SPATIAL AND TEMPORAL PATTERNS OF VEGETATION, TERRAIN, AND GREENNESS IN THE TOOLIK LAKE AND UPPER KUPARUK RIVER REGION

A

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Abstract

With a warming climate, Alaska's arctic tundra vegetation is changing. Here I use four Landsat satellite images and glacial geology, surficial geomorphology, vegetation, slope angle, aspect, and elevation maps to examine spatial and temporal patterns of greenness in the Toolik Lake and Upper Kuparuk River Region in Arctic Alaska. The 30-m resolution of the Landsat images used in this analysis allowed for detection of patterns of heterogeneity in the greenness and in the greening of the landscape. Such studies complement the finer temporal resolution of AVHRR data, which are more appropriate to detect annual variation in greenness and greening across broad regions. This study suggests that the measured changes in AVHRR derived NDVI values are likely the result of a real change in arctic vegetation and are not simply due to technical problems with AVHRR sensors. Between 1985 and 1999 the mean Landsat-derived NDVI across the Toolik Lake and Upper Kuparuk Region increased 0.076 or 15.9%. The greening detected by Landsat data occurred heterogeneously across the landscape with the most rapid change occurring in well-vegetated areas such as tussock tundra and shrubby areas, on areas of nonsorted circles, and at lower elevations.

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INTRODUCTION

Background: A Changing Arctic

Satellite remote sensing studies of changes in greenness patterns in northern latitudes have indicated that the tundra in North America is greening earlier and that maximum greenness values are higher (Myneni *et al.* 1997; Zhou *et al.* 2001; Jia *et al.* 2003; Goetz *et al.* 2005). Most observations of large-scale patterns of vegetation have been based on the calculation of the normalized difference vegetation index (NDVI), which is a commonly used index of vegetation activity derived from multispectral satellite data (developed by Rouse *et al.* 1973). Chlorophyll in green vegetation absorbs strongly in the red wavelengths and reflects strongly in the near infrared (NIR) wavelengths, and the difference of the two is used as an index of vegetation greenness. When normalized by the sum of the reflectance in the same channels, the influence of variation in illumination conditions caused by variation in slope or clouds is minimized. Thus NDVI =(NIR-R)/(NIR+R) (Tucker 1979; Lillesand and Kiefer 1987).

Higher NDVI values are indicative of greater photosynthesis and have been correlated with tundra biomass, leaf area index, intercepted photosynthetically active radiation, and other plant biophysical properties such as CO_2 and methane flux (Reeburgh *et al.* 1998, Oechel *et al.* 2000, Stow *et al.* 2004). Interannual NDVI analysis can show variability in plant phenology (timing of green-up and senescence), changes in standing crop (annual peak NDVI, the maximum greenness that occurs during one growing season) and ecosystem net primary production (seasonally-integrated NDVI, the sum of NDVI values over an entire growing season).

Detection of global-scale long-term trends of vegetation biomass has relied mostly on the Advanced Very High Resolution Radiometer (AVHRR) sensors aboard the National Oceanic and Atmospheric (NOAA)-6 through NOAA-16 weather satellites. Time-series analyses indicate that the two decades following the initial launch of the AVHRR sensors were a period of rapid increase in the NDVI at northern latitudes (Myneni 1997; Zhou 2001; Jia *et al.* 2003). The AVHRR analyses have involved data at 8-km resolution. For example, Jia *et al.* (2003) analyzed a time series of AVHRR satellite data for three bioclimate subzones in northern Alaska and confirmed a long-term trend of increase in vegetation greenness for the Alaskan tundra that has been detected globally for the northern latitudes. Using a 21-yr (1981-2001) time series of 8-km resolution data, Jia *et al.* (2003) found a 16.9% (±5.6%) increase in peak vegetation greenness across Arctic Alaska that corresponds to simultaneous increases in temperature.

The warming trend in Arctic Alaska is described by the summer warmth index (SWI), which is the sum of monthly mean air temperatures greater than 0°C, expressed as °C-mo. During the period of 1981-2001, the Arctic Slope's SWI increased 0.16-0.34 °C mo/yr, with greater NDVI values generally coinciding with warmer temperatures, and drops in NDVI corresponding with colder summers (Jia *et al.* 2003). While summer temperatures affect plant growth most directly, global warming is expected to create an overall increase in air and soil temperatures, more rapid nutrient release from decomposing soil organic matter, and increased summer cloudiness as sea ice melts and allows greater evaporation from the ocean (Chapin *et al.* 1995).

Temporal analysis of NDVI has shown that the arctic is greening, though not homogeneously. Biotic responses to climate change should vary based on latitude, vegetation type, site factors, and other ecological variables. AVHRR NDVI analysis is too coarse to accurately quantify relatively small-scale patterns of landscape heterogeneity and mechanisms for vegetation change, especially in the arctic tundra where heterogeneity in moisture, topography, snow accumulation, and dominant plant growth form can exist over small spatial scales. A single remotely sensed pixel may contain areas that differ widely in patterns of growth, physiological activity, tissue turnover rates, leaf structure and pigment content, LAI, stem area, leaf litter, proportion of exposed soil/rock and, potentially, response to global change (Boelman 2003). Examining vegetation change at a smaller spatial scale can help to characterize underlying mechanisms responsible for heterogeneity in landscapes and ecosystem processes, and identify proximate causes of vegetation change related to climate change.

Furthermore, although the AVHRR data have numerous advantages for studies of broad regional changes because of their daily global coverage and because CO_2 flux data and modeling studies seem to support the greening patterns found using AVHRR data, there has been considerable debate as to the cause of the NDVI increase and even if the change has been real because of numerous technical issues related to degrading orbits of the sensors and calibration of the several satellites involved in the time-series of data (Fung *et al.* 1987). An independent analysis of the greening trend would help evaluate the magnitude and locations of the greening.

For this research I used multiple GIS layers and four 30-m resolution Landsat scenes to describe the relationships between vegetation, glacial geology, surficial geomorphology, slope angle, aspect, and elevation to analyze spatial and temporal patterns of greenness in the Toolik Lake and Upper Kuparuk River Region of Alaska. The spatial analysis investigated the relationships between vegetation types, terrain characteristics, and NDVI. The temporal analysis of the Landsat data was compared to time series that have been developed using AVHRR data. The relatively low temporal resolution of applicable Landsat data for the Arctic makes it difficult to distinguish interannual variability in vegetation from directional vegetation change. The 30-m resolution permits an independent confirmation of the trends shown by other data sources and allows a more detailed analysis of which parts of the landscape have greened the most dramatically.

Background: The Toolik Lake and the Upper Kuparuk River Region

The Toolik Lake and Upper Kuparuk River Region is located in the northern foothills of the Brooks Range in northern Alaska (68°38'N, 149°36'W, elevation 720 m, 254 km north of the Arctic Circle) (Figure 1). The region is treeless and underlain by continuous permafrost 250-300 m thick (Osterkamp 1983). The Arctic consists of five bioclimate subzones (A-E); the most southerly three (C-E) occur in the Alaskan Arctic (CAVM team 2003). The Toolik Lake and Upper Kuparuk River Region is in bioclimate subzone E, the warmest subzone. Subzone E has a mean July temperature of 9-12°C, 80-100% horizontal cover of vascular plants, and 2-3 layers of vertical plant cover, the tallest shrub layer reaching up to 80 cm height (CAVM Team 2003). Winds in this area are primarily out of the Brooks Range to the south and southeast.

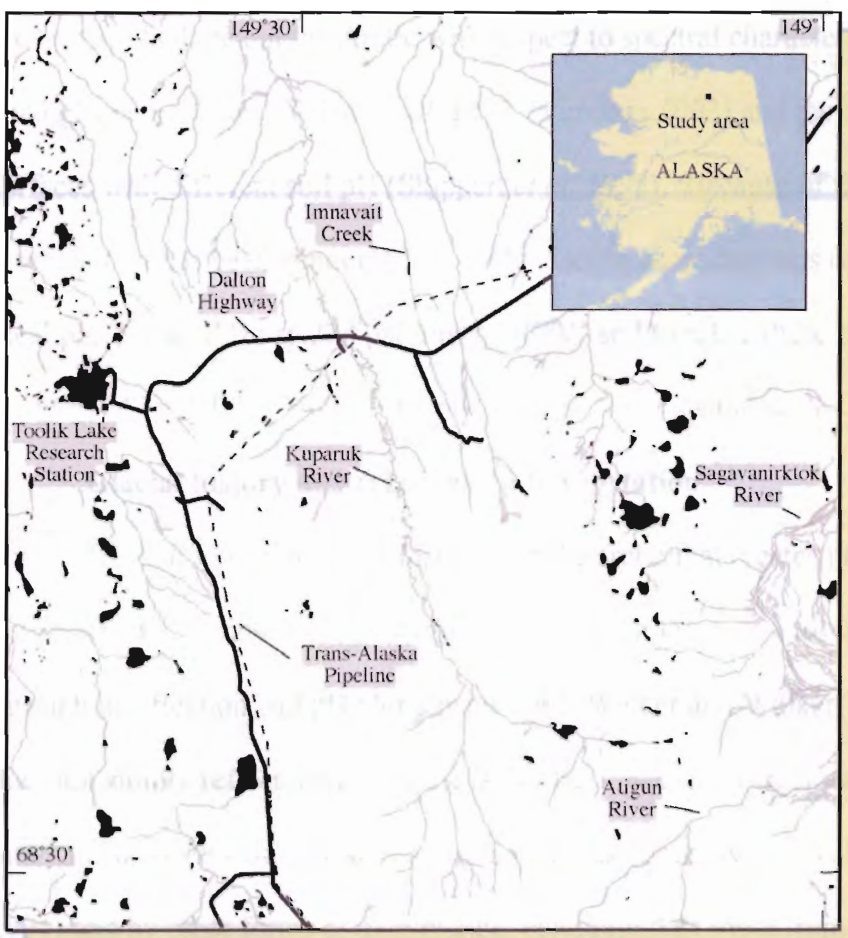

Figure 1. Location of study area in northern Alaska.

I chose this area for the study because of the existence of a 1:25,000-scale GIS database (Walker and Maier, in prep.) of the region that provided detailed information regarding glacial geology (Figure 2), surficial geomorphology (Figure 3, Table 1), vegetation (Figure 4, Table 2), slope angle (Figure 5), aspect (Figure 6), and elevation (Figure 7). The Integrated Terrain Unit Map (ITUM) of this also area includes hydrology, topography, percent water cover, surficial geology, and remotely sensed spectral information. The Toolik Lake and Upper Kuparuk River Region is perhaps the best studied area in the Arctic with respect to spectral characterization of different aged glacial surfaces (Walker *et al.* 1995; Hamilton 2003) and the contrasts between surfaces with different soil pH (Shippert *et al.* 1995). Because of the extensive research that has been conducted on the landscape characteristics of this area, it is an ideal place to analyze spatial patterns of NDVI and to relate these patterns to temporal analyses of NDVI that have been conducted at larger spatial scales.

Glacial history and relationship to vegetation

Glaciation is a major disturbance in the arctic that creates patterns of spatial heterogeneity. Landscape age is often a controlling factor in ecosystem processes through its effect on soil pH (Jorgenson 1984; Walker and Walker 1996). Soil pH does not simply reflect the age of the substrate, however. Circumneutral soils may be maintained on very old surfaces by inputs of loess from rivers (Walker and Everett 1991) and by other forms of disturbance, including dust input from gravel roads (Auerback *et al.* 1997).

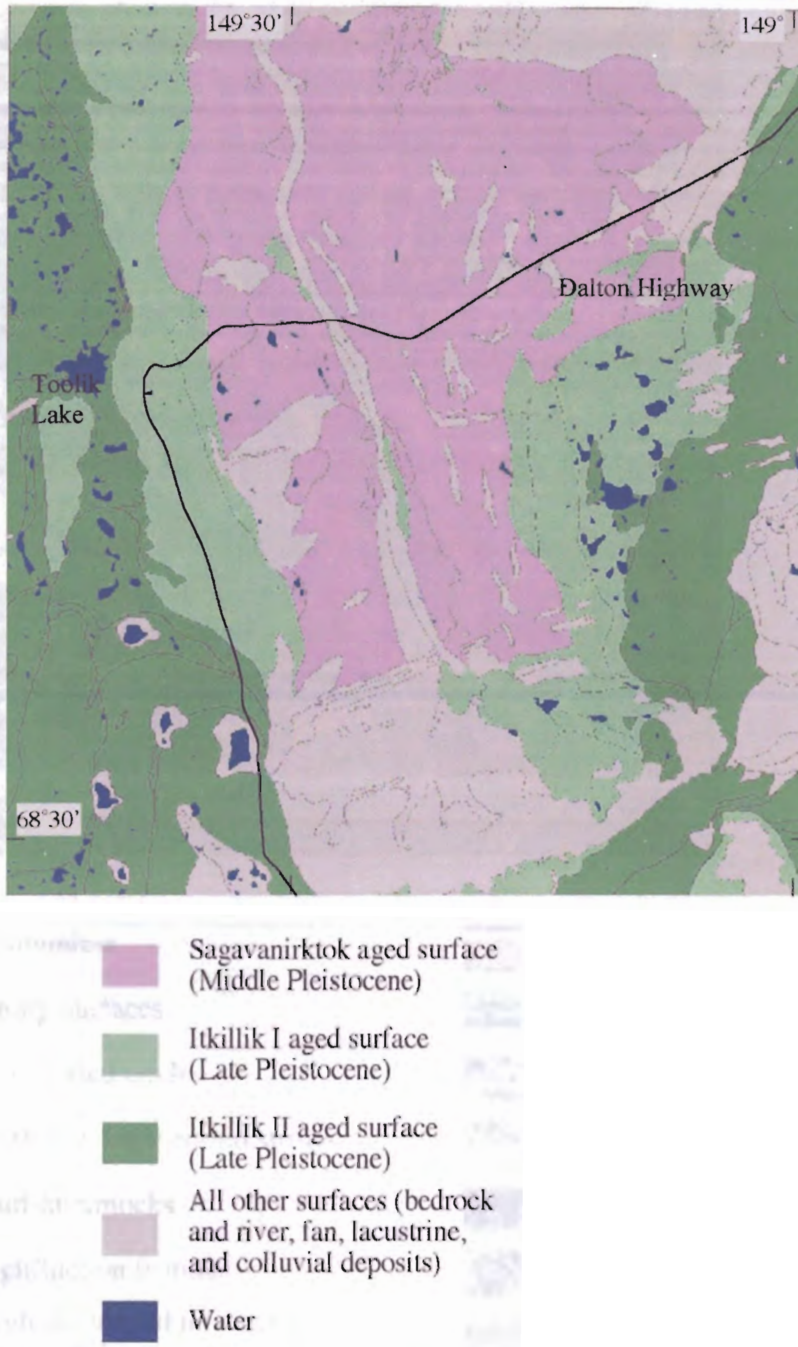

Figure 2. Glacial geology of the Toolik Lake and Upper Kuparuk River Region (Hamilton 2003).

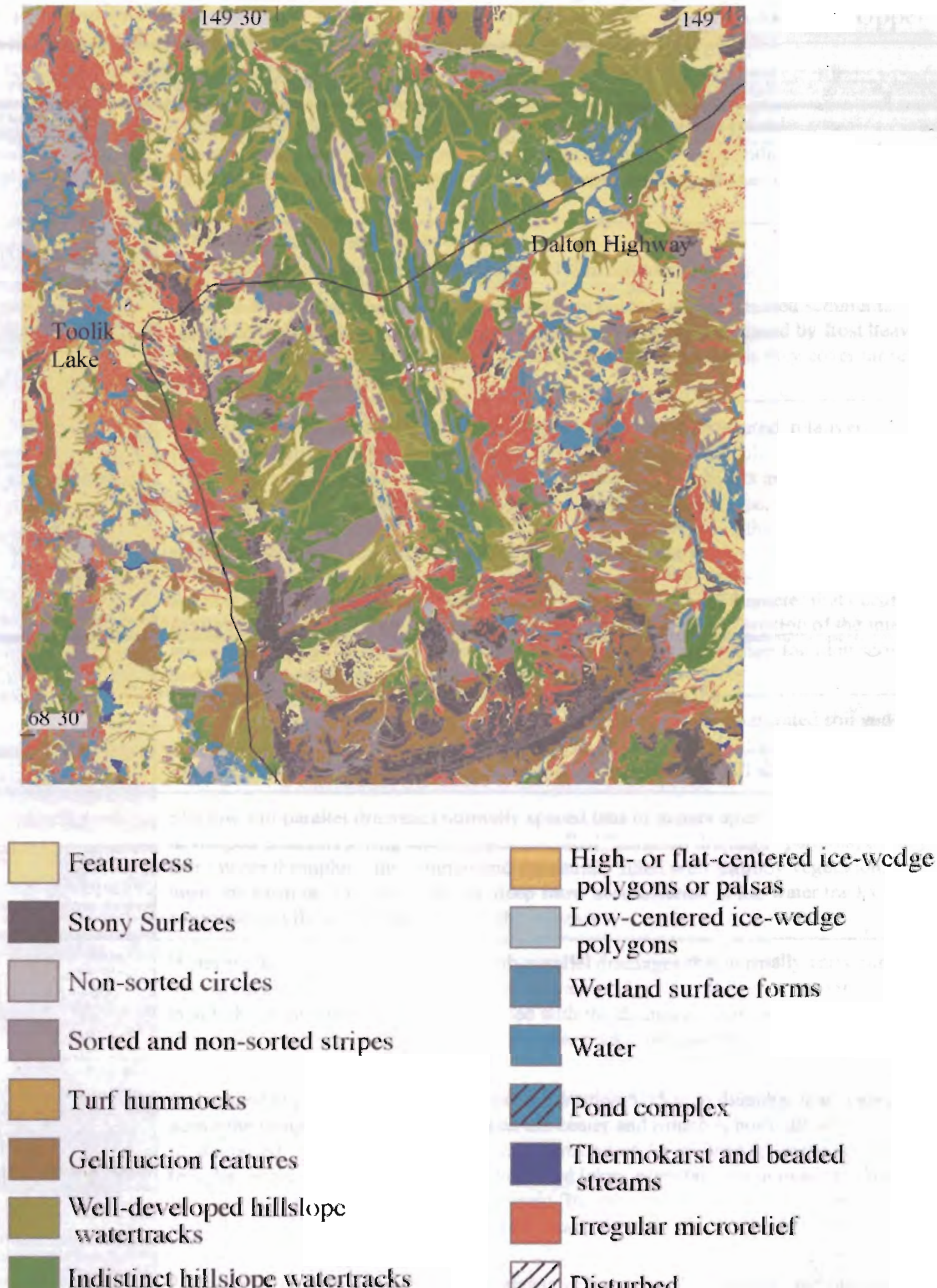

Figure 3. Surficial Geomorphology of the Toolik Lake and Upper Kuparuk River Region (Walker and Maier, in press),

Table 1. Description of surficial geomorphology units for the Toolik Lake and Upper Kuparuk River Region. (1:25,000-scale) (Walker and Maier, in prep.).

Surficial Geomorphology	Description of Unit
Featureless	Areas with no discernable pattern at the mapping scale; however, non-sorted circles, small gelifluction features, and/or poorly developed water tracks can occur in these areas.
Stony surfaces	1. Blockfields, river gravels, bedrock, talus. 2. Rugged rock-dominated till sheets with <1.5 m microrelief.
Non-sorted circles	Small, 0.5-3 m diameter, roughly circular barren patches of fine-grained sediments spaced from 2 to many meters apart, without a border of stones, caused by frost heave; ubiquitous on fine-grained sediments; not differentiated here unless they cover more than 50 % of a map polygon.
Sorted and non-sorted stripes	Patterns on hill slopes that have a striped appearance due to elongated, relatively well-drained stripes 1-3 m wide oriented down the steepest available slope, alternating with moister inter-stripe areas 1-3 m wide; dry elements are usually covered by non-sorted circles that may also be elongated downslope; most stripes are non-sorted with similar grain size of material in the stripe and the inter-stripe areas; sorted stripes and circles occur in rocky alpine areas.
Turf hummocks	Small regularly spaced mounds 20-50 cm in high and 20-50 cm diameter that occur on gentle to steep slopes, caused by a combination of frost cracking, erosion of the inter-hummock troughs, and eolian deposition on the hummock tops; often found in snow bed areas and gelifluction lobes and terraces.
Gelifluction features	Any of a variety of forms related to the slow movement of water-saturated soil and colluvium down slope over a layer of frozen ground; includes gelifluction lobes, streams, sheets, and benches; common on well-vegetated steep hill slopes.
Well-developed hill-slope water tracks	Shallow sub-parallel drainages normally spaced tens of meters apart with well-developed channels giving many slopes so-called "horsetail drainage" patterns; usually carry water throughout the summer and are usually filled with shrubby vegetation, most abundant on long lower slopes; deep snow accumulation in the water tracks contributes to the water flow through the summer.
Indistinct hill-slope water tracks	Water tracks with shallow indistinct sub-parallel drainages that normally carry runoff only during the snowmelt season and immediately after rainfall events; recognized mainly by shrubbier vegetation associated with the drainage; often occur on upper hill slopes and may turn into well-developed water tracks on lower slopes.
High- or flat-centered ice-wedge polygons and palsas	1. Ice-wedge polygons with a raised central portion 5-15 m in diameter that is elevated above the trough portion; relief between the center and trough is normally about 0.5-1 m; the raised centers are caused by thermal erosion of the ice-wedges in the polygon troughs; occur marginal to streams, rivers, and lakes, especially on outwash terraces; flat- and high-centered polygons are present (but not mapped) on many upland surfaces, but the polygons are often totally masked by tussock-tundra vegetation. 2. *Palsas* (organic-rich mounds and plateaus with perennial ice-lenses) and other raised features in colluvial basins often are cracked into high-centered polygons.

Table 1. continued

Low-centered ice-wedge polygons	Ice-wedge polygons composed of a central low, usually wet, *basin*10-15 m in diameter, a better drained *rim* 1-2 m in width surrounding the basin, and a *trough* often wet, overlaying the ice wedge between adjacent polygons; usually have a polygonal shape with 4-6 sides; the rims may compose 30-60 % or more of the total area of the polygon complex; thermokarst ponds commonly occur at the junctions of polygon troughs; caused by thermal contraction (frost) cracking within the permafrost ; not abundant in the region, but occur in association with flat drained-lake basins and river floodplains.
Wetland surface forms	Wet areas, often in colluvial basins, with a mixture of strangmoor, disjunct ice-wedge polygon rims, aligned hummocks, non-aligned hummocks, and lowland water tracks. Strangmoor consists of *strangs*, sinuous ridges many meters long that form perpendicular to the direction of the local hydrological gradient. The strangs are normally up to 0.5 m wide and 0.5 m high. *Disjunct polygon rims* area associated with incompletely formed or eroded low-centered polygons.
Water	Lakes, ponds, and rivers.
Pond complex	Wetland areas with numerous small lakes and ponds that are too small to map individually.
Thermokarst and beaded streams	1. Areas with eroding sub-surface ice that may be buried glacial ice or ice-rich permafrost; this occurs marginal to several kettle lakes on Itkillik-age glacial surfaces. 2. Thermokarst pits that occur at ice-wedge junctions and often associated with ice-wedge polygons.
Irregular microrelief	This unit is used for a number of different situations in which there is considerable microrelief that cannot be ascribed to any of the above features, including rolling topography common on till and outwash surfaces, hillslopes and bluffs with irregular erosion features, and floodplains with a mixture of channels, bars, ponds.
Disturbed	Gravel mines and construction pads.

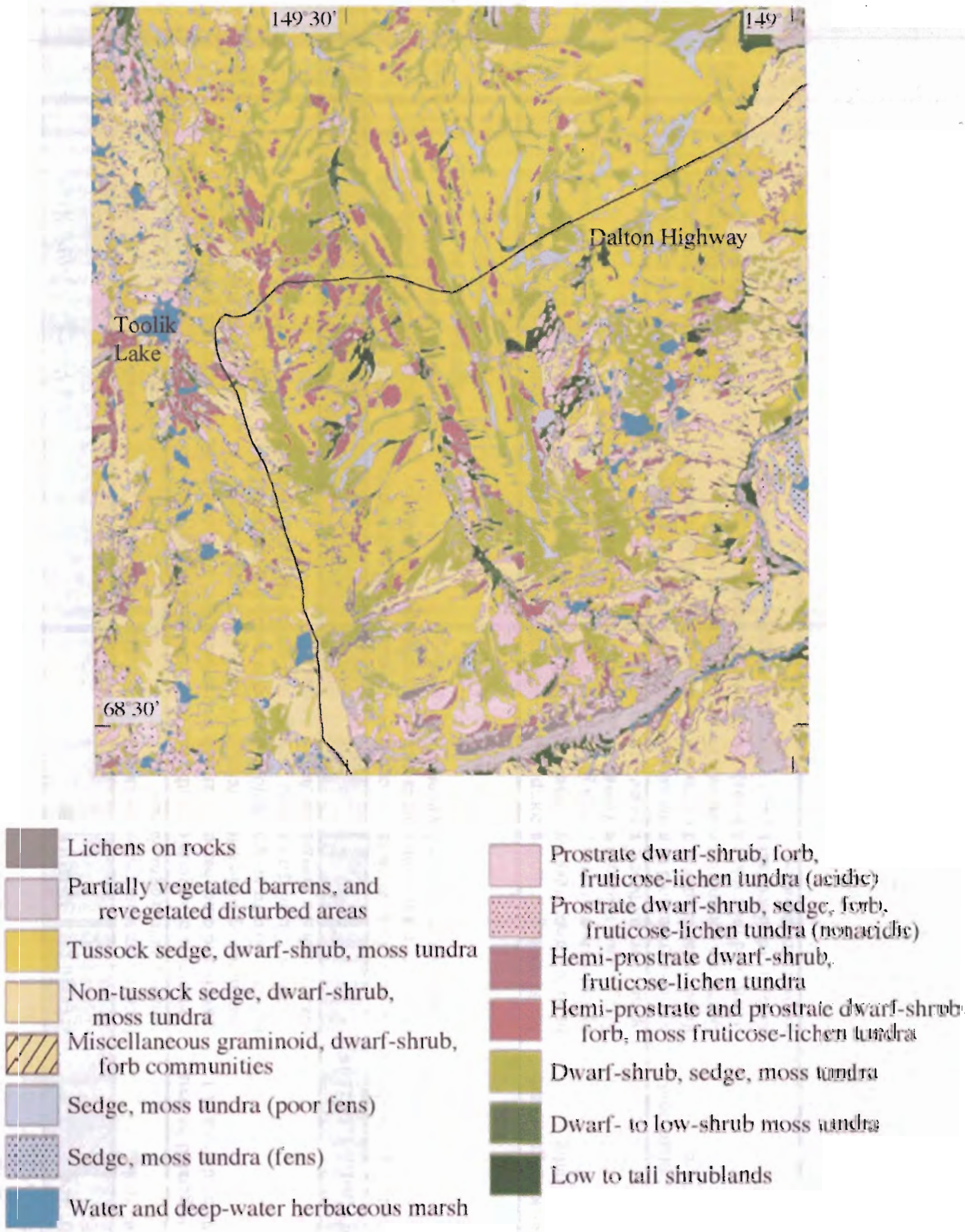

Figure 4. Vegetation of the Toolik Lake and Upper Kuparuk River Region (Walker and Maier, in press).

Table 2. Description of plant communities for the vegetation map of the Upper Kuparuk River Region (1:25,000-scale) (Walker and Maier, in prep.).

Physiognomy	**Plant communities**	**Typical Microsites**	**Ha**	**% of Map**
Barrens				
Lichens on rocks	Lichen communities on rocks, including *Cetraria nigricans-Rhizocarpon geographicum*	Xeric blockfields, glacial erratics.	1,009	1.3
Partially vegetated barrens, and revegetated disturbed areas	Complexes of vegetation with rock or soil on scree slopes, river gravels and other barrens, partially vegetated alpine areas, and areas dominated by non-sorted circles. Dominant plant communities include: *Saxifraga oppositifolia-Saxifraga eschscholtzii*: *Epilobium latifoium-Castillega caudata* ; revegetated gravel pads with *Festuca rubra*; *Anthelia juratzkana-Juncus biglumis*.	Partially vegetated disturbed barrens on gravel pads, abandoned roads, bulldozed areas.	1,805	2.4
Moist graminoid tundras				
Tussock sedge, dwarf-shrub, moss tundra	Moist acidic tussock tundra complexes dominated by graminoids. Dominant plant communities include *Eriophorum vaginatum-Sphagnum* and *Carex bigelowii-Sphagnum*.	Mesic to subhygric, stable, acidic sites with shallow to moderate snow (zonal vegetation for bioclimate subzone E on ice-rich permafrost).	29,029	38.7
Non-tussock sedge, dwarf-shrub, moss tundra	Moist nonacidic tundra complexes . Dominant plant communities include *Carex bigelowii-Dryas integrifolia* and subtypes dominated by *Equisetum arvense*, *Salix glauca* and *Cassiope tetragona* ; *Eriophorum vaginatum-Tomentypnum nitens* and *Carex bigelowii-Sphagnum*, subtype *Cassiope tetragona* .	Mesic to subhygric, circumneutral sites with shallow to moderate snow.	12,963	17.3
Miscellaneous graminoid, dwarf-shrub, forb communities	Various graminoid dominated communities on disturbances including those on landslides and thermokarst areas, and drained lake basins. Dominant communities include *Festuca altaica-Poa glauca* (Disturbed thermokarst areas); *Deschampsia caespitosa-Carex saxatilis* (drained lakes); and *Carex podocarpa-Salix chamissonis* (snowy streamsides).	Miscellaneous sites including deep-snow stream margins, landslides, and some rocky drained lake basins.	192	0.3

Table 2. continued

Wet graminoid tundras and water				
Sedge, moss tundra (poor fens)	Poor fen wetland complexes. Dominant plant communities include: Lower microsites: *Eriophorum scheuchzeri-Sphagnum orientale* and *Eriophorum angustifolium-Sphagnum*. Raised microsites: *Sphagnum lenense-Salix fuscescens.*	Subhydric to hydric, meadows, ponds, acidic poor fens (pH <4.5) in colluvial basins.	1,934	2.6
Sedge, moss tundra (fens)	Rich fen wetland complexes. Dominant plant communities include: Lower microsites: *Carex aquatilis-Carex chordorrhiza* and *Eriophorum angustifolium-Carex aquatilis.* Raised microsites: *Trichophorum caespitosum-Tomentypnum nitens* and *Carex bigelowii-Tomentypnum nitens.*	Subhydric to hydric, water tracks, stream margins, fens (pH>4.5), flanks on solifuluction slopes.	1,158	1.5
Water and deep-water herbaceous marsh	Water; Aquatic vegetation in deeper water. Dominant plant communities include *Arctophila fulva-Hippuris vulgaris* and *Sparganium hyperboreum-Hippuris vulgaris.*	Hydric, lakes, ponds and streams.	1,595	2.1
Prostrate-shrub tundras				
Prostrate dwarf-shrub, forb, fruticose-lichen tundra (acidic)	Dry acidic tundra complexes; Dominant plant communities include *Dryas octopetala-Selaginella sibirica*, *Arctous alpina-Salix phlebophylla*; lichen tundra *Cladonia arbuscula-Stereocaulon tomentosum.*	Xeric to xeromesic, acidic, wind blown, no to shallow winter snow cover. Ridge tops, exposed slopes, dry river terraces .	5,820	7.8
Prostrate dwarf-shrub, sedge, forb, fruticose – lichen tundra (nonacidic)	*Dryas integrifolia-Oxytropis nigrescens*, *Dryas integrifolia-Astragalus umbellatus.*	Xeromesic to mesic non-acidic soils on collluvium or recent alluvium, wind-blown to shallow winter snow cover. Slopes, non-sorted stripes, river terraces. Dominated by *Dryas integrifolia.*	895	1.2
Hemi-prostrate dwarf-shrub, fruticose-lichen tundra	Snowbed complexes. Dominant plant communities include *Cassiope tetragona-Carex microchaeta: Cassiope tetragona-Dryas integrifolia*; *Salix rotundifolia-Sanionia uncinatus* .	Subxeric to mesic, acidic to nonacidic snowbeds.	2,164	2.9

Table 2. continued

Hemi-prostrate and prostrate dwarf-shrub, forb, moss, fruticose-lichen tundra	Dry tundra with shallow snowbeds. Dominant plant communities include *Cassiope tetragona-Calamagrostis inexpansa*. Also includes dry areas with hemi-prostrate birch *Betula nana-Hierochloë alpina.*	Subxeric to mesic, acidic to nonacidic, shallow snowbeds. Mainly on acidic ridge crests and non-sorted stone stripes, and dry glacial till and outwash.	2,116	2.8
Erect-shrub tundras				
Dwarf-shrub, sedge, moss tundra	Moist acidic tundra complexes dominated by shrubs (shrubby tussock tundra). Dominant plant communities include *Betula nana-Eriophorum vaginatum*, and *Salix pulchra-Carex bigelowii*.	Mesic to subhygric, moderate snow, lower slopes	8,445	11.2
Dwarf- to low-shrub, moss tundra	Shrub tundra dominated by dwarf birch or willows. Dominant plant communities include *Betula nana-Rubus chamaemorus* or *Salix pulchra-Sphagnum.*	Subhygric, moderate snow, margins of upland water tracks, palsas, high-centered polygons	601	0.8
Low to tall shrublands	Shrublands dominated by low and tall shrubs including: 1. Shrublands along streams and water tracks dominated by diamond-leaf willow *(Salix pulchra)* where the dominate plant communities include *Salix pulchra-Eriophorum angustifolium* and *Salix pulchra-Calamagrostis canadensis.* 2. Shrublands in riparian complexes dominated by feltleaf willow (*S. alaxensis*), and lanate willow (*S. lanata*); includes tall shrublands and low shrublands. 3. Upland shrublands dominated by glaucous willow (*Salix glauca*) or alder (*Alnus crispa*).	Stream margins upland water tracks, and south facing slopes, mesic to subhydric, often with deep snow.	5,344	7.1
		Total	75,070	100

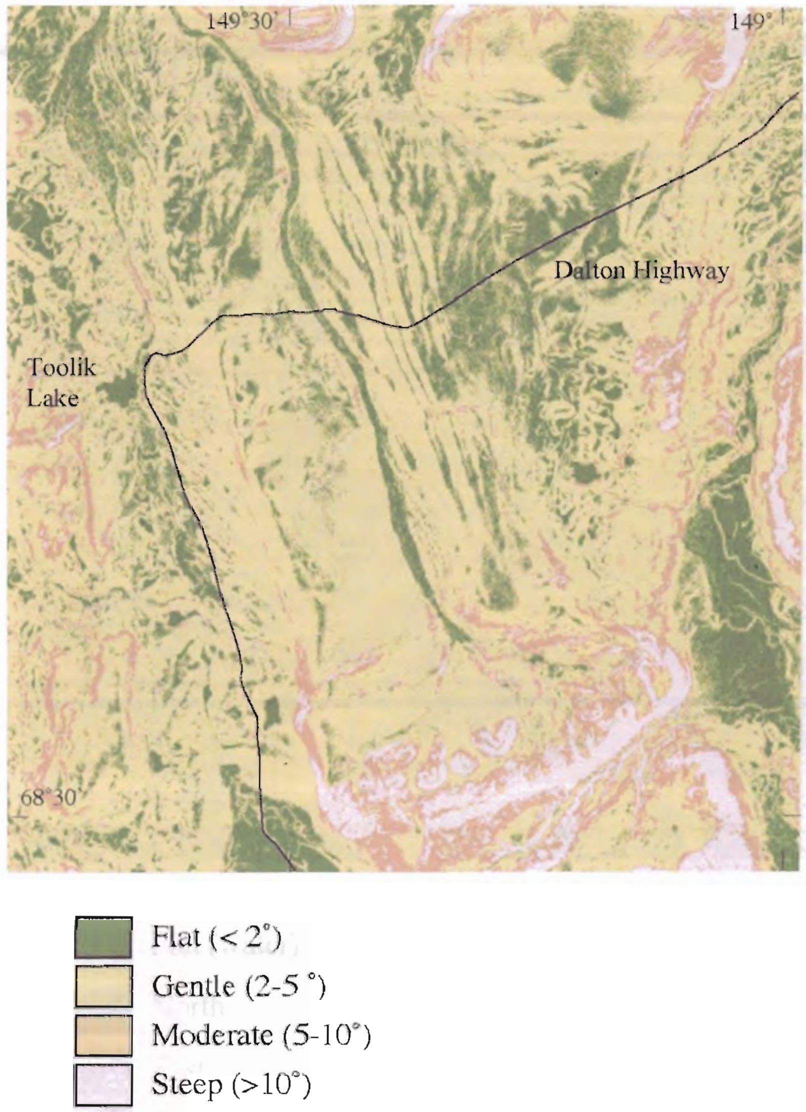

Figure 5. Slope angle of the Toolik Lake and Upper Kuparuk River Region (derived from Nolan 2003).

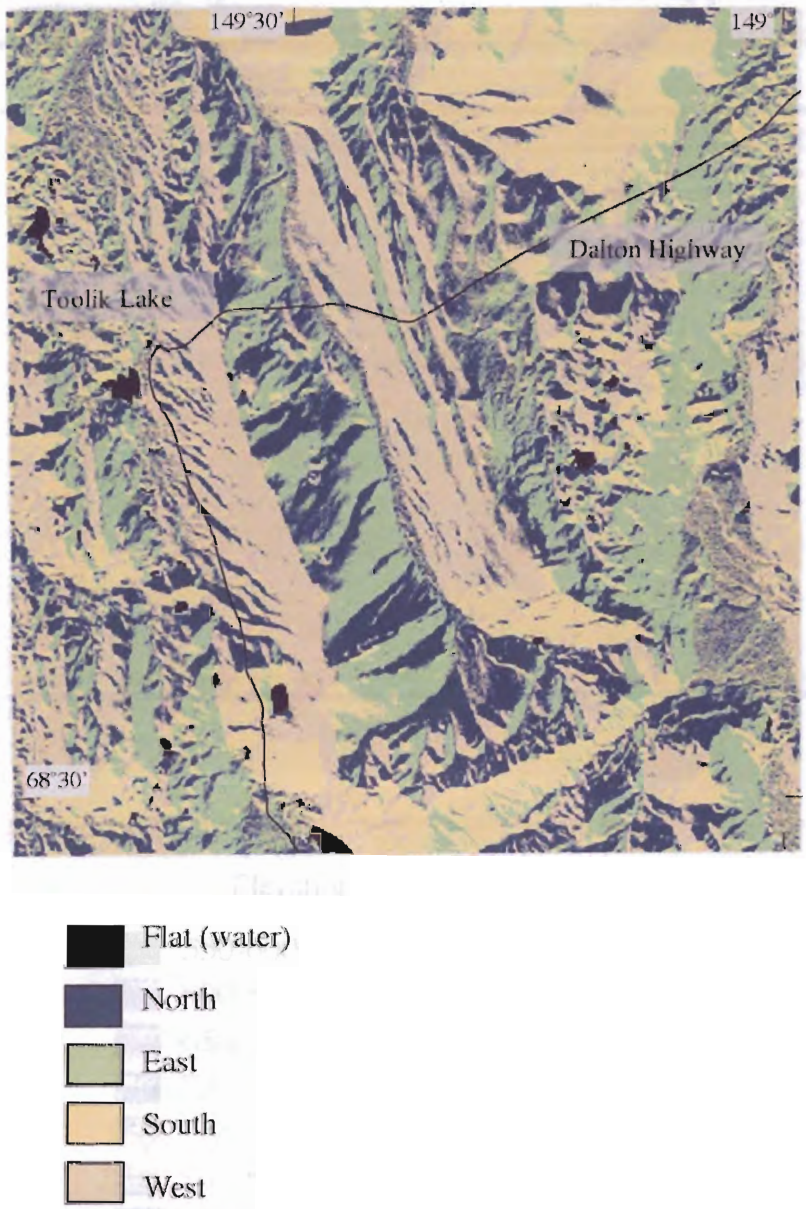

Figure 6. Aspect of the Toolik Lake and Upper Kuparuk River Region (derived from Nolan 2003).

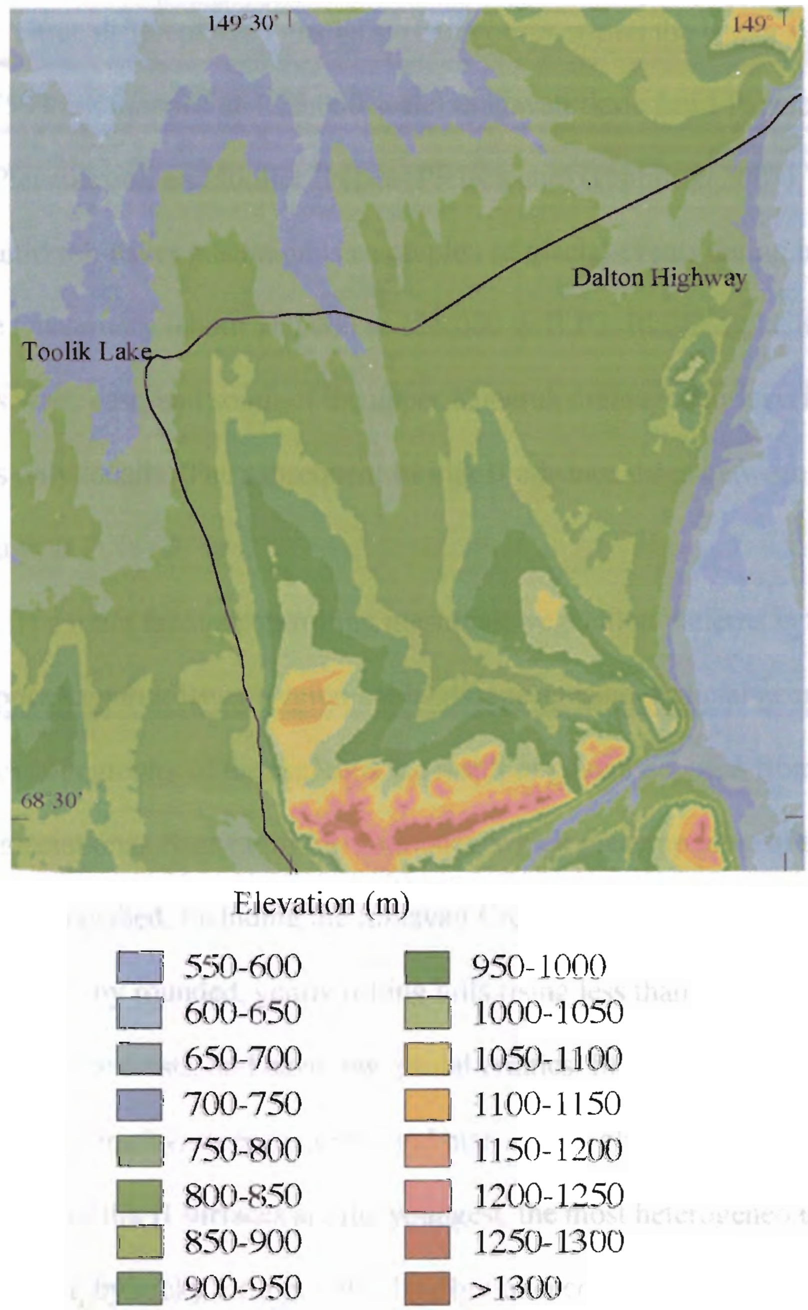

Figure 7. Elevation of the Toolik Lake and Upper Kuparuk River Region (derived from Nolan 2003). Blues, greens, and reds roughly correspond with 333-m elevation intervals, which approximate adiabatic temperature shifts of 2°C.

Three different aged glacial surfaces occur within the Upper Kuparuk River area (750 km^2, mapped at 1:25,000 scale): Sagavanirktok (mid-Pleistocene), Itkillik I (late- Pleistocene), and Itkillik II (late- Pleistocene) (Hamilton 2003). The Sagavanirktok River glaciation is a complex of glacial events dating broadly from the middle Quaternary (about 780,000 to 125,000 yr B.P.) Itkillik I glaciers abutted divides west, east, and south of the upper Kuparuk drainage, but overflowed those divides only locally. The subsequent Itkillik II advance dates between about 25 and 11.5 ka yr B.P.

The main factors controlling mesoscale vegetation patterns in the Toolik Lake and Upper Kuparuk River Region are landscape age and surficial geomorphology. The complex topography of the region is the result of glacial deposits from these three major glaciations. Sagavanirktok I surfaces, which make up most of the Upper Kuparuk watershed, including the Imnavait Creek watershed (Figure 1), are characterized by rounded, gently rolling hills rising less than 100 m from valley bottom to ridge crests, and have few glacial erratics. Itkillik I surfaces have a more irregular topography, steeper slopes, and many small glacial lakes, kames, and moraines. Itkillik II surfaces are the youngest, the most heterogeneous, and are characterized by rocky terrain, only slightly flattened moraine crests, and steep flanks. The landscape is also shaped by surficial geomorphological features, which are created through alluviation, colluviation, and periglacial processes.

Vegetation characteristics, geomorphology, and various ecosystem processes differ on the different-aged glacial surfaces within this map area and have been shown to have important effects on the regional patterns of biomass and NDVI (Walker *et al.* 1995). Jorgenson (1984) first discussed the relationship between vegetation and surface age, noting that landscape evolution results in older surfaces that have more tussock tundra and bogs, whereas younger surfaces tend to have more nonacidic vegetation.

This observation led to the hypothesis that the development of moist acidic tundra (MAT) depends on long-term site stability. Vegetation succession is thought to occur through processes of paludification and ice aggradation, which lead to restricted drainage, a general acidification of the soils, and the introduction of *Sphagnum* mosses to wet hill slopes (Walker *et al.* 1995). A gradual change in soil chemistry, hydrology, and soil thermal properties leads to peat formation, extensive water track development, and tussock tundra on gentle hill slopes (Jorgenson 1984; Walker and Walker 1996).

Analyses of the pollen record by Oswald *et al.* (2003) suggest that the onset of moist conditions due to increased summer insolation and augmented glacial runoff and precipitation between the early and middle Holocene may have triggered processes of plant succession on previously poorly vegetated surfaces. The increased effective moisture on the landscape would have been better retained by fine-textured soils and gentler slopes on Sagavanirktok surfaces, causing paludification and the development of MAT. Better-drained Itkillik surfaces continued to support relatively xeric, sparse, non-acidic vegetation. This is supported by the hypothesis that shifts in effective moisture may be the proximate cause for many of the impacts that climate change has in arctic regions (Mann *et al.* 2002).

Various ecosystem processes also differ on the different vegetation types that correspond with the different aged surfaces. MAT has greater productivity and net carbon uptake than moist nonacidic tundra (MNT) (Walker *et al.* 1995, Eugster and McFadden. 2005). MAT and MNT have similar physiognomies, but there are different species associated with each vegetation type. While both vegetation types are dominated by sedges and dwarf shrubs, MAT has approximately half the vascular plant diversity of MNT but significantly greater leaf area, moss, and shrub cover than the nonacidic vegetation (Walker *et al.* 1995, Hobbie and Gough 2004). MAT may promote more rapid decomposition than MNT, possibly due to higher soil N availability, or due to lower pH, which may promote greater abundance of soil fungi (Hobbie and Gough 2004).

Biomass, leaf area index, and NDVI data were collected from 60 permanent plots within the map area (Shippert *et al.* 1995). Analyses of relationship between field NDVI and vegetation communities mapped at 1:5000 scale show that areas of MAT have higher NDVI and above-ground biomass than MNT, at least partially due to the greater amounts of shrub cover on these surfaces (Walker *et al.* 1995).

Change in the Toolik Lake and Upper Kuparuk River Region

Characterizing patterns of vegetation and NDVI in the Toolik Lake and Upper

Kuparuk River region may provide insight into differential responses of different parts of the landscape to current and future climate. The effects of landscape heterogeneity on soil texture, moisture, pH, nutrient regime, microclimate, disturbance, and other terrain characteristics may influence how different parts of the landscape respond to increased temperatures. There will likely be many complex interactions between these factors that set the stage for changes in arctic vegetation. One could therefore expect a variety of landscape level responses to warming.

For example, based on the role of moisture in past vegetation change, one could expect the most dramatic vegetation changes to occur on acidic, older surfaces, which are typically vegetated by tussock tundra due to their finer grain soils (Oswald 2003; Mann *et al.* 2002). Because of their water retention capacity, changes in moisture should have a larger effect on finer-grained soils. However, analyses by Jia *et al.* (2003) have suggested that the greatest changes in NDVI on the North Slope of Alaska have occurred in moist nonacidic, graminoid-dominated tundra.

Alternatively, experimental studies of the temperature response of arctic plant physiological processes suggest that cold temperatures mainly limit plant growth indirectly by reducing the length of the growing season and the rates of nutrient input from weathering and recycling by decomposition (Chapin *et al.* 1995). These observations suggest nutrient limitation is an overriding influence on tundra production in the low Arctic. Therefore, one might expect the greatest changes in plant production to occur where increased temperatures would increase nutrient availability. If this occurs broadly across entire landscapes, as with a general deepening of the active layer and drying of the soils, it might result in a broad, homogeneous greening. On the other hand, the effects of warming might be more isolated and confined to areas where nutrient flux is most enhanced, possibly along streams or water tracks, which receive concentrated flux of nutrients from thawed soils upslope. If this is the case, the most noticeable change in vegetation may occur in areas with high nutrient flux, such as watertracks and south-facing slopes, which have warmer soils and hence more nutrient mineralization through microbial activity. Conversely, if warming affects the arctic most immediately through its impact on nutrient availability, then we may expect the most noticeable change to occur in the most nutrient limited areas, such as areas of open tundra away from water tracks and with shallow thaw.

Much of the greening that has been documented by remote sensing data is likely to be due to shrub expansion in the arctic. This is supported by long-term experimental plot studies in the Toolik Lake Region. Results from long-term warming and fertilization studies suggest an increase in the abundance of deciduous shrubs relative to evergreen shrubs and nonvascular plants (Chapin *et al.* 1995). In addition to remote sensing and plot level experimental studies, shrub expansion in the arctic has been observed through analysis of oblique aerial photography. Using this method in northern Alaska, Tape *et al.* (2006) found an increase in alder, willow, and dwarf birch, with the change most easily detected on hill slopes and valley bottoms. Shrub increase occurred through the expansion of shrub patch boundaries, the filling in of existing patches, and the growth of individual shrubs (Tape *et al.* 2006). If change in NDVI in the Upper Kuparuk River Region follows the patterns of change observed by Tape et al. then we would expect the greatest changes in NDVI to occur in areas with high NDVI values, which are indicative of shrubs, especially those on hillslopes and valley bottoms.

Due to these factors, I expect temporal analysis of Landsat NDVI in the Toolik Lake and Upper Kuparuk River Region to show the most dramatic increases in greenness to occur on surfaces that are already relatively shrub rich, including older glacial geology surfaces, shrublands, and watertracks.

METHODS

Vegetation-Terrain Relationships

Using ArcGIS I analyzed how the distribution of vegetation types relate to surface age, surficial geomorphology, slope angle, aspect, and elevation. Vegetation of the area was classified according to the Blaun-Blanquet approach, based mostly on 81 permanent plots at Toolik Lake, 73 permanent plots at Imnavait Creek (Walker *et al.* 1994; Walker and Walker 1996), and an analysis of shrubland vegetation (Schickhoff *et al.* 2002). Vegetation and surficial geomorphology were mapped based on aerial photographs at the 1:500, 1:5000, and 1:25,000 scales. Slope angle, aspect, and elevation were calculated from an IFSAR-derived Digital Elevation Model (DEM) of the Kuparuk River Region (Nolan 2003). Slope categories were defined as flat (0-2°)

gentle (2-10°), moderate (10-20°), and steep (20-90°). North was defined as 315°-45°, East as 45°-135°, south as 135°-225°, and west as 225°-315°.

Calculation of Landsat NDVI

NDVI was calculated for the four Landsat images using Arc Map (Figure 8). The first two images (August 3, 1985 and August 8, 1995) were acquired by the Landsat TM sensor aboard the Landsat 5 satellite, which was launched in 1984. The latter two (August 4, 1999 and July 21, 2002) were acquired by the ETM+ sensor aboard the Landsat 7 satellite, which was launched in 1999. They all have 30-m pixel resolution.

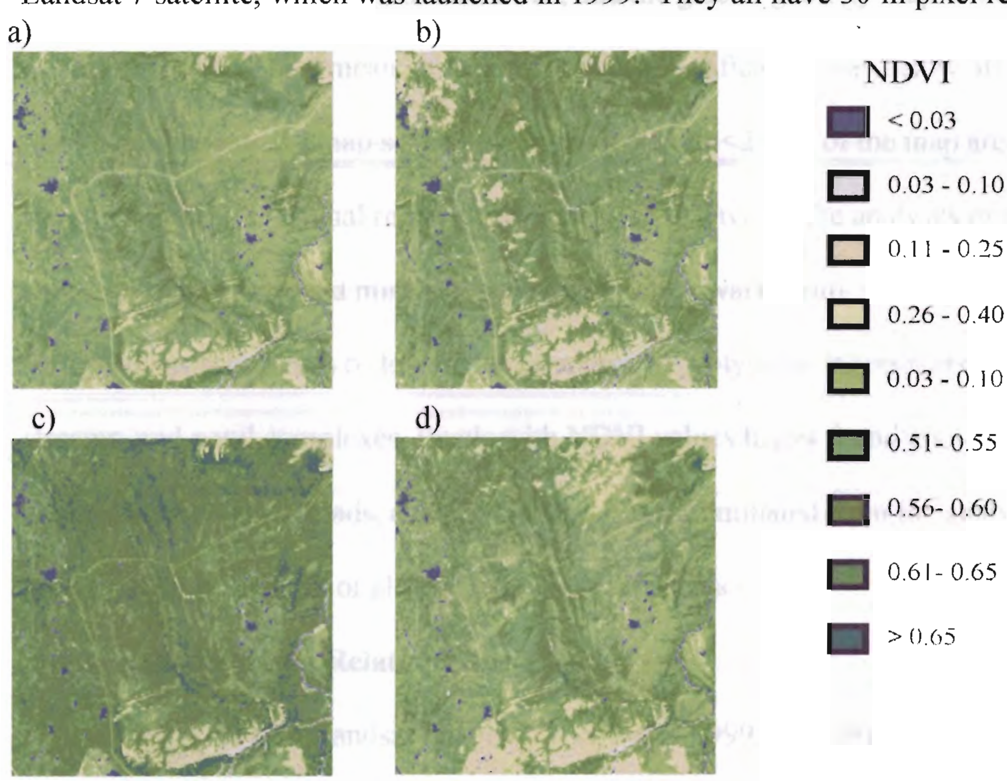

Figure 8. Landsat derived NDVI for the Toolik Lake and Upper Kuparuk River Region acquired a) August 3, 1985, b) August 8, 1995, c) August 4, 1999, and d) July 21, 2002

Due to persistent cloud cover during arctic summers, there are relatively few fine-spatial resolution satellite images (such as Landsat) available. The four used in this analysis were the only ones I found that included the Toolik Lake and Upper Kuparuk River region, had low cloud cover, and were acquired during the time of maximum aboveground productivity in the Arctic (late July-early August).

The maps were registered to the DEM of the Kuparuk River Region (Nolan 2003). Georeferencing correction was performed by using over fifty control points to rectify all four Landsat images, the ITUM, and the glacial geology map to the DEM of the map area. The root mean sqare error for each rectification was below 30 m. I disregarded results for map surface types that covered <2 km^2 of the map area, due to the possible effect residual registration errors would have on the analyses of these surfaces. These included miscellaneous graminoid, dwarf shrub, forb communities, disturbed surfaces, areas of low-centered ice wedge polygons, thermokarst and beaded streams, and pond complexes. Pixels with NDVI values below 0 and above 1, clouded areas, disturbed sites, roads, and pipeline were also eliminated from the analyses. I present the mean NDVI of all four years for each surface.

NDVI-Terrain Relationships

I used the four Landsat images (1985, 1995, 1999, and 2002), all taken during phenologically similar times of maximum above-ground productivity of vascular plants, to examine the spatial patterns of greenness by stratifying the mean NDVI values for these four images according to boundaries of mapped glacial geology units, surficial geomorphology types, plant communities, slope angle, aspect, and elevation.

Change in NDVI

Results of Landsat NDVI temporal analyses between 1985 and 1999 were compared to the analyses of Jia *et al.* (2003) of NDVI of northern Alaska from 1981-2001 using AVHRR data. To complement their 2003 description of change in AVHRR NDVI for the entire Northern Alaska, I also created a maximum NDVI time-series within the just the Upper Kuparuk River Region between 1983-2003 using Gimms AVHRR NDVI (Tucker 2004). The 8-km resolution of this data was too coarse to use to examine spatial patterns of change within the Toolik Lake and Upper Kuparuk River Region because the 750 km^2 of this map area contains only ~12 AVHRR pixels. Time-series of NDVI values were compared to Summer Warmth Index (SWI) data derived from temperature records from Umiat and Toolik Lake weather stations (Shaver and Laundre, unpublished).

I then examined how patterns of change in NDVI between 1985 and 1999 related to mapped surface boundaries. I chose to focus on the 1985 and 1999 images because they represent the period of overlap between our Landsat data and AVHRR data. Also, the 2001 NDVI image showed unexpectedly low NDVI values, likely because its relatively early-season acquisition (mid-July as opposed to early August for the other scenes), when plants typically have not yet reached peak greenness. Temporal patterns of greenness were examined by analyzing change that occurred between 1985 and 1999 in relationship to mapped surface boundaries. This analysis revealed the average amount of change in NDVI between 1985 and 1999 on each surface type.

I also examined the amount of change in NDVI that occurred for each pixel between 1985 and 1999. This analysis showed that between 1985 and 1999 relatively distinct portions of the map area showed especially high amounts of change. I classified pixels according to their amount of change in NDVI, then characterized the surface types of these pixels in order to investigate additional patterns that may have not been apparent when amount of changed was averaged by surface type.

RESULTS

Vegetation-Terrain Relationships

Vegetation and Glacial Geology

The most notable relationship between landscape age and vegetation is the increase in moist acidic tundra and decrease in moist nonacidic tundra over time (Figure 9). Tussock sedge, dwarf-shrub moss tundra covers (acidic) 24.4% of the total Itkillik II area, 38.1 % of the Itkillik I areas, and 61.4% of Sagavanirktok areas. Nontussock sedge, dwarf-shrub, moss tundra (nonacidic), on the other hand, covers 38.9% of Itkillik II surfaces, 16.6 % of Itkillik I areas, and only 2.0% of the Sagavanirktok areas. Older surfaces also tend to be shrubbier. Dwarf-shrub, sedge, moss tundra covers 3.7% of Itkillik II surfaces, 10.0% of Itkillik I areas, and 16.8 % of Sagavanirktok surfaces.

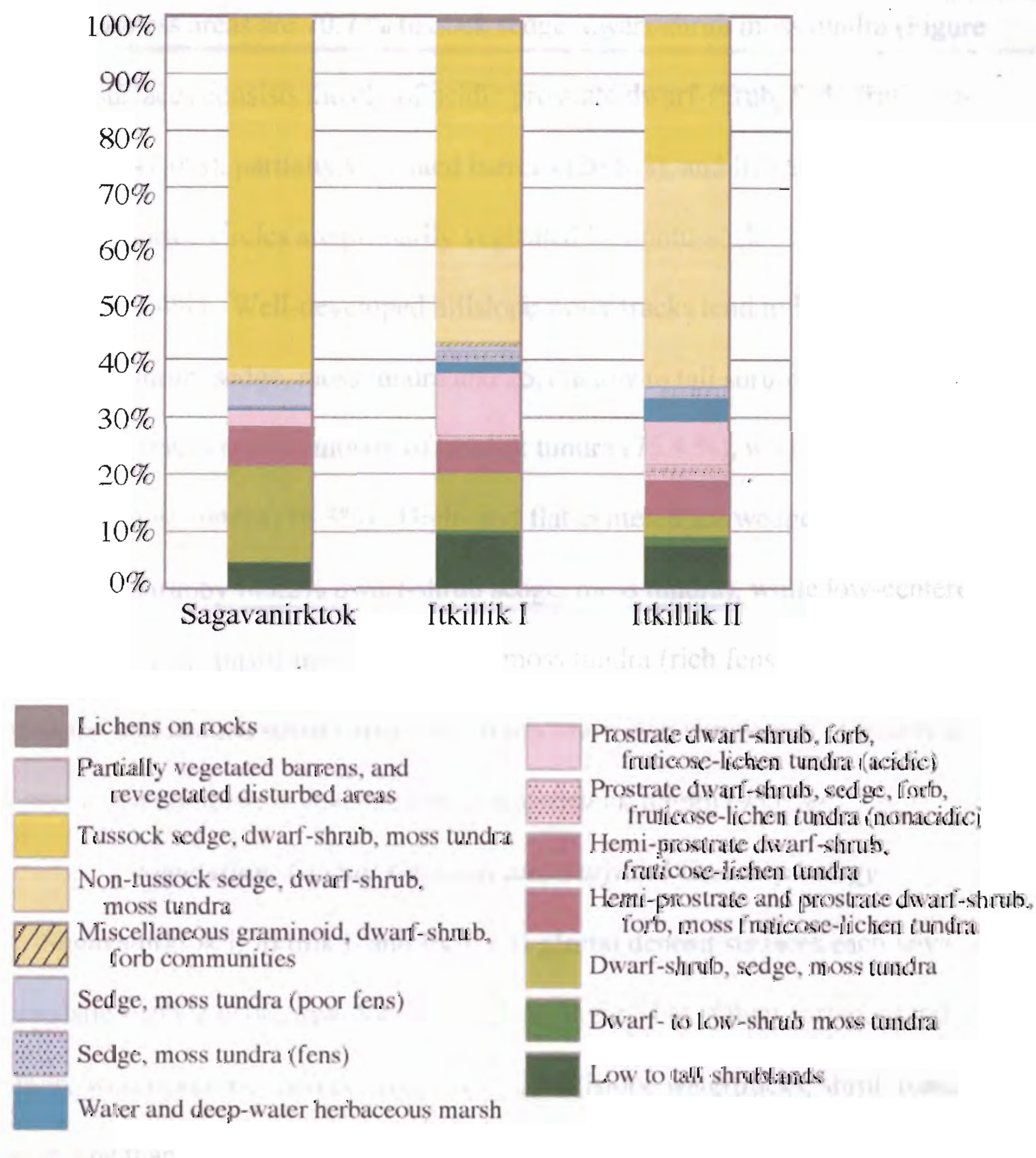

Figure 9. Proportion of vegetation types on different aged glacial surfaces (see Table 2 for descriptions of vegetation units).

Vegetation and Surficial Geomorphology

Featureless areas are 70.7 % tussock sedge, dwarf-shrub moss tundra (Figure 10). Stony surfaces consists mostly of acidic prostrate dwarf-shrub, forb, fruticose-lichen tundra (41.0%), partially vegetated barrens (26.8%), and lichens on rocks (16.5%). Nonsorted circles are primarily vegetated by nontussock sedge, dwarf-shrub, moss tundra (74.4%). Well-developed hillslope water tracks tend to be very shrubby (44.5% dwarf-shrub, sedge, moss tundra and 25.1% low to tall shrublands). Indistinct hillslope water tracks consist mostly of tussock tundra (75.4 %), with some dwarf-shrub, sedge, moss tundra (16.3%). High- and flat-centered ice wedge polygons are also relatively shrubby (43.2% dwarf-shrub sedge, moss tundra), while low-centered ice wedge polygons consist mostly of sedge, moss tundra (rich fens) (57.5%). Thermokarst and beaded stream areas are 30.6% low to tall shrublands. Disturbed areas are almost completely vegetated by acidic tussock tundra (95.6%).

Vegetation, Glacial Geology, and Surficial Geomorphology

Sagavanirktok I, Itkillik I, and Itkillik II glacial deposit surfaces each have characteristic surface geomorphological features (Figure 11). Older surfaces tend to have more well developed and poorly developed hillslope watertracks, shrub tundra, and poor fens than younger surfaces. Younger surfaces have more lakes, nonsorted circles, gelifluction features, stripes, and snowbeds.

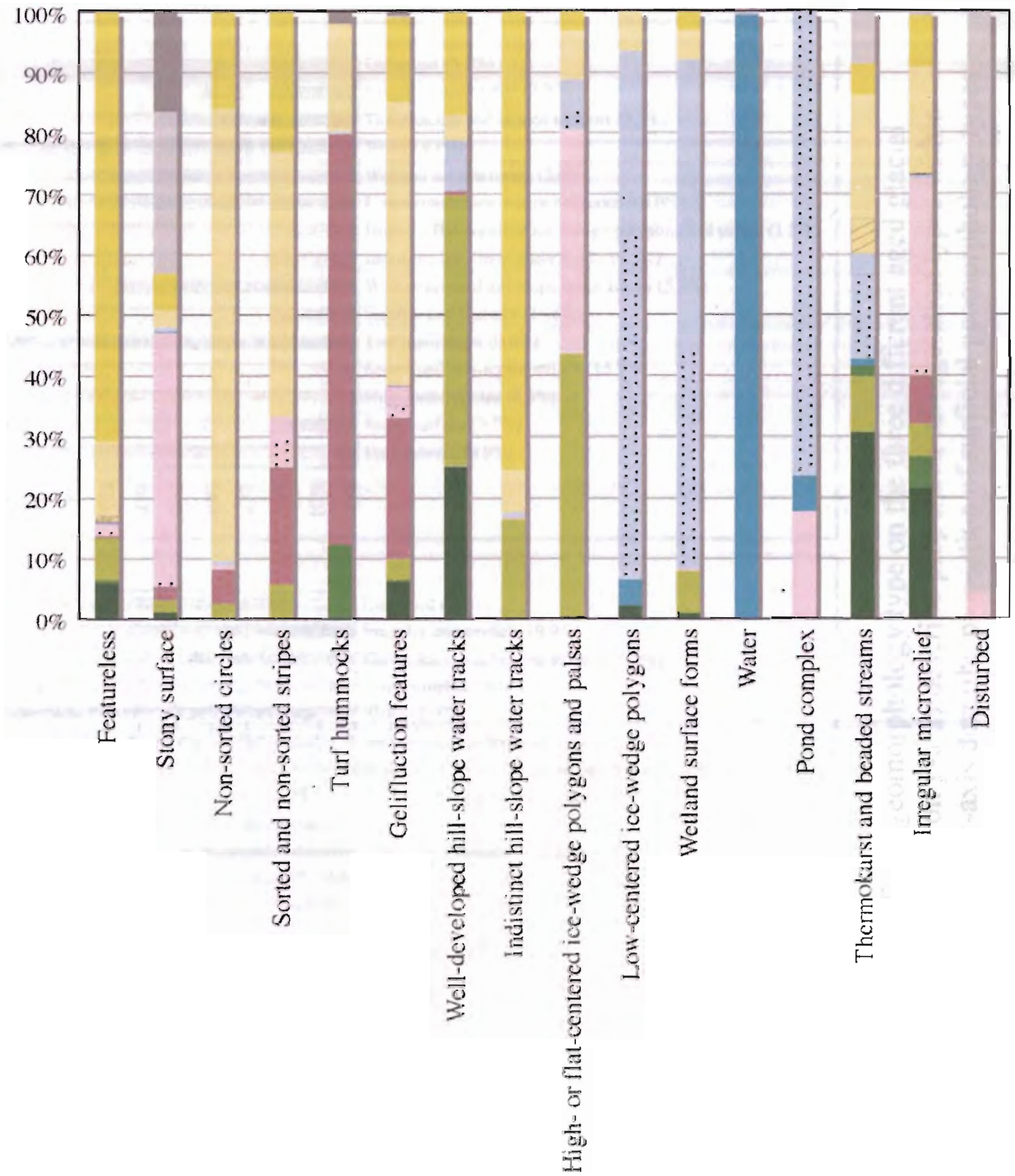

Figure 10. Proportion of vegetation types on different surficial geomorphology types (see Figure 9 for color legend).

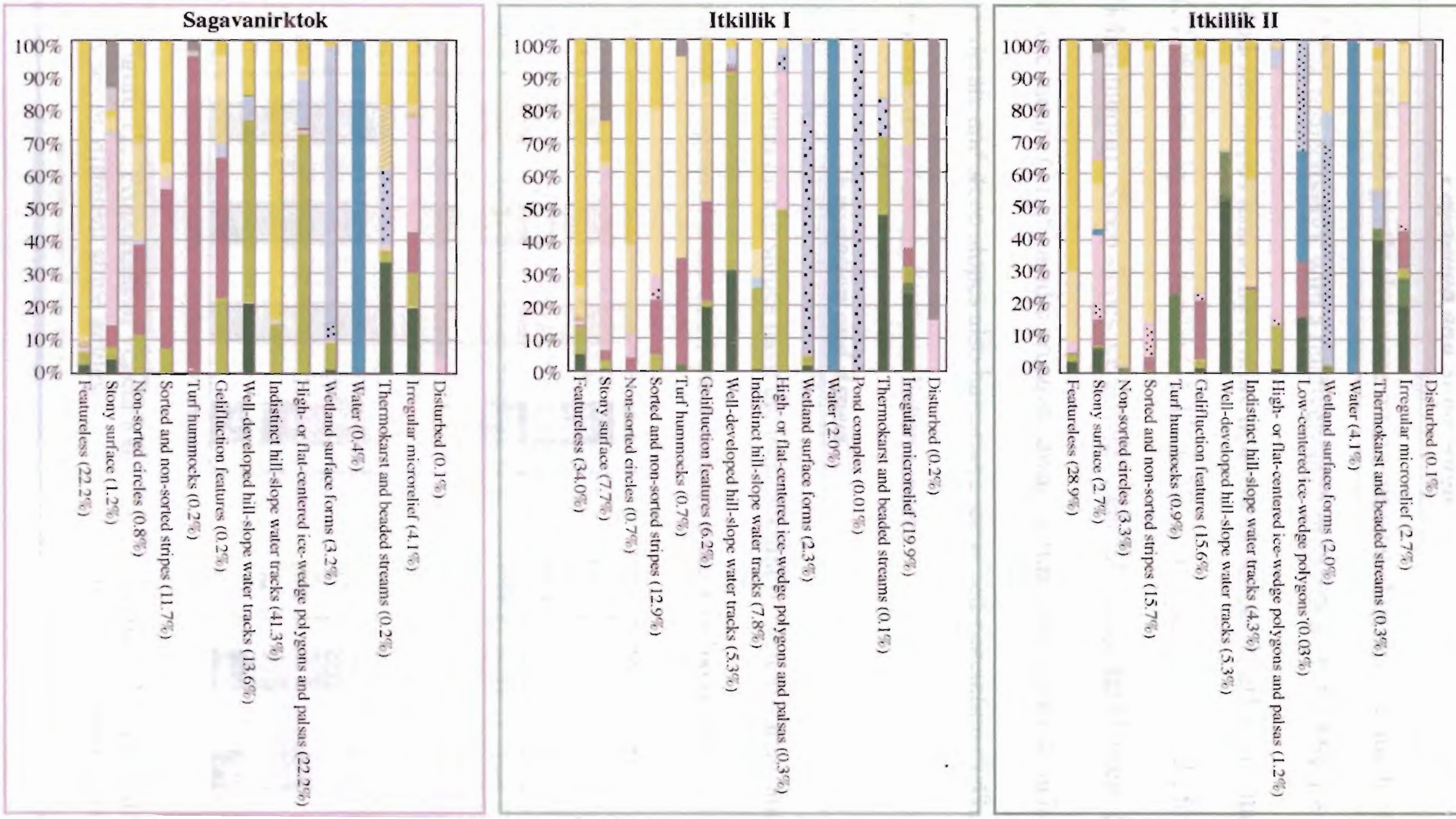

Figure 11. Proportion of vegetation types on each surficial geomorphology type on the three different aged glacial surfaces. See Figure 9 for color legend. Note that percents on y-axis describe proportion of vegetation types within each geomorphology unit, while percentages shown along x-axis describe proportion of surficial geomorphology types on each glacial surface.

Vegetation and Slope Angle

Flat and gentle slopes are mainly vegetated by tussock tundra (34.3% and 44.7%, respectively), with a relatively high proportion of shrubby areas (Figure 12). Moderate slopes tend to have more nontussock sedge, dwarf shrub, moss tundra (27.9%) and dry acidic tundra (16.1% acidic prostrate dwarf-shrub, forb, fruticose-lichen tundra). Steep slopes are generally partially vegetated barrens (27.4%) and dry acidic tundra (21.8% acidic prostrate dwarf-shrub, forb, fruticose-lichen tundra). Moderate and steep slopes also have more snow bed vegetation (9.4% and 9.5% hemi-prostrate dwarf-shrub, fruticose lichen tundra).

Vegetation and Aspect

South facing slopes have the least amount of shrubby areas and the most partially vegetated areas of all the aspects (Figure 13), likely due to steep, exposed

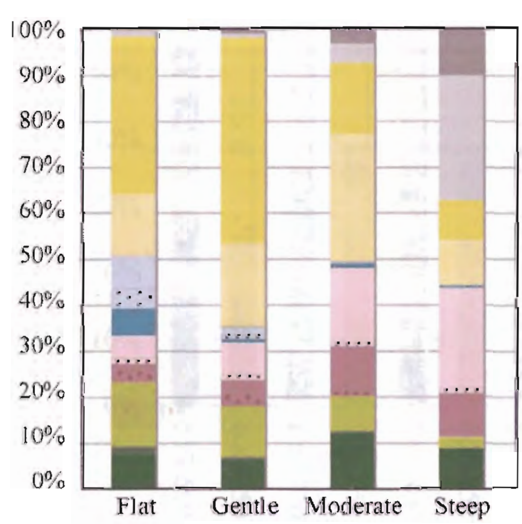

Figure 12. Proportion of vegetation types on different slope angles.

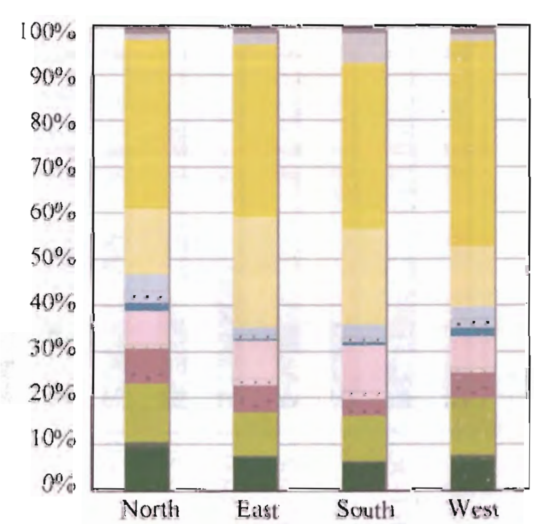

Figure 13. Proportion of vegetation types on different aspects.

slopes. North-facing slopes have the highest proportion of snowbeds, vegetated by hemi-prostrate dwarf-shrub, fruticose lichen tundra.

Vegetation and Elevation

The lowest elevations tend to have the most low to tall shrublands and water. Mid-elevations have the highest proportions of moist tussock and nontussock sedge, dwarf-shrub, moss tundra, although the proportion of nontussock tundra decreases rapidly above 950 m (Figure 14). Shrub cover tends to decrease with elevation, while lichen on rocks, snowbeds, and dry tundra increase with elevation.

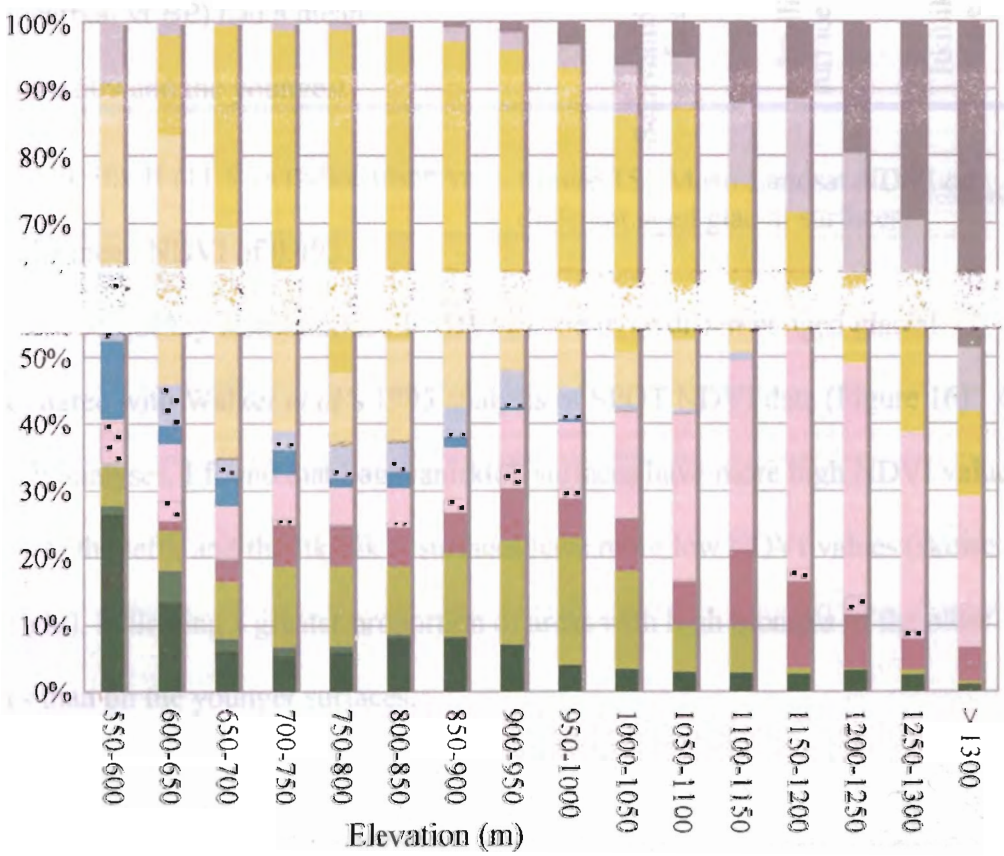

Figure 14. Proportion of vegetation types at different elevations. See Figure 9 for color legend.

NDVI-Terrain Relationships

Glacial Geology

Older surfaces tended to have higher values of NDVI than younger surfaces (Figure 15). The average NDVI on Sagavanirktok surfaces (deglaciated 125,000 radiocarbon yr BP) was 0.530. Itkillik I surfaces (53 ka radiocarbon yr BP) had a mean NDVI of 0.509 and the youngest surfaces, Itkillik II (11.5 ka radiocarbon yr BP), had a mean NDVI of 0.492.

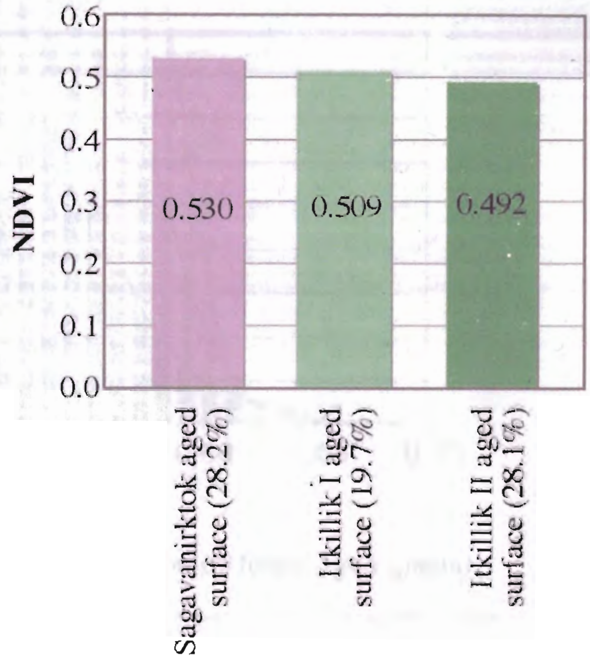

Figure 15. Mean Landsat NDVI on different aged glacial surfaces.

The frequency distributions of NDVI on the three different aged glacial surfaces agree with Walker *et al*'s 1995 analysis of SPOT NDVI data (Figure 16). As with their analyses, I found that Sagavanirktok surfaces have more high NDVI values (skewed to the left), and the Itkillik II surfaces have more low NDVI values (skewed to the right), indicating a greater proportion of areas with high biomass of the older surfaces than on the younger surfaces.

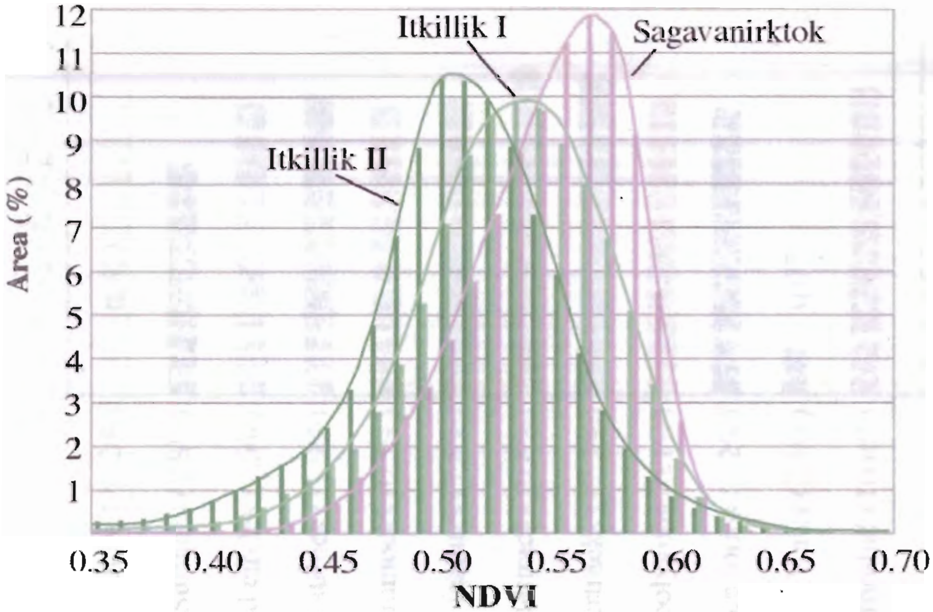

Figure 16. Distribution of Landsat NDVI pixels on different aged glacial surfaces.

Surficial Geomorphology

Well-developed hillslope watertracks and indistinct hillslope watertracks had the highest NDVI values (0.543 and 0.536 respectively) (Figure 17). Featureless areas (those with no discernable surficial geomorphologic patterns at the mapping scale) were relatively green (0.521), as were areas of irregular microrelief (0.514). Stony surfaces and low-centered ice wedge polygons were relatively sparsely vegetated, with mean NDVI values of 0.388 and 0.399 respectively.

Vegetation

Areas of low to tall shrublands had the highest NDVI (0.549), followed by dwarf-shrub, sedge, moss tundra (0.535) (Figure 18). Tussock sedge areas tended to be greener than areas of non-tussock sedge (0.527 and 0.509 respectively). Partially

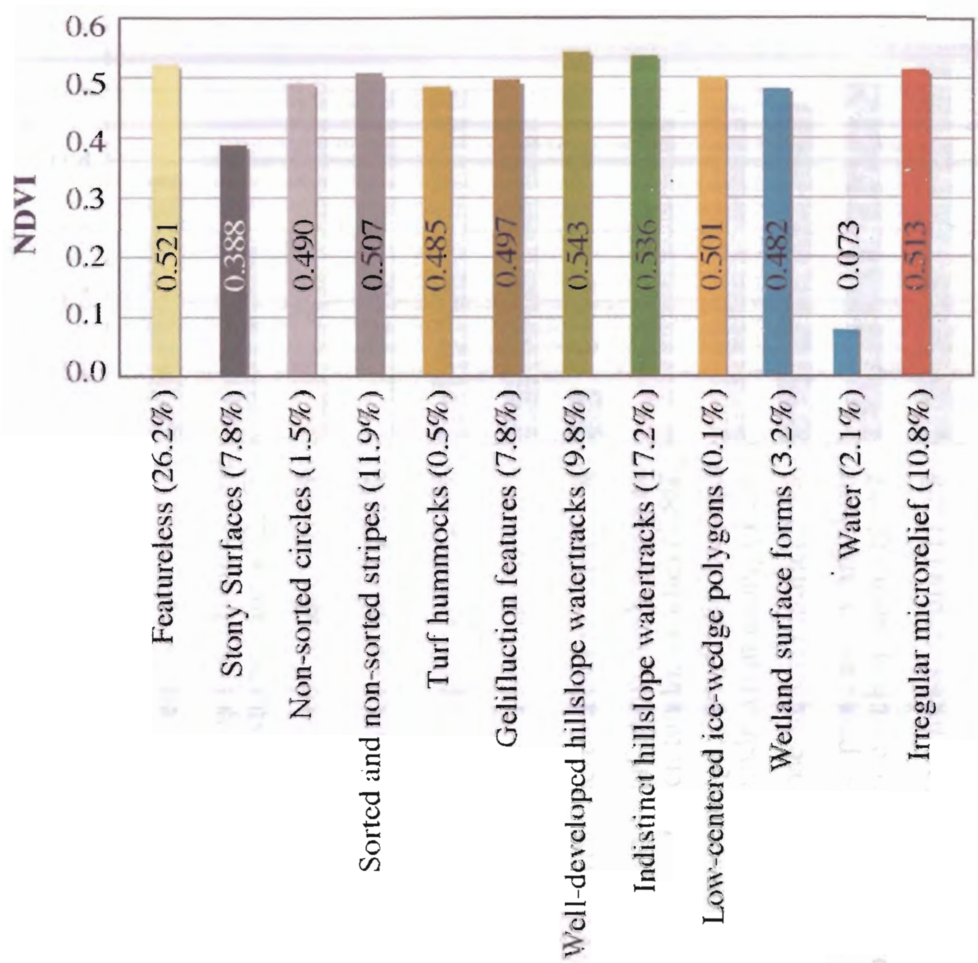

Figure 17. Mean NDVI on different surficial geomorphology types. Percentages in parenthesis are the proportion of the map area occupied by each surficial geomorphologic type.

vegetated barrens, and revegetated disturbed areas had the lowest NDVI (0.294), followed by lichens on rocks (0.378) and acidic prostrate dwarf-shrub, forb, fruticose-lichen tundra (0.464).

Slope Angle

Areas with a gentle slope (2-10°) had the highest greenness values (0.513), followed by moderate slopes (10-20°), with a mean NDVI of 0.495 (Figure 19). Flat

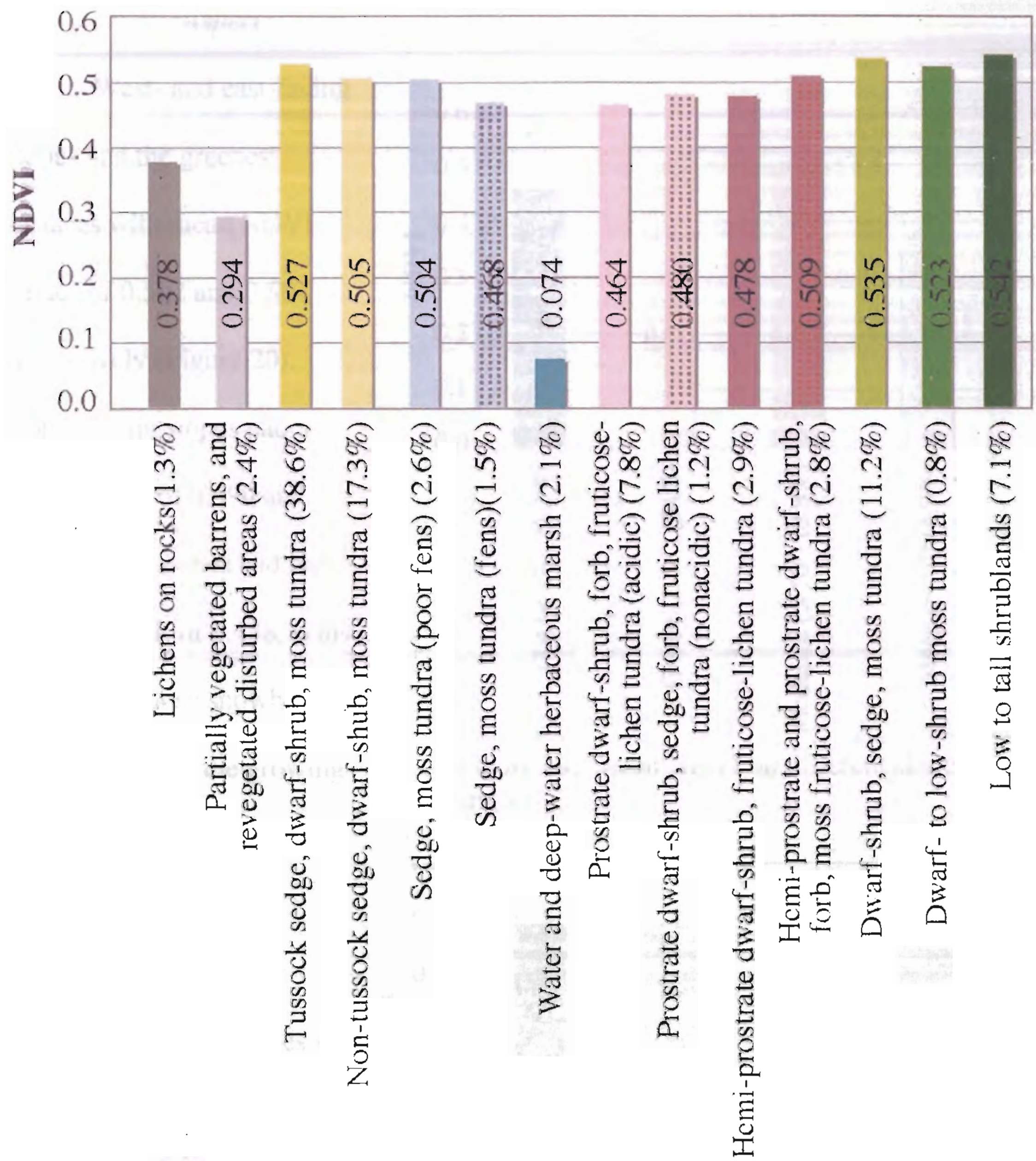

Figure 18. Mean NDVI on different vegetation types.

areas (< 2°) had relatively low NDVI values (0.457), likely because these areas include much standing water. Steep slopes (>20°) had the lowest NDVI values.

Aspect

West- and east-facing slopes had the greenest surfaces with mean NDVI values of 0.502 and 0.504 respectively (Figure 20). North-facing slopes had a mean NDVI of 0.490 and south facing slopes had the lowest NDVI of 0.488. This is likely because snowbeds persist later into the growing season and less direct sunlight is received on north-facing slopes, and many south-facing slopes in this map area are steep, dry, and rocky.

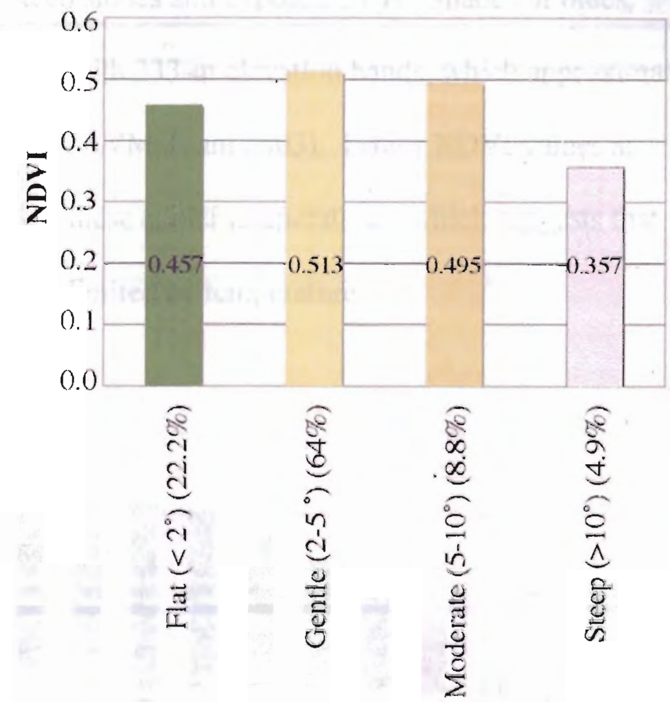

Figure 19. Mean NDVI on different slope angles.

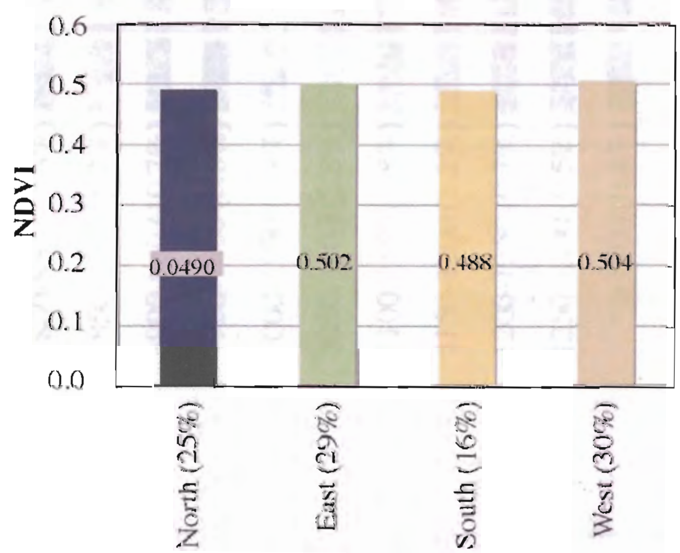

Figure 20. Mean NDVI on different aspects.

Elevation

Areas between 550-660 m had relatively low NDVI values, likely due to water cover (Figure 21). The highest elevation bands had the lowest NDVI, likely because of steep slopes and exposed areas. Shades of blues, greens, and reds correspond roughly with 333-m elevation bands, which approximate adiabatic temperature shifts of 2°C (CAVM Team 2003). Lower NDVI values at higher elevation are likely related to these cooler temperatures, which suggests that plant growth is directly or indirectly limited by temperature.

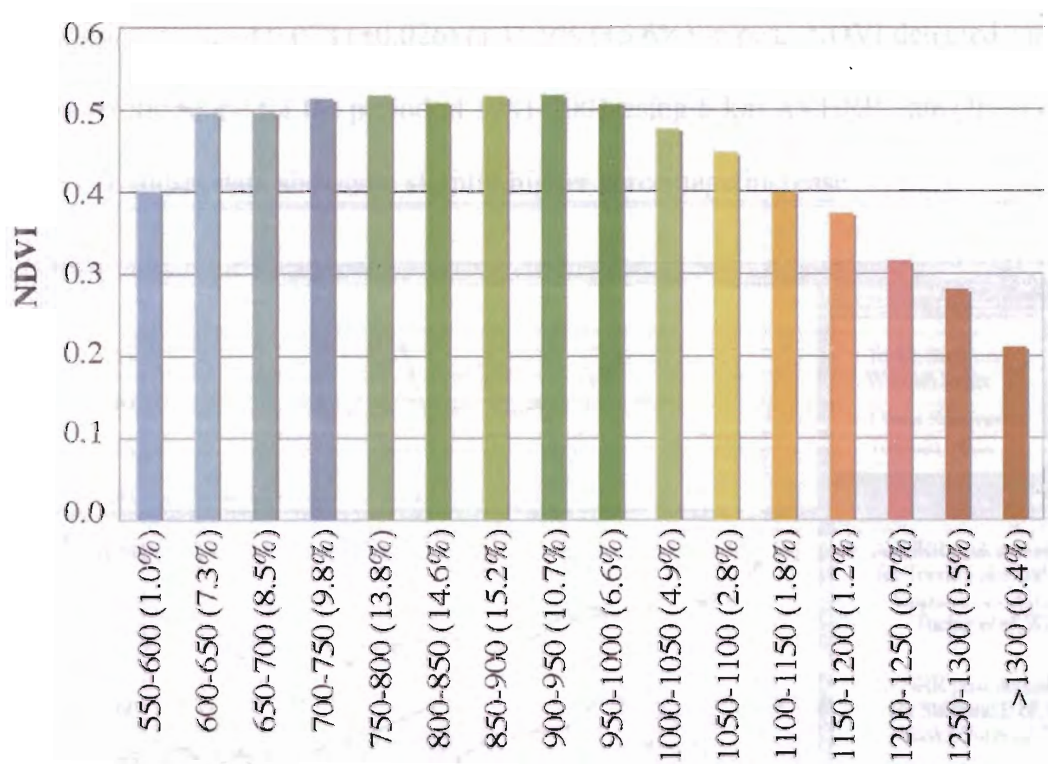

Figure 21. Mean NDVI at different elevations.

Change in NDVI

The Arctic Slope's summer warmth index (SWI) increased 0.09-0.19˚C/yr over the past 22-50 years and 0.16-0.34˚C/yr over the time of the NDVI record (Jia *et al.* 2003). In the 15-year period between 1985 and 1999, the period of overlap between AVHRR data analysis of Northern Alaska by Jia *et al.* (2003) and the Landsat data used here, the mean Landsat-derived NDVI across the Toolik Lake and Upper Kuparuk Region increased 0.076 or 15.9% (Figure 22). This trend appears to agree with the increase of 0.078 (±0.026) or 16.9% (±5.6%) in peak NDVI detected for the entire Arctic Slope for the period of 1981-2001 using 8-km AVHRR data (Jia *et al.* 2003). Landsat data showed a slightly higher percentage increase

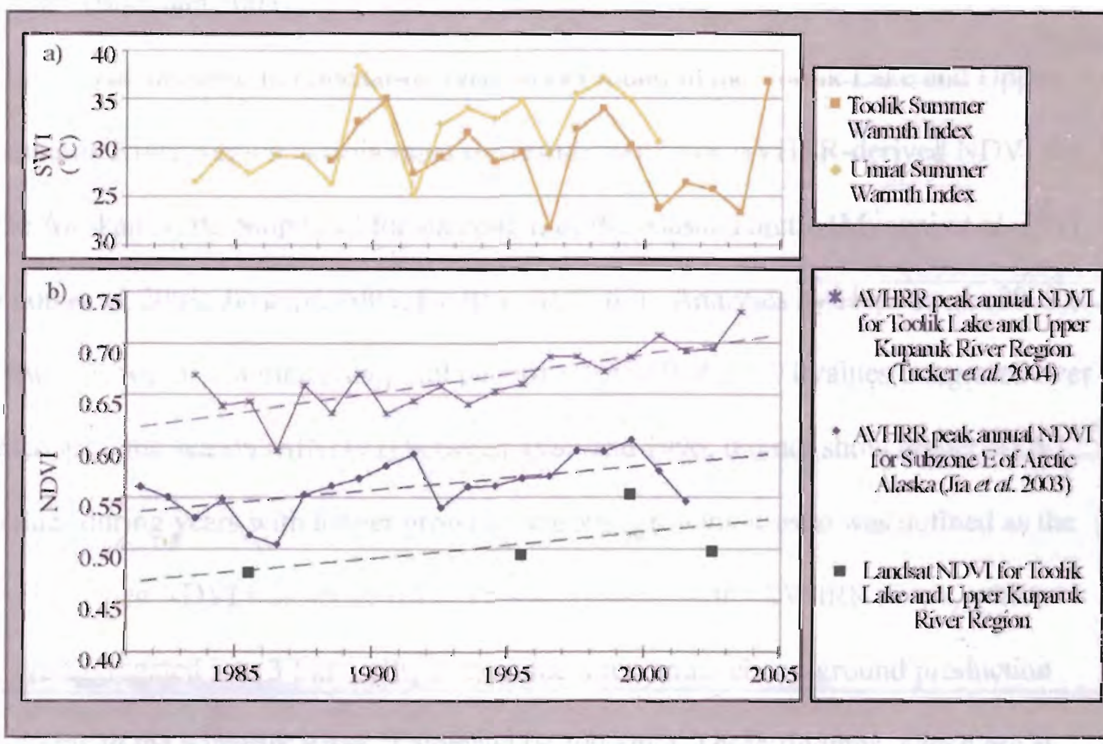

Figure 22. a) Summer temperature record (˚C) at Toolik Lake and Umiat, b) AVHRR NDVI and Landsat NDVI trend between 1981 and 2005.

than the 0.069 ± 0.022 or 12.6% increase in peak AVHRR NDVI detected for Subzone E of the Alaskan arctic, which includes the Toolik Lake and Upper Kuparuk River Region.

While AVHRR and Landsat NDVI both showed asimilar increase between 1985 and 1999, AVHRR data tend to give higher overall NDVI values than Landsat data (Figure 22). This may be due to the sensors themselves. AVHRR sensors were designed by NOAA primarily to conduct research on the oceans and atmosphere. These sensors therefore have wider near-infrared channels than sensors designed for land applications such as Landsat TM/ETM+, SPOT, and some MODIS channels. The spatial resolution, or field-of-views (FOVs), of the sensors may impact NDVI values (Boelman 2003).

The increase in Landsat-derived NDVI found in the Toolik Lake and Upper Kuparuk River Region corroborated the results found for AVHRR-derived NDVI for the Alaskan North Slope and for subzone E of the Alaskan arctic (Myneni *et al.* 1997; Zhou *et al.* 2001; Jia *et al.* 2003; Goetz *et al.* 2005). Analyses by Hope *et al.* (2003), however, which examined temporal patterns of AVHRR NDVI values integrated over each growing season (SINDVI) between 1989 and 1996, did not show higher NDVI values during years with longer growing seasons (growing season was defined as the period when NDVI was above 0.1). This study used 1-km^2 AVHRR pixels, which were aggregated into 3-km^2 cells, to examine interannual above-ground production patterns in the Kuparuk River Watershed (9,200 km^2). These findings, which are at odds with those found by Myneni *et al.* (1997), Zhou *et al.* (2001), Jia *et al.* (2003), Goetz *et al.* (2005), and those presented here, may be due to the spatial extent and areal averaging of NDVI. Local variations or noise at this scale could have obscured temporal NDVI patterns. This study also used half-monthly compositing periods in their calculations of SINDVI, which may have introduced sufficient uncertainty to mask any relationship between season length and SINDVI.

The amount of change in Landsat NDVI varied by surface type. Though surfaces with high absolute change usually tended to have a high percentage change and vice versa, apparent change in greenness was slightly different when expressed as percentage change vs. absolute change in NDVI. For example, surface types with relatively high NDVI values, such as shrubby areas, may show a relatively high rate of actual change, but a low percentage change relative to a surface with a similar rate of change that began with lower initial NDVI values. I therefore report both absolute and percentage change in NDVI between 1985 and 1999 on all surface types (Table 3).

Table 3. Change in NDVI between 1985 and 1999 on different surface types.

Glacial Geology	**Absolute change in NDVI between 1985 and 1999**	**Percent change in NDVI between 1985 and 1999 (%)**
Sagavanirktok	0.082	16.4
Itkillik II	0.079	16.8
Itkillik I	0.077	15.8
Surficial Geomorphology		
Nonsorted circles	0.088	18.9
Turf hummocks	0.086	18.6
High- or flat-centered ice wedge polygons or palsas	0.084	18.0
Featureless	0.083	16.9
Indistinct hillslope watertracks	0.083	16.2
Well-developed hillslope watertracks	0.080	15.3

Table 3. continued

Wetland microrelief	0.079	17.4
Irregular microrelief	0.078	16.0
Thermokarst	0.073	15.1
Sorted and nonsorted stripes	0.072	14.9
Pond complex	0.059	12.3
Stony surface	0.056	14.8
Vegetation		
Tussock sedge, dwarf-shrub moss tundra	0.084	16.8
Dwarf- to low-shrub moss tundra	0.083	16.3
Hemi-prostrate and prostrate dwarf-shrub, forb, moss tundra	0.079	16.4
Sedge, moss tundra (rich fens)	0.079	17.8
Nontussock sedge, dwarf-shrub, moss tundra	0.078	16.2
Sedge, moss tundra (poor fens)	0.077	16.3
Prostrate dwarf-shrub, forb, fruticose-lichen tundra (acidic)	0.077	17.2
Dwarf-shrub, sedge, moss tundra	0.075	14.7
Prostrate dwarf-shrub, forb, fruticose-lichen tundra (nonacidic)	0.067	14.7
Low to tall shrublands	0.067	12.9
Hemi-prostrate dwarf-shrub, fruticose-lichen tundra	0.067	14.6
Lichens on rocks	0.060	16.6
Partially vegetated barrens, and revegetated disturbed areas	0.036	12.6
Water and deep-water herbaceous marsh	0.006	10.0
Slope angle		
Gentle (2-5°)	0.079	16.1
Flat (<2°)	0.074	17.2
Moderate (5-10°)	0.069	14.4
Steep (>10°)	0.052	14.9
Aspect		
East	0.083	17.2
South	0.077	16.6
North	0.075	15.9
West	0.074	15.4
Elevation (m)		
600-650	0.089	19.3
700-750	0.088	18.3
750-800	0.087	18.1
650-700	0.087	18.8
800-850	0.075	15.6
850-900	0.070	14.3
900-950	0.062	12.5
950-1000	0.056	11.4
1000-1050	0.055	12.0
1050-1100	0.051	11.9
550-600	0.050	13.4
1100-1150	0.049	12.7
1150-1200	0.045	12.5
1200-1250	0.044	14.4
1250-1300	0.034	12.1
> 1300	0.027	12.5

Glacial Geology

Sagavanirktok surfaces, the oldest surfaces, which tend to be the most green, showed the largest increase in NDVI (0.082 or 16.4%), followed by Itkillik II surfaces, which were the most recently deglaciated and tend to be the least green (0.079 or 16.8%). NDVI on Itkillik I surfaces changed 0.077 or 15.8%.

Surficial Geomorphology

Nonsorted circles showed the most change in NDVI between 1985 and 1999 (0.088 or 18.9%) followed by turf hummocks (0.086 or 18.6%) and high- or flat-centered ice wedge polygons (0.086 or 18.0%). Featureless areas increased 0.083 or 16.9%. Indistinct hill slope water tracks and well-developed hill slope water tracks increased in greenness 0.083 or 16.2% and 0.080 or 15.3%, respectively. Stony surfaces showed a relatively small amount of change (0.056 or 14.8%)

Vegetation

Tussock sedge, dwarf-shrub moss tundra showed the largest increase in NDVI between 1985 and 1999 (0.084 or 16.8%). Dwarf- to low-shrub moss tundra also showed a large increase (0.083 or 16.3%), followed by hemi-prostrate and prostrate dwarf-shrub, forb, fruticose-lichen tundra (0.079 or 16.4%). Rich fens showed a relatively high percent increase of change (0.079 or 17.8%), as did areas of acidic prostrate dwarf-shrub, forb, fruticose lichen tundra (0.077 or 17.2%).

Partially vegetated barrens and revegetated disturbed areas showed the smallest amount of change in NDVI between 1985 and 1999 (0.036 or 12.65), followed by areas of lichen on rocks (0.060 or 16.6%). Unless they are rapidly being revegetated, one might expect barren areas to show little or no increase in NDVI. Even at this relatively fine scale, nearly every mapped polygon actually represents a complex of many vegetation types. Only the dominant type is shown on the map (Figure 4). Heterogeneity of vegetation types within each vegetation polygon may explain increase in NDVI on barren sites. Hemi-prostrate dwarf-shrub, fruticose-lichen tundra and low to tall shrublands, the vegetation type typified by the highest NDVI values, showed small degrees of change (0.67 or 14.6% and 0.067 or 12.9%, respectively).

Slope angle

The amount of change in NDVI between 1985 and 1999 varied with slope. Areas with gentle slopes (2-10°) showed the largest change, 0.079 or 16.0%, followed by flat surfaces (< 2°) (0.074 or 17.2%). Moderately sloped areas (10-20°) and steep slopes (>20°) showed less change in NDVI (0.069 or 14.4% and 0.052 or 14.9% respectively).

Aspect

East-facing slopes showed the largest increase in NDVI (0.083 or 17.2%), followed by south-facing slopes (0.078 or 16.6%). North-facing slopes changed 0.075 or 15.9 % and west–facing slopes showed a change of 0.074 or 15.4%.

Elevation

The amount of change in NDVI between 1985 and 1999 generally tended to decrease as elevation increased.

Pixel-by-pixel characterization of change in NDVI

The mean amount of change in NDVI between 1985 and 1999 for the entire map area was 0.076 ±0.070. I created four classes of pixels: those that experienced negative change between 1985-1999 (decreased in NDVI), those that changed less than one standard deviation below the mean (NDVI increased between 0-0.006), those that changed within one standard deviation above/below the mean (NDVI increased between 0.006-0.145), and those that changed more than one standard deviation above the mean (NDVI increased more than 0.145) (Figure 23). The proportions of surface types for each of these four categories are shown in Table 4.

Four distinct patches of the map area showed especially large amounts of change in NDVI between 1985 and 1999 (Figure 24 and Table 5). There appears to be a variety of surface types that showed especially high change. The large amount of change in Area 1 appeared to correspond with upland watertracks, Area 2 appeared to be related to the effect of dust from the Dalton highway and disturbance due to an underground gas pipeline that parallels the road, Area 3 is possibly due to human activity near Toolik Lake, and change in Area 4 is on an alluvial fan of the Atigun River.

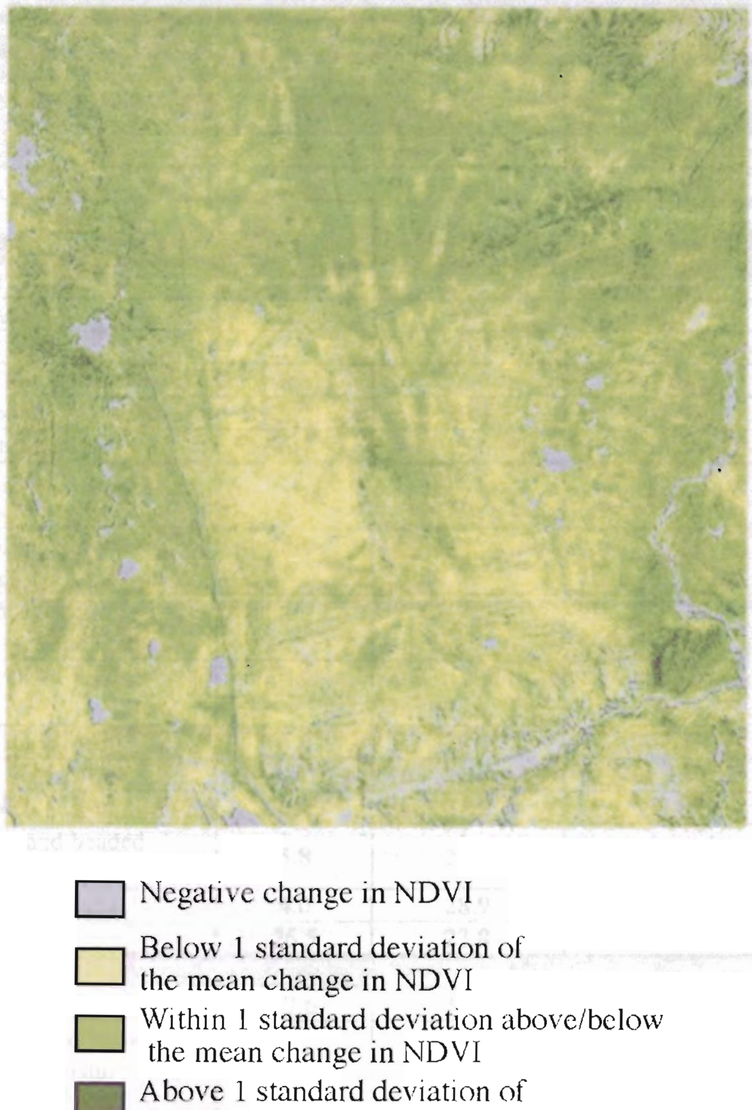

Figure 23. Change in NDVI of each 30 m pixel between 1985 and 1999 relative to the mean amount of change (for the same dates), which was an increase in 0.076.

Table 4. Proportion (%) of surface types of pixels with different degrees of NDVI change

Glacial Geology	Negative change in NDVI	Below 1 standard deviation of mean change in NDVI	Within 1 standard deviation above/ below mean change in NDVI	Above 1 standard deviation of mean change in NDVI
Sagavanirktok	1.3	24.3	71.7	2.7
Itkillik I	3.5	28.5	63.9	4.1
Itkillik II	4.9	24.3	65.0	5.7
Surficial Geomorphology				
Featureless	2.4	21.3	72.0	4.3
Stony surface	18.1	31.8	42.0	8.3
Non-sorted circles	1.9	20.4	69.6	8.1
Sorted and non-sorted stripes	2.8	33.8	60.9	2.5
Turf hummocks	2.2	20.4	71.9	5.8
Gelifluction features	6.4	33.6	55.3	4.7
Well-developed hillslope watertracks	2.1	27.4	66.4	4.2
Indistinct hillslope watertracks	1.4	24.6	70.7	3.2
High- or flat-centered ice wedge polygons and palsas	3.4	26.2	64.3	6.4
Low-centered ice wedge polygons	22.7	43.8	27.6	6.6
Wetland surface forms	3.6	28.4	62.7	5.3
Water	53.3	11.7	13.6	21.5
Pond complex	6.0	33.8	57.0	2.0
Thermokarst and beaded streams	5.8	28.2	59.2	7.3
Irregular microrelief	4.0	28.9	60.6	6.6
Disturbed	26.5	23.8	29.9	20.5
Vegetation				
Lichens on rocks	17.6	36.0	39.8	6.6
Partially vegetated barrens, and revegetated disturbed areas	30.1	28.0	29.5	12.4
Tussock sedge, dwarf-shrub moss tundra	1.8	22.5	72.1	3.6
Nontussock sedge, dwarf-shrub, moss tundra	3.8	27.6	63.0	5.6
Miscellaneous graminoid, dwarf-shrub, forb communities	2.2	27.4	67.7	2.6
Sedge, moss tundra (poor fens)	3.0	32.2	58.9	6.0
Sedge, moss tundra (rich fens)	5.1	27.7	61.1	6.1

Table 4, continued

Water and deep-water herbaceous marsh	47.0	17.1	22.7	13.1
Prostrate dwarf-shrub, forb, fruticose-lichen tundra (acidic)	7.7	29.8	55.6	6.9
Prostrate dwarf-shrub, forb, fruticose-lichen tundra (nonacidic)	5.9	36.8	52.9	4.4
Hemi-prostrate dwarf-shrub, fruticose-lichen tundra	7.0	36.5	51.3	5.2
Hemi-prostrate and prostrate dwarf-shrub, forb, moss, fruticose-lichen tundra	1.9	28.6	65.3	4.2
Dwarf-shrub, sedge, moss tundra	2.3	30.6	63.7	3.4
Dwarf- to low-shrub moss tundra	3.0	23.5	65.9	7.6
Low to tall shrublands	6.6	29.8	58.0	5.6
Slope angle				
Flat (<2°)	8.6	21.4	62.8	7.2
Gentle (2-5°)	2.7	27.3	66.0	4.0
Moderate (5-10°)	8.1	32.4	52.2	7.3
Steep (>10°)	27.8	27.2	32.4	12.6
Aspect				
North	4.9	29.3	60.9	4.8
South	5.1	30.9	59.2	4.8
East	7.2	23.9	61.8	7.1
West	3.2	21.1	70.4	5.3
Elevation				
550-600	22.3	19.1	49.3	9.3
600-650	5.9	13.1	69.8	11.1
650-700	4.4	15.4	73.4	6.8
700-750	3.9	13.8	76.0	6.2
750-800	3.5	15.7	74.9	5.8
800-850	4.3	26.2	65.8	3.7
850-900	4.3	35.5	55.7	4.5
900-950	4.9	44.7	47.4	3.0
950-1000	6.9	51.0	38.9	3.2
1000-1050	9.5	48.8	37.1	4.6
1050-1100	14.3	45.9	33.5	6.4
1100-1150	18.5	41.8	32.5	7.0
1150-1200	24.6	35.6	31.5	8.5
1200-1250	27.9	32.0	30.1	10.0
1250-1300	31.6	33.8	25.9	8.6
>1300	38.1	32.5	23.1	6.8

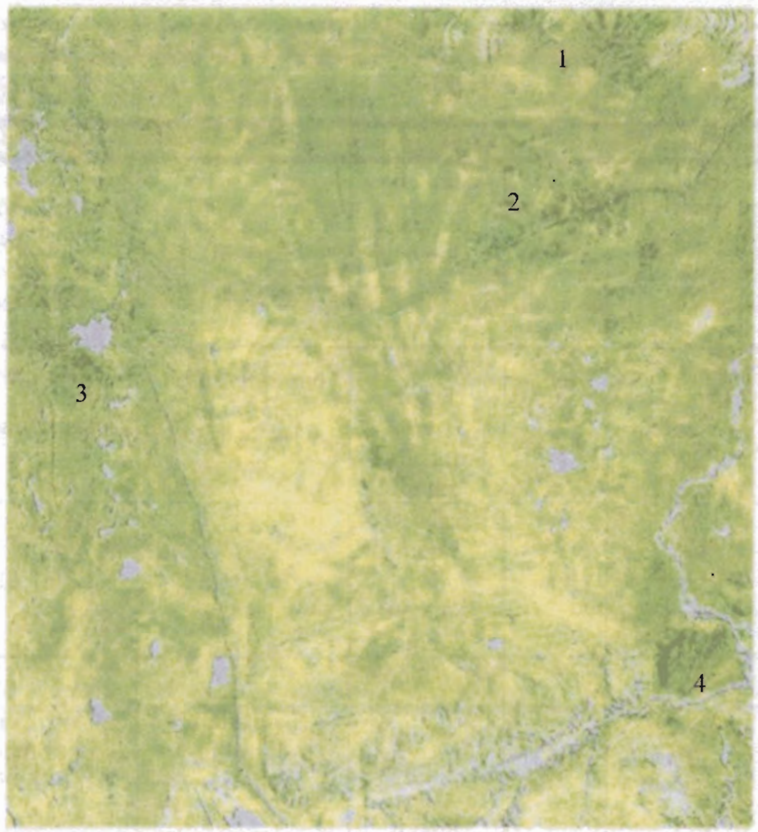

Figure 24. Locations and descriptions of high-change areas. The patches of amplified NDVI change in Area 1 appear to correspond with upland watertracks and are therefore likely due to shrub advance. Area 2 is directly north of and adjacent to the Dalton Highway. This change is likely related to the road's dust shadow, as most of the area's wind comes out of the Brooks Range to the south and southeast. The vegetation in this area may also be affected by the disturbance caused by the installation of an underground pipeline just north of the road in the 1980s. Area 3 is a patch of high NDVI change just south of Toolik Lake that may be related to the large number of research plots and human activity in the area. Area 4 is within an alluvial fan of the Atigun River. The dramatic increase in NDVI may be due to the draining and revegetation of an old river channel. See Figure 23 for color legend.

Table 5. Surface characterization of high-change areas (see Figure 24).

	Glacial Geology	Surficial Geomorphology	Vegetation	Slope angle	Aspect	Elevation (m)
Area 1	Mostly solifluction with some bedrock and Sagavanirktok surfaces	Well-developed hillslope watertracks	Snowbeds and poor fens	Gentle	South-facing	900-950
Area 2	Sagavanirktok	Featureless and indistinct hillslope watertracks	Tussock sedge, dwarf-shrub moss tundra	Flat and gentle slopes	East and north facing	750-900
Area 3	Itkillik II	Featureless	Dry and moist acidic tussock tundra	Gentle	Northeast and northwest	700-750
Area 4	Fan deposits with some Itkillik II	Indistinct hillslope watertracks	Nontussock sedge, dwarf-shrub, moss tundra	Flat	North- and east-facing	600-650

DISCUSSION

Vegetation-Terrain Relationships

The three different aged glacial surfaces all have characteristic vegetation and geomorphology. The results reflect that over long time periods, plant succession in the arctic trends towards more peaty, wetter upland surfaces and the infilling of lakes in lowland sites. Different slope angles, aspects, and elevations also differ in vegetation type proportions. North facing slopes tend to have the most snowbeds, while steep, windblown south-facing slopes support more sparse, xeric vegetation. In their analysis of slope, snow, and vegetation relationships at Imnavait Creek, Evans *et* *al.* (1989) found that the steep, south-facing slopes of E-W trending sandstone strata are nearly snow free in the winter because they are blasted by the prevailing catabatic winter winds out of the Brooks Range. In the summer they are dry and poorly vegetated (Evans *et al.* 1989). Mid-elevations and east/west facing slopes tend to have the most tussock tundra and shrubby areas.

Terrain-NDVI Relationships

The observed spatial patterns of NDVI reflect the relationships that exist between vegetation cover, landscape age, and surficial geomorphology. Older surfaces have greater cover of shrub-rich tussock tundra and shrub-filled water tracks, whereas younger surfaces have more dry, well-drained sites, stony areas, and irregular microrelief (Walker *et al.* 1995). Shrub cover is likely the most important factor that affects canopy greenness. The highest NDVI values occur in portions of the landscape with abundant shrubs, such as water tracks, on moderate slopes, and on older glacial surfaces.

East- and west-facing slopes have higher NDVI values than north- and south-facing slopes. In addition to their tendency to be steep and rocky, south facing slopes are also subject to strong winter winds from the Brooks Range, which lies just south of the study area. Snow is thereby blown from these slopes, reducing winter insulation and also limiting potential for the development of summer watertracks, which tend to be relatively shrubby, from melt-water. The sparser vegetation of these areas has lower NDVI values. While the north-facing slopes in this area are even steeper than the south-facing slopes, their slightly higher mean NDVI values is explained by their protection from winter winds and well-vegetated snowbed areas.

Change in NDVI

This independent analysis of NDVI data from the Toolik Lake region supports the conclusion of Jia *et al.* (2003) that a remarkable greening occurred in northern Alaska during the period 1981-1999. At least locally, this was followed in by a decrease in NDVI corresponding to a summer cooling in 2000-2002. Between 1999 and 2002 the mean Landsat NDVI decreased 12.1%, from 0.55 in 1999 to 0.49 in 2002. This corresponds to a decline in summer warmth over the same period and may be related to the short-term declines in AVHRR NDVI observed in 2000-2001 by Jia *et al.* 2003. The SWI at the Toolik weather station decreased from 30.1 in 1999 to 25.6 in 2002. However, while this period showed a decrease in SWI, the lower Landsat NDVI values in 2002 are more likely related to the earlier acquisition date of the image (July 21 as opposed to early August for the other three scenes). Plants may have not yet reached peak productivity, which would create lower NDVI values.

Patterns of NDVI change between 1985 and 1999 on different surface types

In their analysis of AVHRR NDVI for the Alaskan arctic between 1981 and 2001, Jia *et al.* (2003) also stratified NDVI change by bioclimate subzone and by the four main types of tundra vegetation: moist sandy tundra, moist nonacidic tundra, moist acidic (or tussock) tundra, and shrub tundra. They found that the highest peak

NDVI increases occurred for Subzone D (0.082 ± 0.028, 18.7%), followed by Subzone E (0.069 ± 0.022, 12.6%) and Subzone C (0.056 ± 0.032, 15.1%).

AVHRR data also suggested that temporal changes in peak and time-integrated greenness were greatest in areas of moist nonacidic tundra, which currently have relatively low shrub cover (Jia *et al.* 2003). In my analysis of Landsat data, however, I found that moist tussock tundra showed both a higher absolute (0.084) and a slightly higher percent change in NDVI (16.8%) than nontussock tundra (0.078 or 16.4%).

Landsat data showed that densely vegetated areas tended to have higher rates of change. Low to tall shrublands were a clear exception to this pattern. These areas have high NDVI values but showed relatively small amounts of change (0.067 or 12.9%). Growth of vegetation in areas adjacent to streams may not be limited by warmth and therefore may not be first to respond to climate change. These areas tend to have relatively warm soils, with deep thaw, and high nutrient inputs. Growth of these shrubs may be limited physiologically. Shrubs in open tundra, on the other hand, tend to grow in areas of colder soils, with shallower thaw, and less available nutrients. These areas may show more response to warming. Low amounts of change in areas of low to tall shrublands may be also be due to the nature of the shrubs' increased growth. Because it is an index of greenness, NDVI is unable to detect an increase in secondary growth. Increase in annual woody growth could be examined by studying growth rings of streamside willows.

There is a lack of a clear relationship between surface age and amount of NDVI change. Oldest surfaces showed the largest absolute change, while the youngest surfaces showed the largest percent increase in NDVI. Itkillik I surfaces showed the lowest absolute and percent change of the three different aged surfaces. These results are likely due to the distribution of vegetation types on the different aged surfaces.

Areas characterized by nonsorted circles showed a large increase in NDVI between 1985 and 1999 (0.088 or 18.9%). High-centered ice wedge polygons also showed relatively high rates of change (0.084 or 18.0%). Both of these surficial geomorphologic types are subject to continual disturbance, cryoturbation in the former and thermokarst in the latter.. Perhaps these surfaces are more apt to respond to climate change because of these disturbances, which promote cycling of nutrients, and because they lack the thick moss carpet that exists on undisturbed surfaces, which may serve as a buffer to soil temperature change. The increase in NDVI on these surfaces may be due to shrub advance or to increased graminoid abundance.

Many of the areas that showed negative change in NDVI between 1985-1999 are bodies of water (Figure 23). This likely does not reflect real change in NDVI because water typically has an NDVI value approaching 0, and this should not change from year to year unless water levels change. More likely this negative change in NDVI is a result of variation in illumination conditions between the 1985 and 1999 satellite images that was not completely normalized in the calculation of NDVI. Also, because water has a very low NIR and red reflectance, a small change in reflectance between years would cause a disproportionately large change in NDVI. There also may be an issue of calibration between the Landsat 5 satellite, which took the 1985 image, and the Landsat 7 satellite, which took the 1999 image. If satellite calibration and/or variation in illumination conditions caused water levels to show a decrease in NDVI, the detected increases in NDVI on other parts of the landscape possibly underestimate the real amount of change that occurred. This problem could be remedied through radiometric correction of the different NDVI images. This correction would calibrate the NDVI change to zero in areas that should show no change in NDVI over time, such as water.

The pixel-by-pixel analysis of change in NDVI showed some areas of high change in NDVI that appear to be related to the presence of well-developed watertracks on south-facing slopes (Area 1 of Figure 24). This area consists of upland watertracks. Areas of lowland watertracks, on the other hand, showed small amounts of change. This is likely why areas characterized as well-developed and indistinct watertracks didn't stand out in map analysis as showing exceptionally high degrees of change. The large amounts of change that correspond with upland watertracks may have been canceled out by the small amount of change that corresponded with lowland watertracks. Upland watertracks are typically shrub rich. Lowland watertracks, on the other hand, are often flowing through colluvial basins, which are typically sedge-rich wetlands with few shrubs, and which showed small amounts of change in NDVI between 1985 and 1999.

The enhanced greening in Area 2 (see figure 24) appears to at least somewhat parallel the Dalton Highway. In the early 1980s an underground gas pipeline was installed, running from Prudhoe Bay to Pump Station 4 just north Atigun Pass. The disturbance caused by the burial of this pipeline is still visible today. Much of the revegetation along the buried pipeline consists of various *Salix* species growing to heights over 2 meters. This enhanced shrub growth probably explains much of the detected increase in NDVI in this area.

Much of Area 3 (Figure 24) exists on or in close proximity to the extensive research underway at the Toolik Lake Field Research Station. This research includes fertilization experiments, greenhouse experiments, snowfences, boardwalks to help researchers access research plots, and various other human activity. Perhaps the effects of this research on the vegetation were detectable by Landsat sensors. Area 4 of Figure 24 would be best accessed by a helicopter. A visit to this portion of the landscape may shed some light on the nature of the greening that has clearly been occurring in this area.

A Changing Arctic: What does change in NDVI mean for arctic ecosystems?

Higher NDVI values are indicative of greater photosynthesis occurring in the arctic, likely due to changes in plant species distribution, especially shrub expansion. These changes suggest an increase in plant biomass in the arctic. Defining the precise relationship between NDVI and biomass is difficult due to a lack of long-term, consistent biomass records in the arctic. Correlations between hand-held spectrometer NDVI values, satellite-derived NDVI values, and above-ground plant biomass have been examined by various researchers (Shippert *et al.* 1995; Jia *et al.* 2003; Boelman 2005) and have been shown to be non-linear. There is an asymptotic relationship between biomass and reflectance data because as vegetation density increases absorption of visible light approaches a maximum, beyond which any additional vegetation density does not contribute to NDVI.

One clear problem with using NDVI as an estimate for changes in biomass is that many of the changes in the arctic involve an increase in shrubs. This is likely accompanied by a large increase in woody biomass that would not directly affect the chlorophyll absorption that is detected by NDVI. Indeed, NDVI vs. biomass curves that were created based on SPOT data for the Upper Kuparuk River Region and field biomass samples showed that shrub-rich plant communities, such as *Betula nana-Salix glauca,* have lower NDVI values than would be expected from their model (Shippert *et al.* 1994). Because NDVI data are unable to take into account changes in woody biomass, temporal analyses of NDVI likely underestimate changes in vegetation occurring in the Arctic.

A major implication for change in above-ground plant biomass is the effect this may have on the Arctic's carbon budget. Estimates for the amount of carbon stored in the Arctic vary greatly. Roughly one-third of the global soil carbon pool is thought to be stored in northern latitudes, and in the Arctic tundra as much as 90% of the total ecosystem C resides in organic horizons and frozen mineral soils (Mack *et al.* 2004). The response of soil organic carbon (SOC) to changes in nutrient availability will play a critical role in determining net ecosystem C balance in a changing climate. Investigations into the potential effects of warming on the carbon balance of northern ecosystems have suggested that projected release of soil nutrients associated with high-latitude warming may further amplify carbon release from soils, causing a net loss of ecosystem carbon and a positive feedback to warming (Mack *et al.* 2004).

In addition to its effect on the carbon budget, vegetation change, especially shrub expansion, has the potential to affect the surface energy balance through altering surface albedo (Sturm *et al.* 2005, Chapin 2005), and to affect hydrology by increasing the amount of winter snow trapping, increasing summer transpiration, and by altering active layer depth (Tape *et al.* 2006). Vegetation change will likely be accompanied by many feedback systems resulting from interactions between temperature, moisture, paludification, ice aggradation, soil insulation, and permafrost depth.

Changes in vegetation will also affect habitat for caribou and other wildlife, as has been suggested by interpretations of results of experimental studies near Toolik Lake. For example, inflorescences of the forb species, which disappeared or were strongly reduced in experimental treatments simulating climatic warming, are nutritionally important and selectively grazed by caribou during lactation (White and Trudell 1980) and are the major plant species used by bumble bees and other pollinators (Williams and Batzli 1982). Some treatments of warming and fertilization experiments also lost entire functional groups (lichens, mosses, and forbs) as *Betula* abundance increased. This change is especially significant because lichens are critical to the over-winter nutrition of caribou (White and Trudell 1980) and mosses strongly influence the soil thermal regime. Because the tundra has so few species, any loss of species has a large proportional impact on tundra communities, perhaps leading to profound ecosystem consequences.

CONCLUSIONS

- Analyses of vegetation-terrain relationships showed that different aged glacial surfaces all have characteristic vegetation and geomorphology, suggesting that over time, plant succession in the Arctic trends towards peaty, wetter upland surfaces and the infilling of lakes in lowland sites. In the Toolik Lake and Upper Kuparuk River Region, north-facing slopes tend to have the most snowbeds, while steep, windblown south-facing slopes support more sparse, xeric vegetation.
- The highest NDVI values occurred in those portions of the landscape with abundant shrubs, such as water tracks, on moderate slopes, and on older glacial surfaces.
- This independent analysis of NDVI data from the Toolik Lake and Upper Kuparuk River Region supports the conclusion of Jia *et al.* (2003) that a remarkable greening occurred in northern Alaska during the period of 1981-1999.

- Greening occurred heterogeneously across the landscape, with the most rapid change occurring in well-vegetated areas such as tussock tundra and shrubby areas, on areas of nonsorted circles, and at lower elevations.
- Four distinct areas of the map showed the most intensified greening between 1985 and 1999. These vegetation changes appeared to be related to a variety of factors including shrub advance in upland water tracks, the effects of dust north of the Dalton Highway, intensive research and human activity near the Toolik Lake research station, and an alluvial fan of the Atigun River.

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