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Patterns of Change within a Tundra Landscape: 22-year Landsat NDVI Trends in an Area of the Northern Foothills of the Brooks Range, Alaska

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Abstract

NDVI (Normalized Difference Vegetation Index) calculated from coarse-resolution sensors has shown strong increases since the 1980s on Alaska's North Slope. Finer-resolution satellite data and ground studies are needed to understand the changes in the vegetation that are causing these increases. Analysis of an 823 km^2 area using a Landsat NDVI time series showed that the homogeneous greening at coarser scales was very heterogeneous at 30-m pixel resolution, with a strong influence due to glacial history. Small scattered patches of pixels with significant increases in NDVI occurred throughout the younger, late Pleistocene glacial deposits. On older, mid-Pleistocene deposits, increases occurred in few, larger patches of mostly tussock-sedge, dwarf-shrub, moss tundra, possibly a result of release of nutrients from thawing of ice-rich permafrost. Five percent of pixels had significant linear increases in NDVI from 1985 to 2007 ($n = 6$, $p < 0.05$), while 0.4% showed significant decreases, in small patches whose causes were evident when sampled on the ground. Trends in NDVI varied by glacial history, elevation, slope, and the resulting vegetation conditions. This heterogeneity in response to climate change can be expected throughout much of the Arctic, where complex glacial histories determine existing soil and vegetation characteristics.

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Introduction

The Arctic was expected to be the portion of the globe most affected by climate change, due to feedback effects such as the transition from highly reflective snow and ice to absorptive water and land, and as seen in the polar amplification of past climate fluctuations (Serreze and Barry, 2011). Satellite data have confirmed this, showing that both land surface and sea surface temperatures have increased rapidly in most parts of the Arctic, with an average increase of 0.72 ± 0.10 °C per decade in annual temperatures north of 60°N between 1981 and 2005 (Comiso, 2006), with rates up to 1.35 °C per decade for 1998–2008 (Bekryaev et al., 2010). Sea ice cover in the Arctic has declined approximately 10% per decade between 1979 and 2007 (Comiso et al., 2008). These changes in the environment are having effects on Arctic vegetation. Sea ice trends are correlated with increases in satellite measurements of Arctic summer temperature and NDVI (Normalized Difference Vegetation Index data, an index of photosynthetic capacity; Tucker, 1979) (Bhatt et al., 2010). It is important to understand what these changes in NDVI mean on the ground, as changes in vegetation have wide-ranging implications to ecosystems and the people that depend on them.

NDVI has been shown to be a useful measure for evaluating tundra vegetation on a wide range of scales. NDVI trends from satellite sensors with different spatial resolutions correlate well, and hand-held NDVI measurements from the Arctic have been shown to match satellite data (Fensholt and Proud, 2012; Laidler et al., 2008; Pouliot et al., 2009). Data from trans-Arctic transects show that NDVI is strongly correlated with aboveground plant biomass at the circumpolar level (Raynolds et al., 2012). Ground studies have found that NDVI correlates to tundra plant cover (Laidler et al., 2008), leaf area index (LAI) (Hope et al., 1993), above-ground plant biomass (Riedel et al., 2005), and the age of glacial surfaces (Walker et al., 1995).

Increasing trends in satellite measurements of northern NDVI were first reported in the 1990s and continue to be documented by numerous studies (e.g. Goetz et al., 2005; Myneni et al., 1997; Pouliot et al., 2009). The North Slope of Alaska is one of the places in the Arctic with the largest increases in NDVI (Bhatt et al., 2010). Advanced Very High Resolution Radiometry (AVHRR) NDVI for the southern, Subzone E portion of the North Slope increased by 0.035 NDVI units/decade between 1981 and 2001 (Jia et al., 2003). Between 1982 and 2010, the NDVI of the AHVRR pixels covering the study area showed a trend of 0.074 NDVI units/decade (Bhatt et al., 2010).

In order to better understand the trends in Arctic NDVI reported from coarse resolution sensors (>1 km, e.g. AHVRR), researchers have turned to finer spatial-scale data, such as the 30-m pixel Landsat data. Analysis of Landsat scenes from treeline in the Northwest Territories and Quebec found that increases in NDVI were greatest for broadleaf tree/shrub communities and least for lichen-dominated communities (Olthof et al., 2008). A transect of Landsat scenes across treeline in Quebec found a greater proportion of increasing NDVI pixels in the tundra area than in forested area (McManus et al., 2012). Landsat NDVI time series from four large areas of northern Canada found spatial patterns of increasing NDVI that matched AVHRR data, and related to increases in vascular plants (Fraser et al., 2011). Landsat data from areas 50–200 km northeast of our study area showed that areas with high NDVI values, considered to be areas of shrub cover, expanded on flood-

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plains, along stream channels, and adjacent to rock outcrops (Tape et al., 2011).

Scattered site-specific ground studies provide supporting data for the changes that are seen in the satellite data. Increases in deciduous shrub cover have been documented in the warmest parts of the Arctic, including alders in the northern foothills of the Brooks Range, Alaska (Sturm et al., 2001), willows on Herschel Island, Yukon Territory, Canada (Myers-Smith et al., 2011), and willows in Western Siberia, Russia (Forbes et al., 2009). Differences in the response of different growth forms are consistent with results from the International Tundra Experiment warming chambers, which showed increases in shrubs and decreases in lichen cover (Walker et al., 2006). The experiments also showed differences in responses depending on soil moisture, with shrubs generally increasing in moist and wet plots, and decreasing in dry plots (Elmendorf et al., 2012).

Our study focused on an area of the North Slope of Alaska with increasing NDVI at the 8-km pixel scale. Our study takes advantage of extensive ground mapping in the vicinity of the Toolik Field Station. We used this mapping to analyze trends in NDVI from a time series of Landsat images, supplemented with ground data collected for this project, to identify the physical and biological factors related to changes in this very heterogeneous Arctic landscape.

Methods

STUDY LOCATION

The area analyzed is on the North Slope of Alaska, in the foothills on the north side of the Brooks Range, approximately 148.8–149.7°N and 68.5–68 .8°W (Fig. 1). It is an 823 km^2 area in the vicinity of Toolik Field Station, including the Imnavait Creek study area and the upper reaches of the Kuparuk River. The study extent was chosen to match an area whose characteristics have been mapped based on extensive ground data (Walker and Maier, 2008). Elevations range from less than 600 m in the northwest and south-

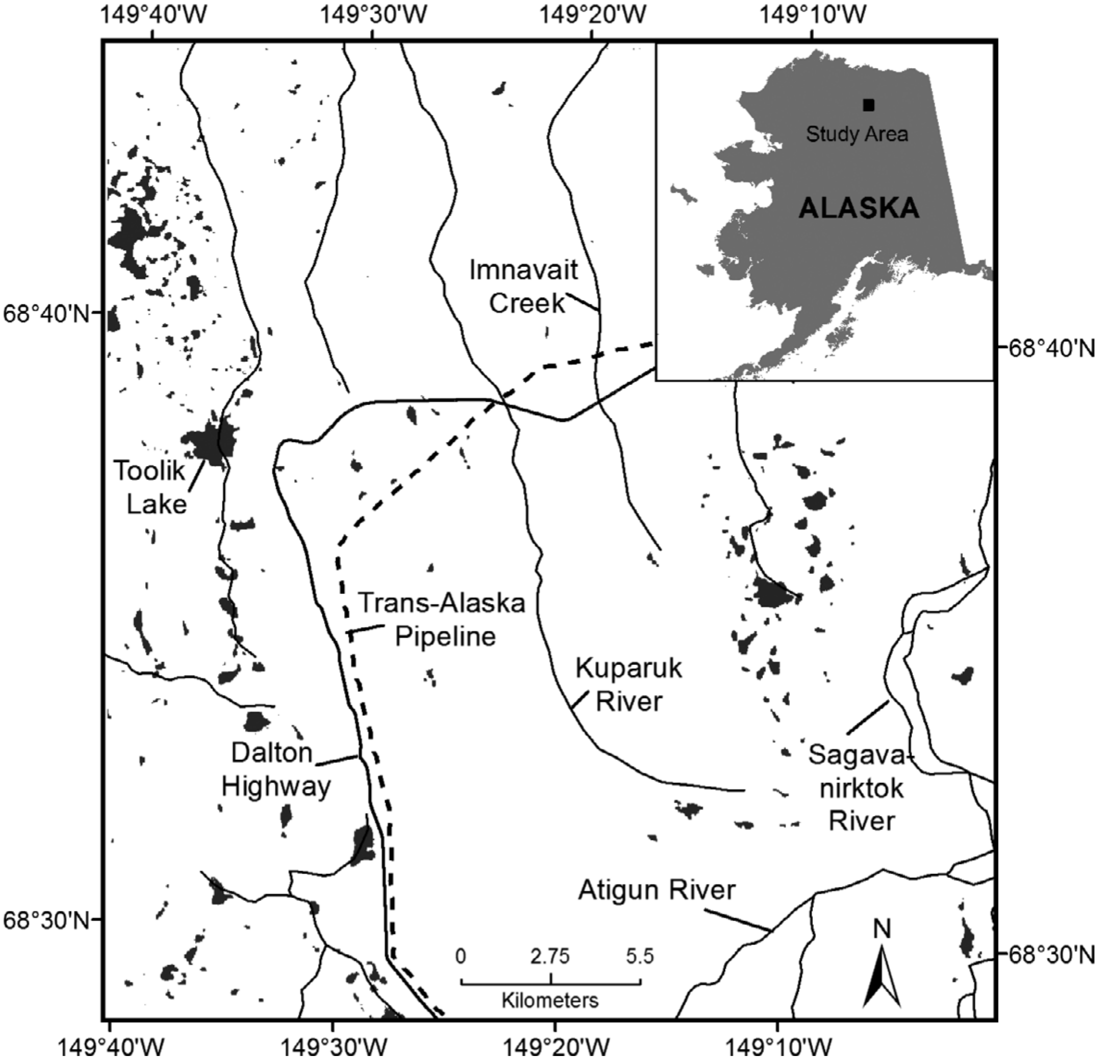

FIGURE 1. Location of study area in the southern portion of the North Slope, Alaska, in the foothills of the Brooks Range. The Dalton Highway is the solid line curving from bottom towards upper right, with a more or less parallel dotted line showing the Trans-Alaska Pipeline. Toolik Field Station is located on the southeast shore of Toolik Lake, in the northwest portion of the study area.

east corners to over 1500 m in the southern portion of the study area, which includes the ridge north of Atigun Gorge. There is a general decrease in elevation from the southern to the northern portion of the study area. Slopes in the study area are mostly gentle (2–5% slope, 30% of area) to moderate (5–10% slope, 38% of area). The area is all north of the latitudinal treeline, in the warmest Tundra Bioclimate Subzone (E) on the Circumpolar Arctic Vegetation Map (CAVM Team, 2003). The climate is relatively warm in the summer and cold in the winter. At Imnavait Creek, in the center of the study area, the mean July temperature was 10.9 °C and the mean January temperature was −21.5 °C, with a mean annual temperature of −7.5 °C (1985–1990) (Hinzman et al., 1996). Mean annual precipitation was 330 mm, with one-third of that falling as snow (10.9 cm water equivalent) (Hinzman et al., 1996).

Glaciers have flowed from the Brooks Range northward through the study area numerous times. Recent advances include the Sagavanirktok advance (mid-Pleistocene), whose deposits cover most of the central portion of the study area, and the younger, late Pleistocene Itkillik advances (Itkillik I deglaciated about 60,000 years ago, Itkillik II deglaciated 11,500–25,000 years ago), whose deposits are found on the western and eastern portions of the study area (Hamilton, 2003). The area is underlain by continuous permafrost (Osterkamp and Payne, 1981). The vegetation is mostly sedge-dominated with two vegetation types covering over half the area: 38.7% cover of tussock-sedge, dwarf shrub, moss tundra, and 17.3% cover of non-tussock-sedge, dwarf shrub, moss tundra; and there are also smaller amounts of erect-shrub, prostrate-shrub, and wetland vegetation types (Munger, 2007; Walker et al., 1994).

Data from SPOT satellite sensors and hand-held NDVI measurements in the study area showed that NDVI increased with landscape age (Walker et al., 1995). NDVI also varied with vegetation type and for areas with different surficial geomorphology, slope angle, and aspect (Munger, 2007). NDVI values were highest for low to tall shrublands (NDVI = 0.54, mean of 4 Landsat scenes, 1985–2002), and lowest for areas of herbaceous marsh (0.07) and partially vegetated barrens (0.29). NDVI values were higher for older-aged landscapes (Sagavanirktok—0.53, Itkillik I—0.51, Itkillik II—0.49) (Munger, 2007).

SATELLITE IMAGERY

Landsat scenes were downloaded from the NASA EROS GLOVIS website. We selected scenes with 30-m pixel resolution from Landsat 4 or later (TM, ETM, ETM+), during peak growing season (29 July–16 August), that were relatively cloud free over the study area. There were six scenes that met these criteria, including scenes from 1985, 1989, 1995, 1999, 2004, and 2007 (Table 1). The date of year of acquisition was compared to AVHRR GIMMS3g data (Pinzon et al., 2007) to verify that the acquisition date was close to annual peak NDVI, and that the years did not have anomalously high or low NDVI (Fig. 2).

At-satellite spectral radiance and spectral reflectance were calculated for Bands 3 and 4 (red and near-infrared, 0.7–0.8 and 0.8–1.1 μm, respectively) (Chander et al., 2009). The band reflectances were radiometrically normalized to the 1985 base year using data from light and dark pseudo-invariant features (Chen et al., 2005), corresponding to unvegetated limestone and water, respectively. NDVI was calculated from the normalized reflectance of Bands 3 and 4: NDVI = (Band 4 − Band 3)/(Band 4 + Band 3). Areas of water were masked using low values in Band 2 (B2 1985 DN ≤ 23). Areas of cloud and cloud shadow were manually masked using Band 3, Band 5, and by checking for large differences in NDVI between scenes. Data lost due to the malfunction of the Landsat-7 scan-line corrector were masked using the files provided with the Landsat-7 scenes. Area covered by the masks in different years ranged from 3.1–18.6% of the study area (Table 1).

TREND ANALYSIS

Trends in NDVI were calculated on a pixel basis using linear regression analysis and tested for significance using the ''R'' statistical program (R Development Core Team, 2010). All unmasked pixels in each year were evaluated. Pixel locations for which there were fewer than 5 scenes with data (more than 1 missing year) were not included in the trend analysis. NDVI trends were analyzed by elevation, hill-slope, and aspect classes using data from a 5-m resolution Star3i ortho-rectified radar image of the study area (Nolan, 2003). GIS shapefile maps of environmental characteristics of the area (Walker and Maier, 2008) were registered to the Landsat

TABLE 1

Landsat imagery used for analysis of Normalized Difference Vegetation Index (NDVI) trends in an area of the foothills of the Brooks Range, Alaska.

Landsat scene	Path/Row	Satellite	Year	Date	Percent of scene masked (water, cloud, shadow, striping in L7-SLC-off)
LT50730121985216XXX07	073/012	Landsat 5	1985	4 August	3.1
LT40740121989210XXX02	074/012	Landsat 4	1989	29 July	18.6
LT50720121995221XXX00	072/012	Landsat 5	1995	9 August	14.7
LE70730121999215AGS00	073/012	Landsat 7 SLC on	1999	3 August	4.0
LE70730122004229EDC02	073/012	Landsat 7 SLC off	2004	16 August	9.3
LE70730122007221EDC00	073/012	Landsat 7 SLC off	2007	9 August	8.0

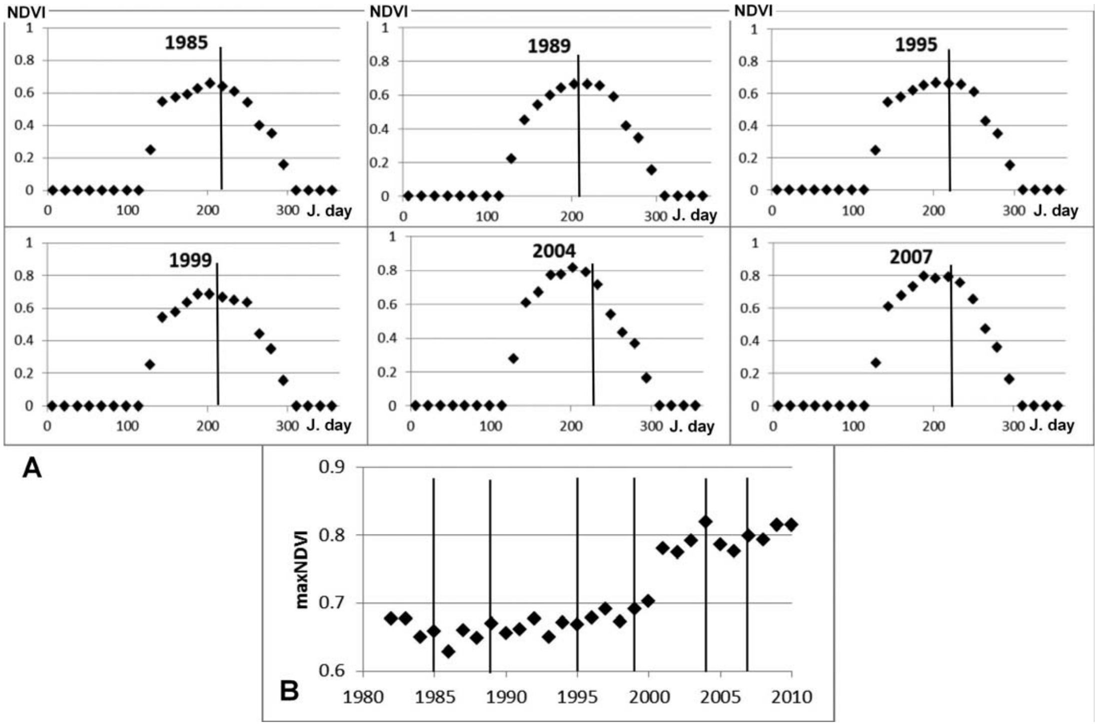

FIGURE 2. (A) Vertical lines represent the day of year that each Landsat scene was acquired, shown in relation to the seasonal pattern of Normalized Difference Vegetation Index (NDVI) increase and decrease from GIMMS3g Advanced Very High Resolution Radiometry (AVHRR) data, averaged for the 7 pixels covering the study area in the Upper Kuparuk River basin, North Slope, Alaska. (B) Vertical lines represent the years of the Landsat scenes, shown in relation to maximum annual NDVI from GIMMS3g AVHRR data averaged for the study area.

image. Average NDVI trends were calculated for categories of vegetation type, surficial geomorphology, surficial geology, and glacial geology.

Regression tree analysis in ''R'' (R Development Core Team, 2010) was used to model the importance of variables in determining the value of the NDVI trends. A range of parameter settings was tested, and the run with the lowest squared error loss is reported here. The subsample size was set at 0.5, meaning that a random half of the data was used to develop each additional tree. The learning rate, set at 0.1 for large data sets, shrank the contribution of each tree to <1 to prevent overfitting (Elith et al., 2008). The number of nodes/tree (the number of levels of branching in each classification tree) was set at 6. The number of trees was set to 10,000. Models of the entire study area used 8 mapped variables to explain the variation in NDVI: vegetation type, landform, surficial geology, glacial geology, geomorphology, elevation, slope, and aspect. Additional models were run for categories within the two most important variables: within the two major glacial geology types (Sagavanirktok and Itkillik) and within 5 elevation categories (570–650, 750, 850, 950, and 950–1518 m). Results of the relative importance of the variables in modeling NDVI trends are reported (sum of all variables = 100).

GROUND DATA

An informal non-random check of some of the areas of change was made by foot traverses in August 2011. Areas on different glacial surfaces with differing NDVI trends (positive, negative, no trend) within one-day walking distance of the Dalton Highway were selected (overnight camping is prohibited in the Toolik Lake Research Natural Area) (Fig. 1). Detailed data were collected from 53 plots, and notes were made on vegetation patterns in areas with different NDVI trends adjacent to and traversed between plots. Location was determined by navigating to specific Landsat pixels using a Trimble GPS unit. Data collected included latitude, longitude, slope, aspect, topographic position, landform, presence of patterned ground and snowbanks, and any evidence of permafrost degradation or other recent landscape changes. Ground cover was described, including live and dead vegetation, water, bare soil, and rocks. Vegetation cover was described by percent cover of different plant life forms. Species cover of dominant plants was recorded using Braun-Blanquet cover categories (1 = 1–5%, 2 = 6–25%, 3 = 26–50%, 4 = 51–75%, 5 = 76–100%). Soil pits were dug to over 50 cm depth or to permafrost if the active layer was less than 50 cm. Thickness of live moss, dead moss, peat, A and B horizons were measured for each site. Active layer depth, soil moisture, soil texture, and rock fragments were described. Differences between categories were tested using *t*-tests with Bonferonni's correction for multiple comparisons (R Development Core Team, 2010).

Results

TREND ANALYSIS

Average NDVI of the study area increased over the study period (1985–2007) at a rate of 0.006 NDVI units/decade, a 3.2% increase in NDVI over the 22 years (Fig. 3, part A). Most of the

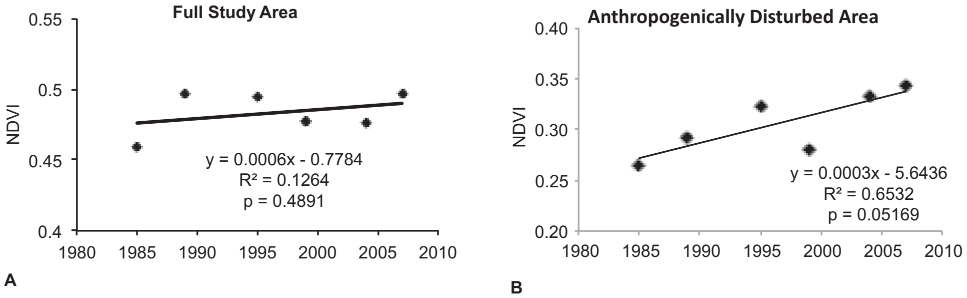

FIGURE 3. (A) Average Landsat NDVI of the study area in the Upper Kuparuk River basin, North Slope, Alaska (1985, 1989, 1995, 1999, 2004, and 2007); (B) NDVI of anthropogenically disturbed areas from the same Landsat scenes.

area showed no significant change ($p > 0.05$, 94.6%), 5.0% showed significant increases, and 0.4% showed significant decreases over the study period (Fig. 4). Most of the areas with significant change increased at a rate slower than 0.05 NDVI units/decade (Fig. 5).

The increases and decreases were not evenly distributed across the landscape (Fig. 4). The greatest increasing trends in NDVI were on revegetating abandoned gravel pads, old road material excavations, and stabilized river terraces. The largest decreasing trends in NDVI were on eroding river terraces and new road material excavation sites. Anthropogenic barrens showed the largest positive trend in NDVI over the study period ($p = 0.05$; Fig. 3, part B) at 0.03 NDVI units/decade, 5 times the average rate of increase and a 21% increase over the study period. However, this type was not very common, occurring on only 0.16% of the area. Of the most common land-cover types, tussock tundra (moist, acidic, tussock-sedge, dwarf shrub, moss tundra; 38.7% of area) increased at a rate slightly above the average of the study area (0.007 NDVI units/decade), while non-tussock-sedge tundra (moist, non-acidic, non-tussock-sedge, dwarf shrub, moss tundra; 17.3% of area) showed a smaller positive trend (0.005 NDVI units/decade). Vegetation types dominated by prostrate shrubs (<15 cm in height) located in snowbeds and on dry ridges showed greater increases in NDVI than those dominated by taller dwarf or low shrubs, generally located in drainages or floodplains.

The two major glacial surfaces in the study area had distinct rates of NDVI increase (Fig. 6, part A) and distinct spatial distribution patterns of pixels with significant trends (Fig. 4). The older, Sagavanirktok glacial surfaces had a lower average increase in NDVI (0.0068 units/decade), with pixels with significant positive trends grouped in few, relatively large patches. Significant increases occurred on 8.1 km^2 of this glacial unit, 2.8% of the area covered by these deposits, mostly in tussock tundra (Table 2). The younger Itkillik glacial surfaces had greater average NDVI trend (0.0078 units/decade), occurring in small, common, well-distributed patches. Significant increases occurred on 23.5 km^2 of this glacial unit, 6.0% of the area covered by these deposits. Increases were distributed among several vegetation types and were most common in areas of non-tussock-sedge tundra, tussock tundra, and acidic prostrate-dwarf shrub tundra (Table 2).

The NDVI trend decreased with the steepness of the land surface (Fig. 6, part B) and also decreased with elevation for areas above 650 m (Fig. 6, part C), meaning that steep, high-elevation (mountainous) areas had the lowest increases in NDVI. However, the lowest elevation category (570–650 m), which included river terraces with both large decreases and increases in NDVI, had a smaller average rate of increase than higher elevation categories. Increases were greater on south- and west-facing slopes than on north- or east-facing slopes, and greatest on flat areas with no aspect. Geomorphologic units that included bare ground, such as disturbed areas, frost circles, or gelifluction features had the largest increases in NDVI.

Results of the regression tree modeling show the relative importance value for each independent variable in the model, which together sum to 100. For the whole study area, glacial geology and elevation were the most important variables in modeling the variation in NDVI trends (Table 3). Vegetation type, geomorphology, and aspect were also important, while slope, landform, and surficial geology were the least important variables. Regression tree analysis of the entire study area had squared error losses of 38% after 10,000 runs, meaning that over one-third of the variability was still unaccounted for by the 8 model variables. Elevation was the most important variable within each of the different glacial surface models, and was 2–3 times more important than any other variable for the Itkillik deposits. Conversely, glacial geology was the most important variable within all elevation categories. Geomorphology was also an important variable for the highest elevation categories, and vegetation type for the lowest elevations.

GROUND DATA

Boundaries between areas of increasing NDVI and areas with no change in NDVI usually coincided with visible changes in vegetation communities on the ground. On Itkillik-aged surfaces, ridges with NDVI increases usually had dry, prostrate dwarf-shrub vegetation, and were adjacent to moist, non-tussock-sedge, shrub tundra slopes that showed no increase in NDVI (Fig. 7, part A). On Sagavanirktok-aged glacial surfaces, increases in NDVI occurred on gentle slopes with tussock-sedge, shrub vegetation interspersed with colluvial basins and drainages with sedge-moss tundra (poor fens) that showed no change (Fig. 7, part B).

Areas of change on Sagavanirktok-aged glacial surfaces were usually on gentle slopes with tussock tundra vegetation and mesic silt-clay or silt-clay-loam soils, averaging 1.6 cm of live moss, 3.0 cm of dead moss, 9.4 cm of peat, and a 33 cm active-layer depth ($n = 14$). Cover of willows averaged 4.4%, dwarf birch 13.4%, ericaceous shrubs 20.2%, *Dryas* 3.8%, tussock-sedge (*Eriophorum vaginatum*) 10.5%, mosses 52.8%, and lichens 11.3%.

In contrast, areas of change on Itkillik-aged surfaces were slightly steeper on average (3% slope) with drier, subxeric silt-clay soils with frost scars or mounds (not tussocks) and 12.2% bare ground ($n = 13$). They had less surface organic matter than the greening areas of the Sagavanirktok surfaces, averaging 1.2 cm of

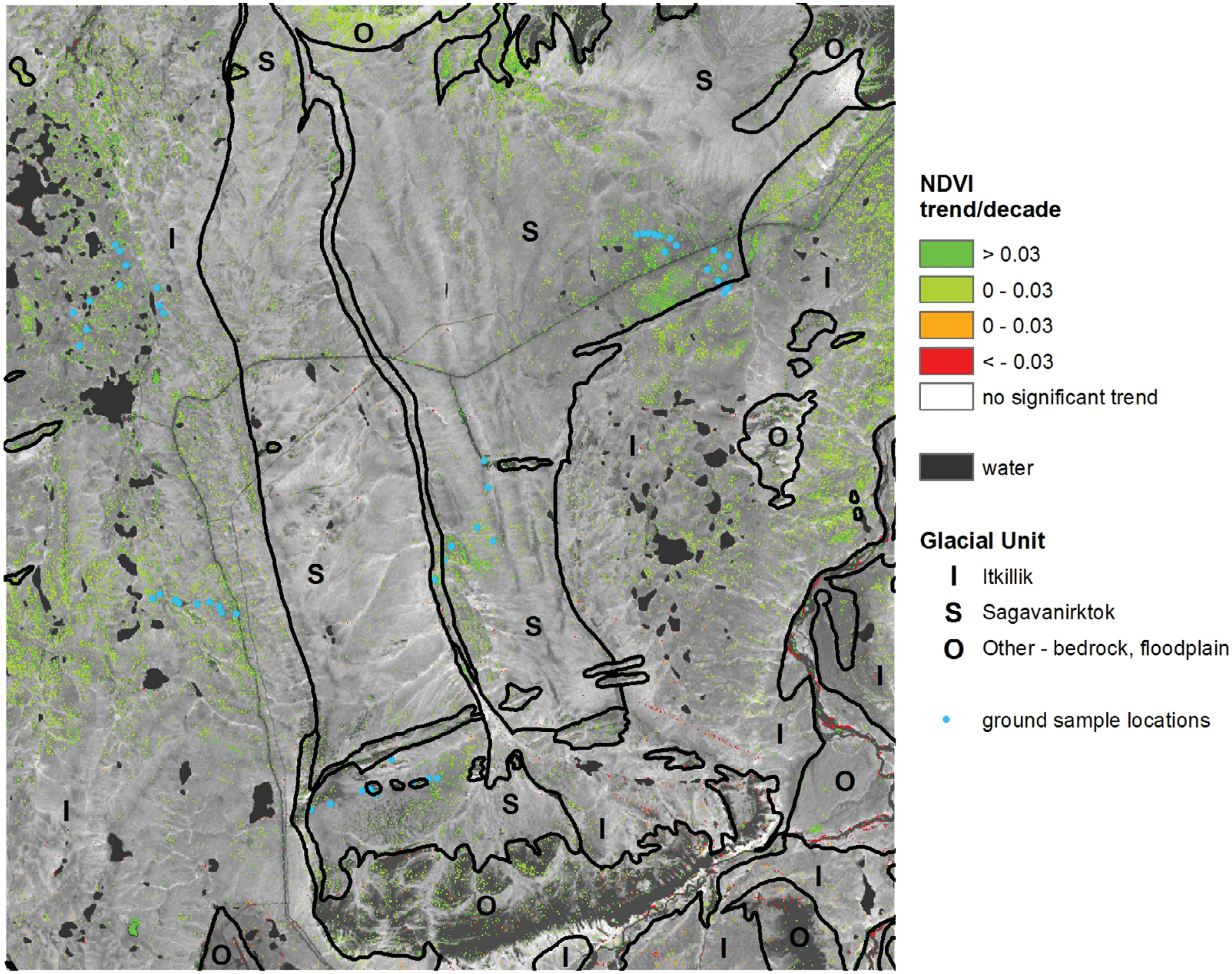

FIGURE 4. Trends in NDVI ($p < 0.05$) in the foothills of the Brooks Range, Alaska, based on linear regression of Landsat data from 1985, 1989, 1995, 1999, 2004, and 2007 (30 × 30 m pixels). Pixels with significant positive trends are green, significant negative trends are red (mostly along rivers), water is black. Mid-Pleistocene Sagavanirktok glaciation is in center (S), late Pleistocene Itkillik glaciation is on west and east (I). Blue points show location of 2011 ground sampling sites. Background image is Landsat NDVI from 4 August 1985, shaded from dark to light gray (low to high NDVI).

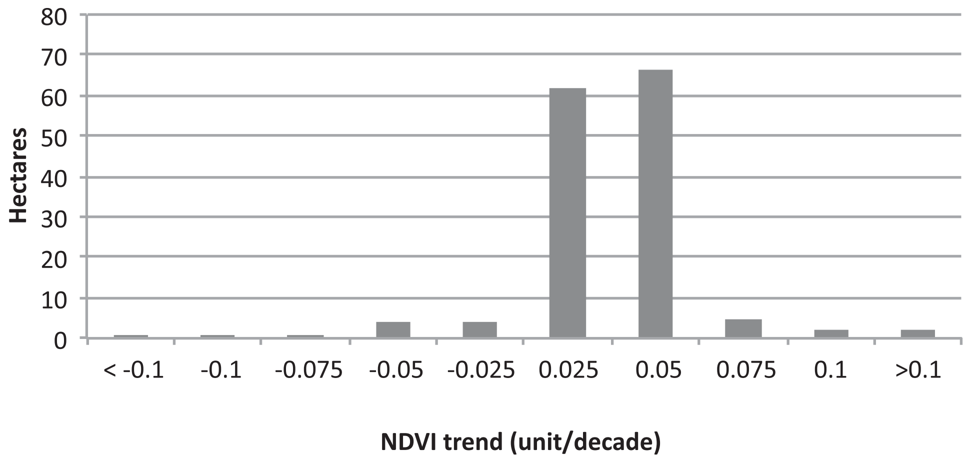

FIGURE 5. Hectares covered by Landsat pixels with significant linear trends in NDVI ($p < 0.05$) in an area of the foothills of the Brooks Range, Alaska, 1985–2007. 95% of the pixels in the study area had no significant trend (2593 ha), and are not included in the graph.

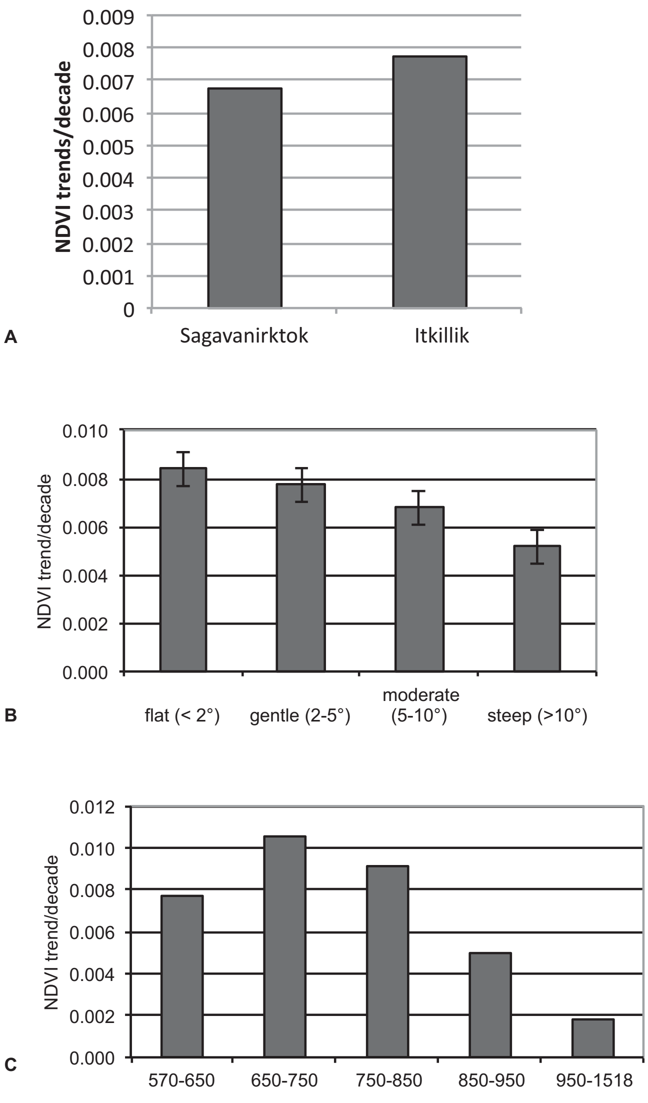

FIGURE 6. NDVI trend (units * decade^{-1}) for areas of (A) two major glacial ages, mid-Pleistocene Sagavanirktok glaciation and late Pleistocene Itkillik glaciation; (B) different steepness; and (C) different elevations in an area of the foothills of the Brooks Range, Alaska, based on Landsat data from 1985 to 2007.

live moss, 1.4 cm of dead moss, 3.7 cm of peat, and an active-layer depth that was >50 cm (actual depth could often not be measured due to rocky soils). Cover of willows averaged 11.3%, dwarf birch 8.1%, ericaceous shrubs 25.3%, *Dryas* 8.6%, tussock-sedge 4.8%, mosses 28.4%, and lichens 12.2%.

There were significant differences in the vegetation types between the plots with change and no change on the Sagavanirktok deposits. Within Sagavanirktok sites, plots with change had more cover of evergreen shrubs, less of deciduous shrubs, less of graminoids, and less of litter (Table 4). Though there were quantitative differences between sample sites that changed and those that did not on Itkillik surfaces, none of the differences were significant. Areas that changed on Sagavanirktok and Itkillik surfaces had significantly different slope, aspect, and microrelief patterning. The Sagavanirktok sites had greater soil moisture, thicker peat layers, more cover of *Sphagnum* mosses and *Dactylina arctica* (''dead man's fingers''), and less cover of crustose lichens. The non-changing sites on Sagavanirktok surfaces were significantly higher in elevation than those on Itkillik surfaces, had less pleurocarpous (branched) moss cover, and more *Sphagnum* moss cover.

Discussion

The results of this study confirm the usefulness of NDVI trend analysis using Landsat data for examining change in tundra landscapes over the satellite record. Large increases and decreases in NDVI matched expected areas of anthropogenic change and natural change, with the greatest increases occurring in areas that would be expected to be rapidly revegetating, such as abandoned gravel pads, old road material excavations, and revegetating river gravel bars. Conversely, the greatest decreases were in areas that would be expected: new excavations and eroded riparian areas.

Areas adjacent to direct human disturbance, such as the Dalton Highway and the Toolik Field Station, show general greening. The gravelly shoulders of the Dalton Highway experience warmer summer temperatures from the lack of insulating vegetation. In addition, there is a fertilization effect from the road dust (Walker et al., 2001). As a result, vegetation along the Dalton Highway tends to be taller and include more shrubs and forbs and less moss cover than the surrounding tundra. An area to the west of Toolik Field

TABLE 2

Area (ha and %) with significant ($p < 0.05$) positive trend in NDVI in different vegetation types within different glacial-aged surfaces, based on Landsat data (1985–2007) in an area of the foothills of the Brooks Range, Alaska. Sagavanirktok surfaces are mid-Pleistocene in age, Itkillik surfaces are late Pleistocene in age.

	Area with significant ($p < 0.05$) positive trend in NDVI (hectares and %)	
Vegetation Type	Sagavanirktok	Itkillik
Anthropogenic barrens	7.7 (18.3)	15.1 (23.5)
Lichens on rocks	17.3 (5.7)	16.5 (8.6)
Partially vegetated barren	7.4 (11.0)	30.7 (10.3)
Tussock-sedge, dwarf shrub, moss tundra	526.3 (3.4)	653.9 (5.5)
Nontussock-sedge, dwarf shrub, moss tundra	26.5 (3.9)	707.9 (6.4)
Sedge-moss tundra (poor fens)	25.7 (1.7)	7.8 (2.5)
Sedge-moss tundra (rich fens)	3.9 (3.5)	33.8 (3.8)
Water and herbaceous marsh	5.4 (6.1)	74.3 (5.6)
Prostrate dwarf-shrub, forb, fruticose-lichen tundra (acidic)	69.9 (6.9)	345.2 (11.0)
Prostrate dwarf-shrub, sedge, forb, fruticose-lichen tundra (nonacidic)	0.0 (N/A)	33.3 (4.1)
Hemi-prostrate dwarf-shrub, fruticose-lichen tundra	4.1 (1.8)	72.5 (5.5)
Hemi-prostrate and prostrate dwarf-shrub, forb, moss, fruticose-lichen tundra	62.9 (4.5)	43.8 (6.3)
Dwarf- to low-shrub, sedge, moss tundra	106.1 (1.9)	116.6 (4.0)
Low to tall shrublands	22.7 (1.6)	93.6 (3.3)

TABLE 3

Relative influence of variables in regression tree analysis of change in NDVI in an area of the foothills of the Brooks Range, Alaska, 1985–2007. The analysis was conducted for the entire study area, separately by glacial surface, and separately by elevation category. The importance values of the eight variables sum to 100 for each model.

	Relative importance value in regression-tree model							
	All	Glacial Surface		Elevation (m)				
Variable		Sagavanirk-tok	Itkillik	570–650	650–750	750–850	850–950	950–1518
Glacial geology	23.7	N.A.	N.A.	29.0	35.3	40.9	21.2	30.2
Elevation	21.3	29.8	37.2	N.A.	N.A.	N.A.	N.A.	N.A.
Vegetation	14.4	19.1	16.6	23.1	14.7	16.8	18.4	16.3
Geomorphology	10.9	18.1	12.4	12.3	13.9	13.2	18.8	20.8
Aspect	10.7	10.2	12.6	12.0	11.5	11.0	12.1	11.4
Slope	7.0	9.0	7.5	10.7	5.8	5.8	10.7	8.8
Landform	6.4	5.3	5.0	8.1	8.9	6.1	10.8	5.6
Surficial geology	5.7	8.6	8.7	4.8	9.8	6.3	8.1	6.9
Squared error loss	*32*	*45*	*38*	*85*	*25*	*43*	*43*	*33*

N.A. = not applicable.

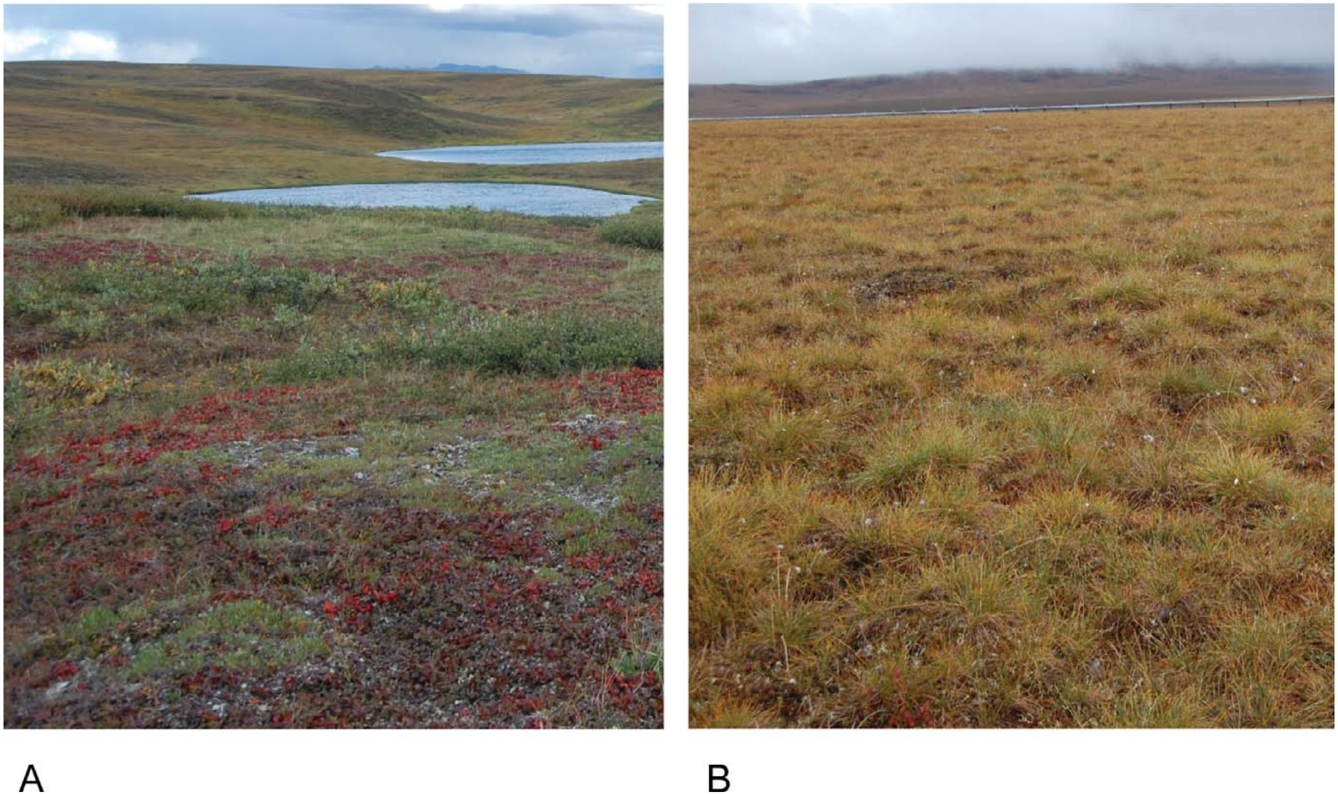

FIGURE 7. Photographs of characteristic areas of showing positive trends in NDVI (1985–2007) in the foothills of the Brooks Range, Alaska. (A) Prostrate dwarf-shrub, forb, fruticose lichen tundra on Itkillik glacial surface; (B) tussock-sedge, dwarf-shrub, moss tundra on Sagavanirktok glacial surface.

Station that showed increases in NDVI is an area of intensive experimentation, including plots that are being warmed, fertilized, selectively pruned, and otherwise manipulated and sampled. The direct and indirect effects of these activities (including simply walking to the sites) are likely contributing to the increasing NDVI. Compression of tundra vegetation by traffic often leads to greening of the tundra (Felix et al., 1992).

On older, mid-Pleistocene glacial landscapes, discrete patches on gentle slopes covered with tussock-sedge, dwarf shrub, moss tundra were the areas with the largest NDVI increases. The patchy distribution of these areas and the fact that most of the mid-Pleistocene surface with similar surface characteristics showed no changes suggest that subsurface characteristics differentiate these areas. The distribution of ice-rich permafrost is not well mapped but is known to be patchy (Hamilton, 2003). A possible explanation is that increased soil temperature has melted ice-rich permafrost, increasing groundwater transport and availability of nutrients in these areas. Arctic plants are known to respond more strongly to the indirect effects of warming on nutrient availability than to the direct effects of temperature and CO_2 on growth processes (Chapin, 1983). Total nitrogen in plant biomass has been shown to increase following thawing of permafrost (Schuur et al., 2007). Borehole data from Galbraith Lake in the southwest corner of the study area show steadily increasing ground temperatures from 1993 to 2010, with increases extending as far as 60 m in depth, indicating a very long-term warming trend in soil temperatures (Romanovsky, 2012).

Partially vegetated sites, with low initial NDVI and high cover of prostrate evergreen shrubs, were the sites with the greatest trends of increasing NDVI on the younger, late Pleistocene glacial landscapes. These sites have been slowly revegetating since the last glacial retreat. More favorable climatic conditions (Kaufman et al., 2009), including warmer temperatures as evidenced by increases in lake and soil temperatures (Hinzman et al., 2005; Romanovsky, 2012), and increased precipitation (Wahren et al., 2005) are likely accelerating this process.

A simplistic view of tundra response to climate change might lead one to expect that all tundra vegetation is increasing due to warmer temperatures. This is the view that one gets looking at coarse scale trends in AVHRR for the North Slope of Alaska (Bhatt et al., 2010; Goetz et al., 2005). More detailed spatial analysis reveals variation in responses in the landscape, with only 5% of this study area showing a significant increase in NDVI. An increase in the number of years with cloud-free imagery would likely increase the area showing significant change, but two Landsat time series studies in northern Canada also found that a relatively small proportion of the landscape was responsible for the overall increase in NDVI (<26%, 30%, respectively; Fraser et al., 2011; McManus et al., 2012). Sites at high elevations or with steep slopes showed little increase in NDVI, and south- and west-facing slopes had higher rates of NDVI increase than north- or east-facing slopes, confirming results seen in Quebec (McManus et al., 2012). It is likely that the spatial heterogeneity in vegetation change continues at even smaller spatial scales, given that the responses of tundra vegetation to experimental warming vary considerably by life form and species, and differ depending on soil moisture (Elmendorf et al., 2012).

TABLE 4

Characteristics of ground sites (±s.d.) sampled in an area of the foothills of the Brooks Range, Alaska, August 2011. The sites were divided by glacial age (Sagavanirktok, mid-Pleistocene and Itkillik, late Pleistocene) and NDVI trend (significant [$p < 0.05$] positive trend and no significant trend in NDVI). Significant statistical comparisons are in bold type.

Characteristic	Sagavanirktok sites with increased NDVI ($n = 14$)	Sagavanirktok sites with no change in NDVI ($n = 13$)	Itkillik sites with increased NDVI ($n = 13$)	Itkillik sites with no change in NDVI ($n = 9$)	Significant differences, *t*-test $p < 0.05$*
Elevation (m)	827.3 ± 182.1	**906.9 ± 160.3**	830.2 ± 138.8	**763.0 ± 53.8**	d
Soil moisture (scale 1–9)	**5.0 ± 0.7**	5.3 ± 0.8	**4.2 ± 0.7**	5.1 ± 1.7	c
Depth of peat (cm)	**9.4 ± 6.1**	10.5 ± 6.9	**3.7 ± 4.5**	9.3 ± 11.5	c
Evergreen shrub cover (%)	**18.9 ± 10.4**	**2.5 ± 5.6**	22.5 ± 13.2	12.0 ± 10.2	a
Deciduous shrub cover (%)	**16.9 ± 8.2**	**30.4 ± 15.2**	25.9 ± 12.7	19.7 ± 5.1	a
Graminoid cover (%)	**3.4 ± 5.2**	**14.3 ± 10.4**	2.2 ± 2.1	9.1 ± 8.8	a
Pleurocarpous (branched) moss cover (%)	7.1 ± 9.9	**8.6 ± 17.7**	12.5 ± 9.6	**28.6 ± 15.2**	d
Sphagnum moss cover (%)	**32.5 ± 23.7**	**26.2 ± 24.1**	**3.1 ± 8.3**	**3.3 ± 7.1**	c,d
Dactylina lichen cover (%)	**1.3 ± 1.5**	1.2 ± 1.5	**0 ± 0**	0.7 ± 1.3	c
Crustose lichen cover (%)	**1.2 ±1.8**	1.9 ± 5.6	**5.2 ± 4.7**	2.6 ± 6.6	c
Dead plant litter cover (%)	**1.7 ± 2.9**	**5.1 ± 3.0**	3.5 ± 3.5	2.8 ± 2.2	a

*includes Bonferonni's correction for multiple comparisons.

a = Sagavanirktok sites with increased NDVI vs. Sagavanirktok sites with no change in NDVI.

b = Itkillik sites with increased NDVI vs. Itkillik sites with no change in NDVI (*none significant*).

c = Sagavanirktok with increased NDVI vs. Itkillik sites with increased NDVI.

d = Sagavanirktok with no change in NDVI vs. Itkillik sites with no change in NDVI.

The NDVI trend for AVHRR pixels covering the study area showed an increase over the satellite era averaging 0.074 units/decade (12.4 km pixels, AVHRR GIMMS3g) (Bhatt et al., 2010). The increase in NDVI in the study area using Landsat data was less than 10% of this rate (0.006 units/decade). Differences in NDVI trends using data from different satellite sensors have been shown to differ in scale, while agreeing in the direction of the trend (Martinez-Beltran et al., 2009). The Arctic is an especially difficult place to compare sensors due to low sun angle and frequent cloud cover (Fensholt and Proud, 2012). Due to this problem, we focused our investigation on variation across the tundra landscape, rather than quantification of the trend in NDVI.

Decreases in NDVI occurred in less than 1% of the study area, and occurred as small patches (generally <100 m^2, smaller than 3 × 3 pixels). Ground visits to these sites revealed obvious changes that could account for the decrease in NDVI, such as pits and gullies caused by melting ice and erosion in areas adjacent to drainages, changes in stream channels, and one site with dead vegetation (*Cassiope tetragonum* in a south-facing snowbank in the southern portion of the study area that was likely winter-killed due to loss of snow cover).

Ground observations emphasized the importance of the specific time period used in trend analysis. In theory, areas whose NDVI decreased and subsequently increased during the study period would show no significant trend in the analysis. This was not a large concern for this study, as disturbances that decreased NDVI during the study period affected minimal portions of the area ($<1\%$). Also, because tundra vegetation grows relatively slowly, the 22-year study period was not long enough for revegetation to mask decreases in NDVI, as evidenced by the gravel pads created during construction of the Dalton Highway in the 1970s which are still showing strong increases in NDVI.

Our study did not show large increases in NDVI for vegetation types dominated by shrubs >15 cm tall (erect-dwarf, low, or tall shrubs). This is in contrast to studies that have documented the expansion of tall shrubs on the North Slope in Alaska and Canada (Myers-Smith and Hik, 2010; Tape et al., 2006). We also did not find increases in NDVI along drainages, where existing shrub cover might be expected to expand. An analysis of Landsat NDVI from an area north of our study area showed that an increase between 1986 and 2009 in the number of high NDVI value pixels was occurring along drainages, likely due to an increase in erect deciduous shrubs (Tape et al., 2011). Our results also did not confirm the meta-analysis of the International Tundra Experiment, which showed decreases in shrubs in dry sites in response to climate change (Elmendorf et al., 2012). We found that relatively dry vegetation types dominated by prostrate dwarf shrubs had some of the largest increases in NDVI, though we could not differentiate which plant growth form was responsible for the increase. Although this study did not show concentration of NDVI increases in shrub-dominated vegetation types, almost all vegetation types include a shrub component, and it is possible that the shrub species were responsible for the increase in NDVI. One of the reasons our study might differ from those further north is its location close to the

Brooks Range mountains, in a landscape formed by relatively recent glaciation. The large range in elevation and variation in glacial deposits play strong roles in controlling existing vegetation in our study areas and dominate the responses to climate change.

We hope to repeat this analysis in an area farther north that has not been glaciated, where the AVHRR data show even stronger greening trends. A more homogeneous landscape would allow us to identify the responses of different parts of a typical toposequence from hill-crest to slope to basin, allowing us to extrapolate the results to larger regions of the North Slope of Alaska. We would also like to look more closely at areas that are not changing, to investigate the buffering processes that result in their NDVI remaining unchanged.

Conclusions

The Landsat time-series analysis of an 823 km^2 area in the foothills of the Brooks Range, Alaska, showed an increase of NDVI, but the increase was not homogeneously distributed on the landscape. Different spatial patterns of greening occurred on different glacial surfaces. Pixels with significant increases were scattered throughout the younger, late Pleistocene Itkillik surfaces. Increases were less common and occurred in fewer, larger locations on the older, mid-Pleistocene Sagavanirktok surfaces. Five percent of the pixels had significant increasing trends in NDVI, and 0.4% had significant decreases. Increases in NDVI were not concentrated in erect-shrub-dominated vegetation types or along drainages.

Ground transects showed that boundaries between areas with differing NDVI trends coincided with changes in vegetation types and landforms. The younger, Itkillik surfaces showed increases on ridges partially vegetated with prostrate shrubs, adjacent to areas with no increase on moister, more completely vegetated slopes and basins. The older, Sagavanirktok surfaces showed increases on gentle slopes with tussock tundra vegetation, and none in the interfingered, broad, moist drainages. Similar large areas of Sagavanirktok-age tussock tundra showed no increases in NDVI, leading to the hypothesis that increasing NDVI in these areas was due to changes in hydrology and nutrient availability, possibly as a result of thawing of ice-rich permafrost in the ''greening'' areas. Though uncommon, and occurring in very small patches, causes for decreases in NDVI were recognizable on the ground, related to specific disturbance events (e.g. erosion, thermokarst, plant die-off).

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