). Ten evenly spaced 4-m transects were placed across each 4 × 30 m plot. Within each 4 m transect, 20 points spaced at 20 cm were sampled, resulting in each plot having 200 sample points (10 transects × 20 points per transect). At each point all species were tallied, however multiple ''hits'' of the same species per point were recorded only once. Percent cover within a plot was determined by dividing the number of ''hits'' on a plot by two. Points with no living vegetation were recorded as soil, water, or litter and were summarized as non-vegetated.

The number of plots in and the percent cover of each of the seven vegetation types in the coastal plain of the Arctic NWR (Walker and others 1982) are as follows: wet sedge tundra, n = 1, 13%; sedge willow tundra, n = 5, 30%; sedge—*Dryas* tundra,

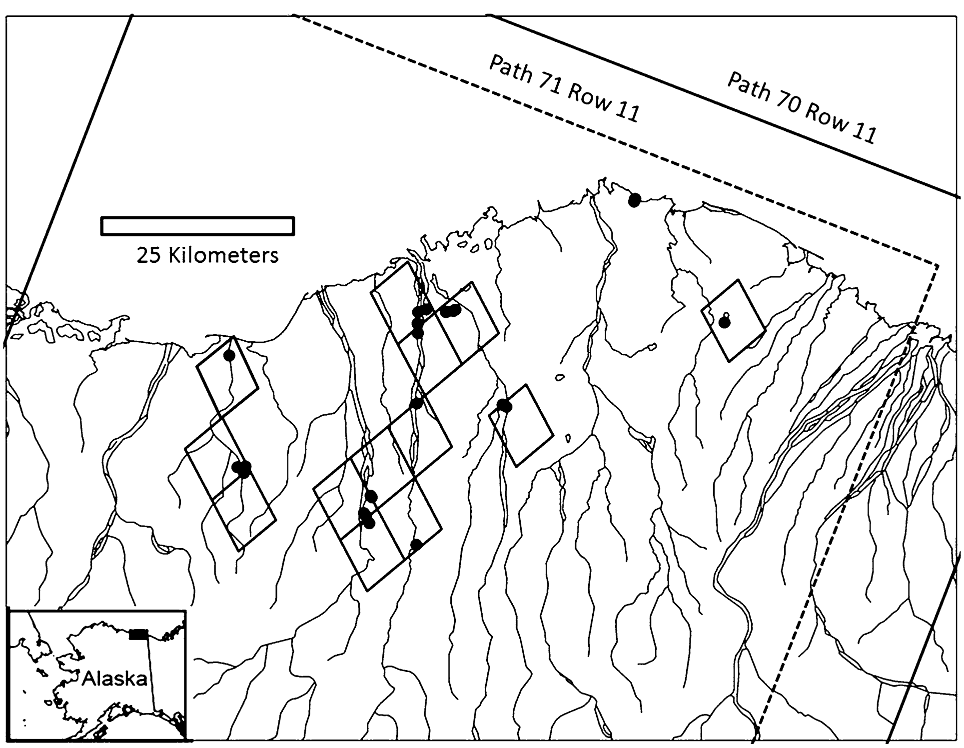

Figure 1. Locations of the 27 field plots in the coastal plain of the Arctic National Wildlife Refuge as well as the Landsat scenes and the AVHRR cells. Note that plots near the coast did not have AVHRR cells analyzed because of their proximity to the ocean.

n = 6, 13%; tussock tundra, n = 5, 28%; shrub tundra, n = 2, 5%; riparian shrubland, n = 5, 2%; *Dryas* terrace, n = 3, 3%. The two shrub plots were pooled with the tussock tundra plots and the one wet sedge plot was pooled with the sedge willow for purpose of analysis (Figure 2).

Surface NDVI

Surface measures of plot NDVI were made on 25 of the 27 plots in 24–29 July, 2009 within 1–2 days of when plant community cover was measured. These measurements were made to provide insights into differences in surface NDVI between vegetation types and to understand the relationships between plant community composition and surface NDVI. Each plot had a total of 10 measures of NDVI made at 3-m intervals down the center of the plot. The fraction of the plot measured by surface NDVI was 12%. Both the undisturbed and disturbed plots of each plot pair were measured. Relationships between plant community composition and surface NDVI were based only on undisturbed plots. Surface measurements of NDVI in the disturbed plots were made to determine if there were differences between disturbed and undisturbed plot NDVI that might influence Landsat NDVI values. In addition, measurements were also made at 10, 20, 30, and 40 m in each of the four cardinal directions from the center of each undisturbed plot. These perimeter measures of NDVI were made to assess variability in NDVI outside each plot. Measures of NDVI were made with a UniSpec DC (PP Systems, Amesbury MA) with two sensors. One sensor was held at 1.04 m above the ground and had an optical view of 20° allowing for sampling a circle of the tundra below about 135 cm in diameter (1.4 m^2). The other sensor measured sky irradiance. A white reference standard was used to calibrate sensors and to calculate reflectance (Spectralon, Labsphere, North Sutton, NH, USA). Canopy reflectance values were interpolated to 1 nm wavelength intervals between 400 and 1100 nm prior to calculations of NDVI. Reference measures of reflectance were made at each plot (approximately every 10 measurements). Surface measurements were taken between 1000 and 1600 local time. Surface NDVI was calculated as $NDVI = (NIR_{800} - R_{660})/(NIR_{800} + R_{660})$.

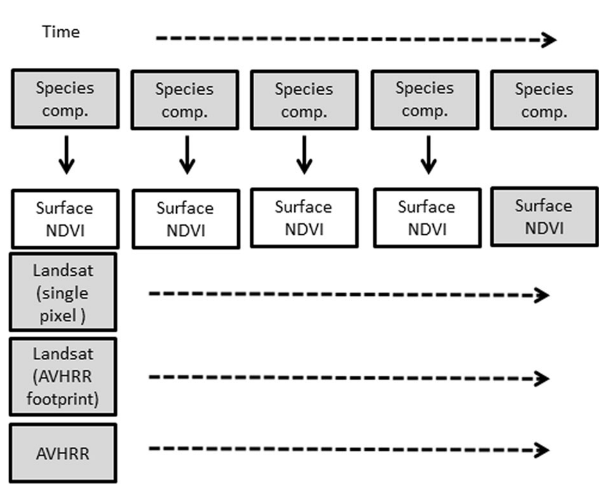

Figure 2. Field and remotely sensed data used to generate four time series of NDVI (surface, Landsat single pixel over field plots, Landsat matching AVHRR foot print, and AVHRR) measurements. *Gray-filled boxes* indicate data and *white-filled boxes* indicate modeled values. Modeled surface NDVI values are generated from the relationship between surface NDVI and species composition in 2009. Time is from 1984 to 2009 and is not to scale.

Landsat NDVI

Landsat NDVI of the 27 plots was calculated from available imagery from 1984 to 2009. Images with 30-m pixel resolution from Landsat 4–5 TM and Landsat 7 ETM+ with dates from between July 16 and August 18 of each year were downloaded from the NASA EROS GLOVIS web site (Table 1). Years with cloud-free images include 1992, 1999, 2000, 2004, 2005, 2006, 2007, 2008, and 2009.

The dates of the Landsat imagery were close to peak NDVI. The NDVI of Alaska tundra at sites along a north–south transect 200–300 km west of this study area increased gradually from early May until it peaked between July 22 and August 4 (Jia and others 2004). NDVI then steadily decreased until the end of the growing season in early October (Jia and others 2004). Values of NDVI for Landsat scenes were calculated using ARCGIS 10.0 (ESRI) software. Digital numbers in bands 3 and 4 (red and near-infrared, 0.7–0.8, and 0.8–1.1 micrometers, respectively) were used to compute at-satellite spectral radiance and spectral reflectance (Chander and others 2009). NDVI values were radiometrically normalized to the 1992 base year from pseudo-invariant features (Chen and others 2005) such as water and gravel airstrips. Missing data from the malfunction of the Landsat 7 scan line corrector were masked based on the files with the Landsat 7 scenes. Landsat NDVI values were also determined for the aggregate of all of the Landsat pixels within the same area as the AVHRR pixels for each year in which Landsat data were available.

Table 1. Landsat Scenes Used in this Study

Scene	Date	Satellite/sensor
Path 71/row 11	7/16/1992	Landsat-4/TM
Path 71/row 11	8/5/1999	Landsat-7/ETM+
Path 71/row 11	7/22/2000	Landsat-7/ETM+
Path 70/row 11	7/26/2004	Landsat-7/ETM+
Path 70/row 11	8/14/2005	Landsat-7/ETM+
Path 70/row 11	8/9/2006	Landsat-5/TM
Path 71/row 11	8/11/2007	Landsat-7/ETM+
Path 71/row 11	7/28/2008	Landsat-7/ETM+
Path 70/row 11	7/16/2009	Landsat-5/TM

AVHRR NDVI

Trends in maximum NDVI derived from GIMMS AHVRR data (Pinzon and others 2005; Tucker and others 2005) were used to provide insights into trends in NDVI at a coarser scale and to identify years with anomalously low or high NDVI values. The GIMMS AVHRR NDVI values represent the maximum NDVI for two composited periods each month, the first 15 days of the month and the remaining days. We examined trends in NDVI corresponding to the two composited periods overlapping peak growing season, July 16 to July 31 and August 1 to August 15 for each year from 1988 to 2006. A single NDVI value for each year was generated by averaging the NDVI values of the 8 × 8 km pixels in which the 27 field plots occurred for the two composited periods.

Analysis

Statistical analyses were carried out with SAS 9.2 (SAS Institute, Cary, NC) and SigmaPlot 12 (Systat Software Inc., Chicago, IL). In all ANOVA analyses, the data were tested for normality (Shapiro–Wilk) and homogeneity of variance (Levene's). If data failed these tests, data were transformed to meet these conditions. All post hoc analyses of significant effects beyond the main effects were carried out using Tukey's Honest Significant Difference. In all analyses $P < 0.10$ was used as the significance level unless otherwise noted.

Linear regression was used to examine trends in plant functional group, total vascular, total non-vascular, non-vegetative, and total vegetated cover for the five vegetation types. This analysis was done across dates (1984–1986, 1988, 1991, 2002, and 2009) (SAS 9.2). Linear regression (SAS 9.2) was used to compare the relationship between NDVI measured on the surface at the plot level and NDVI measured with Landsat 7 ETM+. One of the riparian plots was not included in analyses involving Landsat data because it occurred within 10 m of the Hula Hula River and its NDVI values may have been influenced by the water in the river. Differences in plot-level NDVI between the five vegetation types and between undisturbed and disturbed plots were analyzed with a split-plot design ANOVA (Proc Mixed, SAS). Multiple linear regression analysis (Proc Reg, SAS) was used to determine the relative influence of each of the major functional plant groups and non-vegetative cover on plot NDVI. Backwards elimination was used to remove functional groups that were not significant ($P < 0.10$). The results of this regression analysis were then used to model plot NDVI for each plot for all years in which plant cover was measured. Trends in satellite-(Landsat and AVHRR) derived NDVI across dates were analyzed with linear regression (SAS 9.2).

Results

Plot Composition

None of the vegetation types had increases in total vegetative cover. Over the course of the 25 years of the study, sedge *Dryas* had decreases in total vegetative cover ($P = 0.109$) of 12.5% (Figure 3). Sedge *Dryas* ($P = 0.024$) and tussock tundra ($P = 0.063$) also had increases in non-vegetative cover of 10 and 5%, respectively. The sedge *Dryas* and tussock tundra vegetation types had decreases in total non-vascular species cover of 22.5% ($P = 0.002$) and 17.5% ($P = 0.022$), respectively. For the sedge *Dryas,* these decreases were associated with significant declines in lichens of 15% ($P = 0.007$) whereas for the tussock tundra the declines were associated with declines in lichens of 5% ($P = 0.089$) and declines in bryophytes of 10% ($P = 0.002$). The sedge *Dryas* vegetation type had a significant increase in graminoids (grasses, sedges, and rushes) of 7.5% ($P = 0.018$). The sedge willow and *Dryas* terrace vegetation types both had significant decreases in graminoids of 7.5% ($P = 0.058$) and 0.5% ($P = 0.097$), respectively. The riparian shrublands had a significant decrease in forbs and horsetails of 7.5% ($P = 0.007$). Deciduous and evergreen shrubs did not show any changes in cover on any of the tundra types (Figure 3).

Surface NDVI

Results of split-plot ANOVA indicated that there were significant differences in plot-level NDVI be-

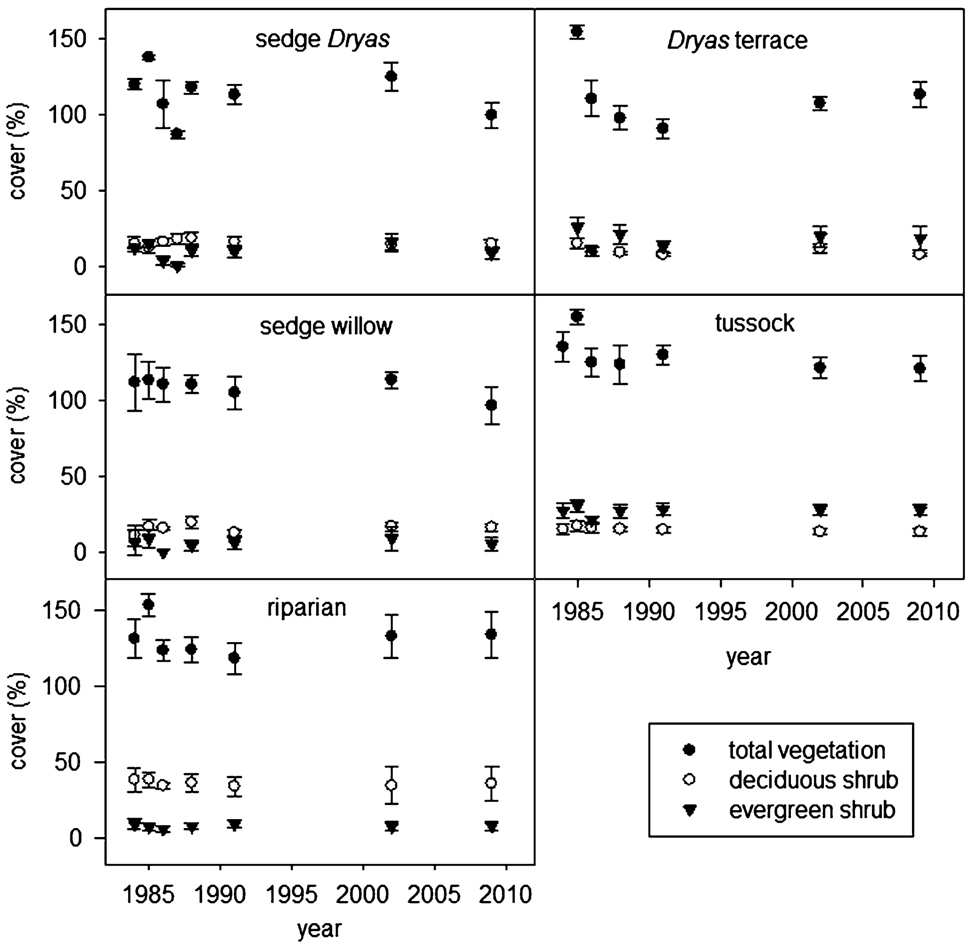

Figure 3. Trends in the total vegetative cover, and deciduous and evergreen shrub cover for the five tundra types.

tween vegetation types ($F_{4,20} = 5.65$, $P = 0.003$) but not between undisturbed, disturbed, or perimeter NDVI ($F_{1,20} = 0.01$, $P = 0.9$). Nor was there a significant interaction between vegetation type, disturbance, or perimeter NDVI values ($F_{4,20} = 0.24$, $P = 0.914$). Post hoc analyses found that there were significant differences between the undisturbed plots of different vegetation types (Figure 4) with the highest values occurring in the tussock tundra and riparian shrubland vegetation types.

Deciduous and evergreen shrubs were the only plant functional groups that were significantly related to surface NDVI. Cover of these two groups explained 72.9% of the variation in NDVI across 25 of the field plots as defined by the equation NDVI = 0.176 + (0.008 × deciduous shrub cover) + (0.007 evergreen shrub cover) ($F_{2,22} = 29.55$, $P < 0.001$) (Figure 5). The strong relationship between surface-measured NDVI in 2009 and NDVI modeled from surface measurements of cover type increases confidence when applying the model to the time series of cover type measurements for comparison with Landsat NDVI.

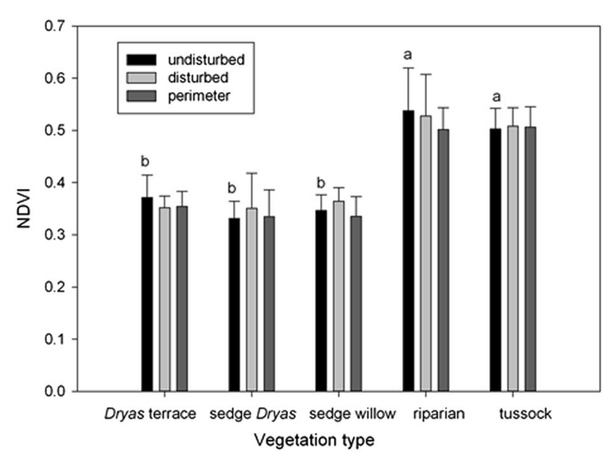

Figure 4. Patterns of NDVI across five vegetation types in the northern Alaskan tundra measured in July 24–29, 2009. *Bars* represent the mean of (n = 3–7) plots with *error bars* representing ±1 s.e. of the mean. *Black bars* are undisturbed plots, *light gray bars* are plots that were disturbed during oil exploration activities in 1984–1985, and *dark gray bars* represent NDVI taken in a 40 m area outside the undisturbed plots. *Bars* with different letters indicate significant differences ($P < 0.05$) between undisturbed plots of different vegetation types.

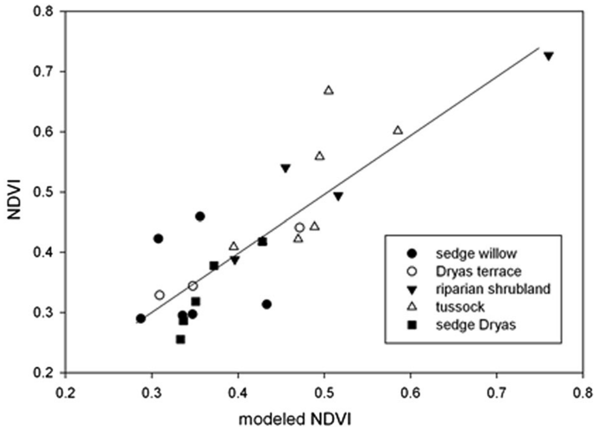

Figure 5. Relationship between NDVI measured at the plot level and NDVI derived from the equation NDVI = 0.176 + (0.008 × deciduous shrub cover) + (0.007 evergreen shrub cover) ($P < 0.001$, $R^2 = 0.73$) for 25 field plots across five vegetation types.

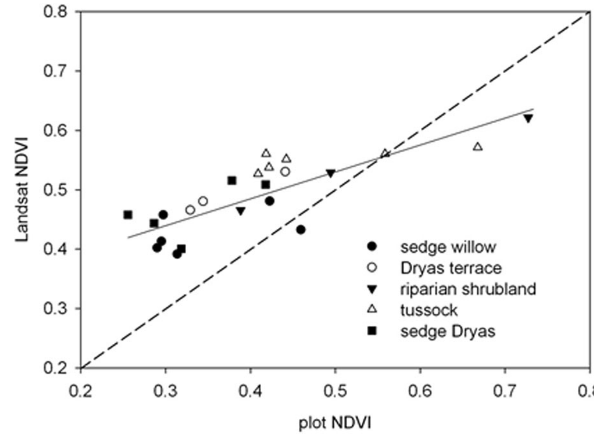

Figure 6. Relationship between NDVI measured at the surface level (July 24–29, 2009) and NDVI derived from Landsat 7 ETM + (July 16, 2009). Landsat NDVI = 0.424 × plot NDVI + 0.319.

Landsat and AVHRR NDVI

There was a highly significant relationship between surface-measured and Landsat values of NDVI ($P < 0.0001$, $R^2 = 0.65$) (Figure 6). The high R^2 value in Figure 6 illustrates that surface-measured NDVI, and therefore surface-measured cover, is strongly related to variability in Landsat NDVI, and therefore it is expected that cover changes that affect modeled NDVI (see Figure 5 above) will be manifested in Landsat NDVI. Riparian shrublands and tussock tundra had the highest NDVI values for both Landsat- and surface- measured NDVI. Similarly, sedge willow and sedge Dryas had the lowest NDVI values for both Landsat and surface-measured NDVI (Figure 6).

None of the vegetation types showed significant changes in Landsat NDVI (Figure 7). Linear regressions of modeled values of NDVI based on measured shrub cover indicated that where tussock tundra NDVI decreased slightly ($P = 0.123$, $a = -0.001$), none of the other vegetation types showed changes (Figure 7). With the exception of 2004, the other years (1991, 1992, 2000, 2005, 2006) used for analysis of trends in Landsat NDVI did not appear to have anomalously low or high NDVI based on the GIMMS AVHRR data (Figure 8). In spite of the high values of the GIMMS AVHRR NDVI data in 2004, this year was included in the Landsat NDVI trend analysis because the Landsat data were not anomalously high. Neither the single pixel per field plot Landsat NDVI ($P = 0.494$, $a = -0.002$) nor the aggregate of all Landsat NDVI pixels in the AVHRR footprint ($P = 0.448$, $a = 0.002$) showed significant changes over time (Figure 8). These two Landsat NDVI values tended to be similar to each other across all dates. There was a significant increase ($P = 0.005$, $R^2 = 0.37$) in GIMMS AVHRR NDVI for the pixels in which the field plots occurred (Figure 8). The slope of the regression was 0.005 NDVI units per year. The GIMMS AVHRR data were not available for 2007, 2008, and 2009.

Discussion

The plant community composition data generally support the lack of trends seen in the Landsat data. There were relatively few changes in species composition or total vegetative cover over the 25-year time frame (1984 to 2009) including none of the large increases in deciduous shrubs found in other studies (Tape and others 2006; Walker and others 2006; Elmendorf and others 2012b; Lang and others 2012). Because tundra canopy cover (Laidler and others 2008) and the associated metrics of leaf area index (Hope and others 1993) and above ground plant biomass (Riedel and others 2005) are positively correlated with NDVI, changes in plot canopy cover should lead to changes in plot NDVI. The only vegetation type to show changes in canopy cover was the sedge *Dryas,* which exhibited decreases in total vegetative cover of 12% as well as increases in non-vegetative cover of 10%. In spite of these changes, this tundra type did not show significant decreases in Landsat NDVI. A potential explanation for the lack of change in Landsat NDVI for this vegetation type is that the declines in total vegetative cover and increases in non-vegetative cover were relatively modest. In addition, there

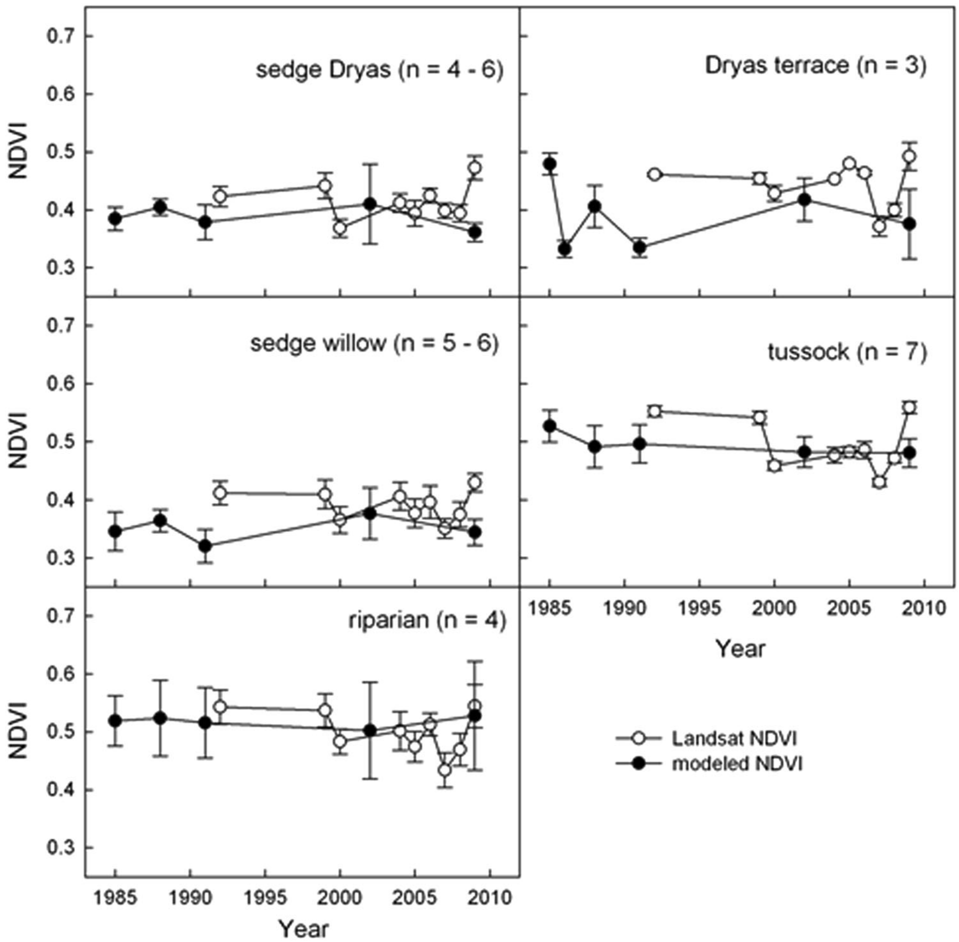

Figure 7. Trends in Landsat and modeled NDVI. Modeled values of NDVI were determined from the relationship between plant functional group cover and surface NDVI in 2009 and applied to values of plant functional group cover for all years when plant cover was measured. *Symbols* are the means of n = 3–7 and *error bars* represent ± 1 s.e. of the mean.

were no declines in deciduous and evergreen shrubs, functional groups with the strongest influence on NDVI.

The lack of changes in deciduous shrub cover is not consistent with the increases in shrubs seen in some studies (Arft and others 1999; Tape and others 2006; Myers-Smith and others 2011) or with the trends seen in studies of patterns of change in fine-scale NDVI where increases in Landsat NDVI often occur in vegetation dominated by shrubs (Fraser and others 2011; Tape and others 2011; McManus and others 2012). However, at a study site approximately 250 km from this study, Raynolds and others (2013) found that increases in Landsat NDVI were not associated with shrub-dominated systems. In addition, as noted by Elmendorf and others (2012a) in their analysis of global trends in tundra vegetation (which includes data from this study), deciduous shrubs showed no changes in cover in many field sites. These authors suggest that variations in trends between sites could be attributable to other site-specific factors such as hydrology, season length, and herbivory (Fraser and others 2011; Cahoon and others 2012). Furthermore, at sites in northern Alaska Tape and others (2012), found that within tundra vegetation types, shrub expansion appears to be localized to higher resource environments such as floodplains, stream corridors, rocky outcrops, and/or in areas with deeper active layers (Tape and others 2012). These and other studies suggest that the results of this study are consistent with other studies in suggesting that increases in deciduous shrubs are not ubiquitous across all Arctic tundra types.

The lack of an increase in Landsat NDVI for the riparian plot with large increases in deciduous shrub cover is surprising (Figure 9), and suggests that there is a disconnect between the measures of plot species composition and Landsat NDVI for this plot. A potential explanation for this disconnect may be that the Landsat NDVI for this plot was influenced by perimeter points. The mean surface-measured NDVI for this plot was 0.73 (s.e. = ±0.01) whereas the perimeter points around this plot had a mean of 0.57 (s.e. = ±0.04). This suggests that Landsat NDVI values were likely influenced by conditions outside the plot that may have limited the response of Landsat NDVI.

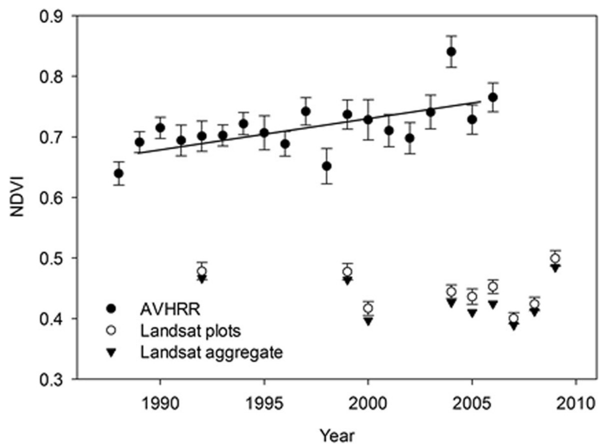

Figure 8. Trends in NDVI of 27 field plots derived from GIMMS AVHRR and Landsat data. The AVHRR values represent the average of the maximum NDVI for the two periods closest to peak growing season, July 16 to July 31 and August 1 to August 15 for each year from 1988 to 2006, for the $n = 13$ AVHRR pixels covering field plots. Values are the means of the 8 × 8 km pixels in which the field plots occur; *error bars* represent ± 1 s.e. of the mean. The *regression line* indicates a significant increasing trend ($P = 0.005$, $R^2 = 0.37$). *Open symbols* represent the Landsat-derived values of NDVI averaged across all the plots and represent the mean of $n = 22$–26 plots depending on the availability of Landsat scenes for a plot and a year. *Closed triangles* represent the mean value of the aggregate of all Landsat NDVI pixels for same area as the 13 AVHRR pixels. Standard errors were not calculated for *closed triangles* but standard deviations ranged from ±0.08 to 0.12.

Another factor contributing to the lack of change in Landsat NDVI for the riparian plot in question is that NDVI saturates at higher values of leaf canopy cover (Riedel and others 2005). NDVI saturated at fractional cover values of 40% of the deciduous shrub *B. nana* in another study (Blok and others 2011a). Consequently, increases in canopy cover for areas with already high canopy cover, particularly for deciduous shrub, may not result in increased NDVI (van Wijk and Williams 2005; Blok and others 2011a). However, the high correlation in Landsat NDVI among the four plots with differing deciduous shrub cover suggest that saturation was not an important effect on NDVI trends.

The lack of increases in NDVI may also be attributable to errors in spatial registration of plots and spatial mismatching of plots with Landsat pixels. Both of these may limit the ability to detect trends accurately. For the majority of plots, the lack of a significant difference between plot and perimeter NDVI suggests that surface-measured NDVI values were consistent across a relatively large area around the plot. This consistency should have reduced errors associated with spatial registration of plots and mismatches of plot and Landsat NDVI data.

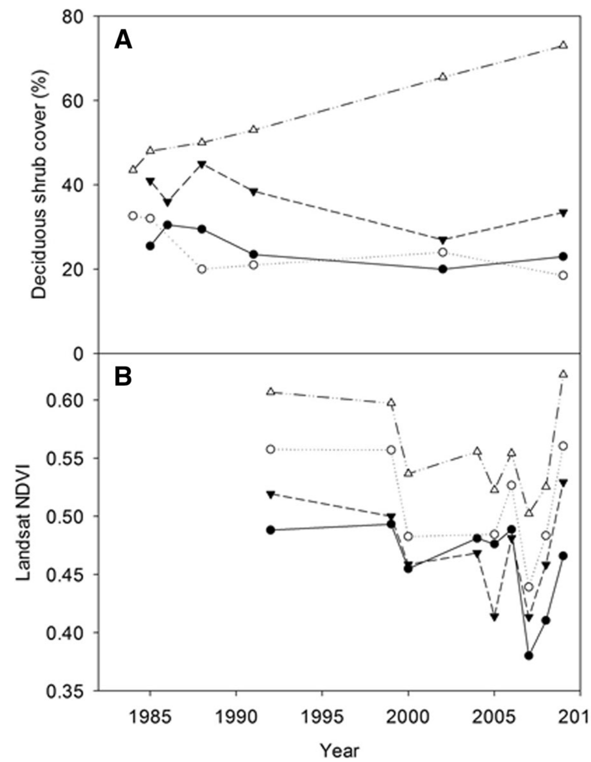

Figure 9. Trends in deciduous shrub cover (**A**) and Landsat-derived NDVI (**B**) for four riparian shrubland plots. The same *symbols* represent the same plots for both **A** and **B**.

The Landsat NDVI data appear to show temporal correlations among plots (Figure 9). These correlations were present in both radiometrically normalized and non- normalized data but appeared to be more pronounced in normalized data. Although normalization may have increased temporal correlations among plots, there were no differences in the Landsat NDVI trends for normalized or non-normalized data. A potential reason for temporal correlations in Landsat NDVI may be that certain dates were too early (16 July 1992, 16 July 2009) or too late (14 August 2005) in the growing season and did not represent peak NDVI values for the year. Our selection of dates was consistent with those used by other researchers. For example Jia and others (2004), found that peak NDVI occurred between July 22 and August 4, and Raynolds and others (2013) used Landsat NDVI scenes from July 29 to August 16 at sites 250 km from our study sites. Arctic systems are characterized by high interannual variability in productivity (Epstein and others 2004). This variability along with a shortened growing season can contribute to temporal correlations among plots and limit NDVI trend detection in Arctic systems particularly for limited sampling intervals by Landsat data (16 days) (Forkel and others 2013; Raynolds and others 2013). Forkel and others (2013) suggest that NDVI trend detection in Arctic systems is improved when aggregated time series or seasonal trend models of NDVI are used.

Arctic tundra dynamics and NDVI can be strongly influenced by microtopography (Gamon and others 2013). Gamon and others (2013), working in wet sedge tundra in northern Alaska, found that variations in elevation of less than 1 m had impacts on tundra plant composition and NDVI. In their study, microsites with lowered elevation tended to have moister soils with greater presence of graminoids and higher NDVI. However, low sites also had greater presence of standing water. Closer examination of the variations in surface-measured NDVI within the plots of this study found similar trends to those of Gamon and others (2013). In the sedge *Dryas* vegetation type, three of the disturbed plots and one of the undisturbed plots had NDVI sampling points that occurred over water with NDVI values at or near zero. Also in the sedge *Dryas* vegetation type, one of the control and one of the disturbed plots had NDVI points that occurred over depressions or troughs dominated by graminoids. The values of NDVI in troughs were 1.2–1.7 times greater than the average value of vegetated points (without water) on those plots. A closer examination of one of the sedge *Dryas* plots found that water increased from 0% in 1986, 1987, 1988, and 1991 to 22% in 2009. There was not, however, a significant decrease in Landsat NDVI for this plot over that time frame as would be expected by increases in water on this plot. Part of the explanation for the lack of a decrease in NDVI may be that graminoid cover also increased on this plot from 1.5% in 1986 to 21% in 2009, suggesting that increases in graminoid cover compensated for potential declines in NDVI due to increased water. As permafrost degradation associated with climate change can lead to increases in water impoundment in Arctic lowland tundra (Jorgenson and others 2006), similar fine-scale changes may be occurring elsewhere that are not detected with satellite imagery.

The results of this study indicate that although there were increases in coarse-scale NDVI as seen with AVHRR data, neither the aggregate of Landsat NDVI pixels over the AVHRR area nor the Landsat NDVI centered on field plots showed increases. The lack of change in Landsat NDVI over plots is consistent with the relatively few significant changes in total vegetative cover and species composition on most of the study plots between 1984 and 2009. As mentioned above, the changes in sedge *Dryas* cover were likely too small to be detected by Landsat NDVI. These results highlight the heterogeneity of patterns of change observed at fine scales that are not apparent at coarse scales in Arctic tundra ecosystems (Fraser and others 2011; McManus and others 2012; Raynolds and others 2013).

The positive trend in AVHRR NDVI over the study region from 1988 to 2006 (Figure 8) was similar to the positive trends in NDVI seen in other studies in the Arctic using the AVHRR data (Goetz and others 2005; Myneni and others 1997; Verbyla 2008; Pouliot and others 2009; Bhatt and others 2010; Beck and Goetz 2011). The rate of change in AVHRR NDVI in this study (0.005 NDVI units/year) was within the range of values of found by Verbyla (2008) of 0.0025–0.0075 and less than the rates seen by Raynolds and others (2013) of 0.007 NDVI units/year. The lack of increases in Landsat NDVI over field plots (Figure 7) is consistent with other studies of changes in Landsat NDVI in the Arctic that show that a relatively small proportion of the Arctic tundra is experiencing changes in NDVI. For instance, in the foothills of the Brooks Range, approximately 250 km southwest of this study, although the AVHRR NDVI data showed increases, the finer-scale Landsat data showed very heterogeneous changes in NDVI, with only 5% of pixels having significant increases (Raynolds and others 2013). Similarly, in an area in Canada 200 km east of this study, only 6% of the Landsat pixels showed increases in NDVI whereas 1% showed decreases (Fraser and others 2011). In other regions of the Canadian Arctic, less than 26% of the area showed a significant increase in NDVI (Fraser and others 2011). A study in northern Quebec, Canada found that 30% of the pixels showed significant increases in Landsat NDVI from 1986 to 2010 (McManus and others 2012).

The lack of change in Landsat NDVI is potentially associated with the reduced numbers of samples of dates that limit the ability to detect trends (Forkel and others 2013; Raynolds and others 2013). Satellites collect AVHRR data orbit daily, so that a representative growing season value can be obtained for every year despite cloudy conditions. Landsat satellites repeat their orbits every 16 days, so cloudy areas with short summer seasons may lack peak growing season data for many years. However, based on the available Landsat NDVI, it seems unlikely that additional years would have changed the overall trend or lack thereof. Another potential explanation for the lack of trends in Landsat NDVI is that available Landsat scenes may represent interannual extremes in NDVI and therefore may inordinately influence NDVI trends. However, the AVHRR NDVI values do not suggest that the Landsat NDVI values represent extremes in the time series.

The discrepancy between trends in NDVI as seen with AVHRR and Landsat NDVI in this and other studies (Macander and others 2012; Raynolds and others 2013) highlight the difficulties in interpreting NDVI trends at differing scales or with different sensors (Jiang and others 2006; Williams and others 2008; Guay and others 2014). As mentioned above Raynolds and others (2013), found that although 12-km AVHRR NDVI increased by 0.074 NDVI units per decade for their 823 km^2 study area between 1982 and 2010, aggregated Landsat NDVI for the same area only increased by 0.006 NDVI units per decade ($P = 0.489$). Macander and others (2012), working in north western Alaskan tundra, found that although much of their 57,000 km^2 study area showed increases in NDVI when examined with coarser-scale 12.4 km AVHRR, only 30% of the region showed increases when analyzed with finer-scale 1-km AVHRR and 30-m Landsat data. The analysis of trends for the coarser-scale AVHRR data included dates from 1981 to 2010 whereas the finer-scale (1 km) data ranged from 1990 to 2011. The NDVI of the coarser-scale sensor increased by 0.05 NDVI units per decade whereas that of the finer-scale sensor increased by 0.023 NDVI units per decade. Jiang and others (2006) suggested that NDVI measured at different spatial resolutions are not comparable in areas with dark soils or shadows. Consequently, the variation in vegetation types used in this study that include the presence of shadows in taller vegetation such as riparian plots and the presence of water on some plots (for example, sedge *Dryas*) may limit the ability to make comparisons in NDVI across differing spatial resolutions (surface and Landsat). A recent analysis of trends in NDVI from five commonly used satellite sensors found that there was regional variation in the NDVI trends over high latitude regions (Guay and others 2014). Although in general there were similar trends in NDVI among sensors for the tundra region of the north slope of Alaska, for other regions there were large discrepancies (Guay and others 2014). These authors highlight the challenges of making comparisons between satellite sensors including differences in resolution, spectral bandwidths, and calibrations (Guay and others 2014).

The combination of coarse- and fine-scale satellite data used in this study along with surface measures of NDVI and repeatedly measured field plots provides unique insights into the patterns of change in Arctic tundra. The data from this study suggest that there have been relatively few changes occurring at these field sites. However some plots have seen changes, for example, there were increases in water cover on a sedge *Dryas* plot and increases in deciduous shrub cover on a riparian shrubland plot. In contrast to other studies, there have not been wide spread increases in deciduous shrub cover across the tundra types. These increases are often implied when there have been increases in NDVI. To provide a comprehensive sampling of trends in tundra dynamics, future efforts should be directed at developing fine-scale assessments of patterns of change across the landscape. These efforts should include sampling of surface NDVI along with plant, ground, snow, and water cover measurements and environmental measurements (temperature, soil moisture, permafrost depth) to provide a more complete picture of the patterns and determinates of change in these systems.

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