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2009 Environ. Res. Lett. 4 045004

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Spatial and temporal patterns of greenness on the Yamal Peninsula, Russia: interactions of ecological and social factors affecting the Arctic normalized difference vegetation index

D A Walker¹, M O Leibman², H E Epstein³, B C Forbes⁴,
U S Bhatt¹, M K Reynolds¹, J C Comiso⁵, A A Gubarkov²,
A V Khomutov², G J Jia⁶, E Kaarlejärvi⁴, J O Kaplan⁷,
T Kumpula⁸, P Kuss⁹, G Matyshak¹⁰, N G Moskalenko²,
P Orekhov², V E Romanovsky¹, N G Ukraintseva² and Q Yu³

¹ University of Alaska Fairbanks, Fairbanks, AK, USA

² Earth Cryosphere Institute, Russian Academy of Science, Siberian Branch, Tyumen, Russia

³ University of Virginia, Charlottesville, VA, USA

⁴ Arctic Center, University of Lapland, Rovaniemi, Finland

⁵ NASA Goddard Space Flight Center, MD, USA

⁶ Chinese Academy of Sciences, Institute for Atmospheric Physics, Beijing, People's Republic of China

⁷ Swiss Federal Institute for Forest Snow and Landscape Research, Birmensdorf, Switzerland

⁸ University of Joensuu, Joensuu, Finland

⁹ University of Berne, Berne, Switzerland

¹⁰ Moscow State University, Moscow, Russia

Received 30 March 2009

Accepted for publication 3 July 2009

Published 15 October 2009

Online at stacks.iop.org/ERL/4/045004

Abstract

The causes of a greening trend detected in the Arctic using the normalized difference vegetation index (NDVI) are still poorly understood. Changes in NDVI are a result of multiple ecological and social factors that affect tundra net primary productivity. Here we use a 25 year time series of AVHRR-derived NDVI data (AVHRR: advanced very high resolution radiometer), climate analysis, a global geographic information database and ground-based studies to examine the spatial and temporal patterns of vegetation greenness on the Yamal Peninsula, Russia. We assess the effects of climate change, gas-field development, reindeer grazing and permafrost degradation. In contrast to the case for Arctic North America, there has not been a significant trend in summer temperature or NDVI, and much of the pattern of NDVI in this region is due to disturbances. There has been a 37% change in early-summer coastal sea-ice concentration, a 4% increase in summer land temperatures and a 7% change in the average time-integrated NDVI over the length of the satellite observations. Gas-field infrastructure is not currently extensive enough to affect regional NDVI patterns. The effect of reindeer is difficult to quantitatively assess because of the lack of control areas where reindeer are excluded. Many of the greenest landscapes on the Yamal are associated with landslides and drainage networks that have resulted from ongoing rapid permafrost degradation. A warming climate and enhanced winter snow are likely to exacerbate positive feedbacks between climate and permafrost thawing. We present a diagram that summarizes the social and ecological factors that influence Arctic NDVI. The NDVI should be viewed as a powerful monitoring tool that integrates the cumulative effect of a multitude of factors affecting Arctic land-cover change.

Keywords: Nentsy, reindeer herding, gas development, Bovanenkovo, plants, disturbance, climate change, infrastructure

1. Introduction

1.1. Overview: using NDVI as a tool to look at land-cover change on the Yamal

The Yamal region in northwest Siberia is a hot spot of Arctic land-cover change due to rapid resource development, active geomorphic changes, climate change, and growth of the local reindeer herds, (Vilchek 1996, Forbes 1999a, 1999b, 2008, Forbes *et al* 2009, Dobrinsky 1997, Melnikov and Grechishchev 2002, Moskalenko 2005, Walker *et al* 2009c). A thin layer of tundra vegetation provides key resources to the people and animals of the Yamal and protects the underlying permafrost from thaw. We are using the normalized difference vegetation index (NDVI) in conjunction with detailed ground-level surveys to better understand how the major forces of change affect the vegetation.

The NDVI is an index of vegetation greenness. Green plants have high reflectivity in the near-infrared wavelengths and absorb red wavelengths for photosynthesis. The normalized difference vegetation index (NDVI) is defined by the equation: $NDVI = (NIR - VIS) / (NIR + VIS)$, where NIR is the reflectance of the Earth's surface in the near-infrared channel (0.725–1.1 μm) and VIS is the reflectance in the visible portion of the spectrum or the red channel (0.5–0.68 μm) (Tucker 1976, Tucker and Sellers 1986). The observed spatial and temporal changes to vegetation greenness represent changes to the fraction of photosynthetically active radiation (fPAR) that is absorbed by the leaves and stems of the plant canopy, which is in turn a function of numerous properties of the vegetation including its vertical and horizontal structure, species composition, phenological stage, and health of the plants.

The NDVI has recently gained a lot of attention because a long-term trend of increased NDVI has been detected in parts of the Arctic (Myneni *et al* 1997, Jia *et al* 2003, 2004, Stow *et al* 2004, Jia *et al* 2006, Verbyla 2008, Goetz *et al* 2009). For example, in northern Alaska, the time-integrated NDVI has increased 20% during the period of satellite observations (1982–2007) (Walker *et al* 2009a, 2009b, 2009c). These changes are not, however, universal. Much smaller changes have been observed in parts of the Eurasia tundra (Walker *et al* 2009a, 2009b, 2009c). The causes of these changes are not well understood but have been attributed to a variety of factors, including an increase in the extent and abundance of shrubs (Sturm *et al* 2001, Tape *et al* 2006, Lantz 2008), local effects of anthropogenic disturbances and differential response of different vegetation types (Munger 2007), northward movement of trees from the sub-Arctic (Lloyd 2005, Lloyd and Bunn 2007), and longer growing seasons and increasing land temperatures (Jia *et al* 2003, Goetz *et al* 2005). Analysis of circumpolar patterns of NDVI in relationship to variables in a circumpolar geographic information system have documented the influence of land temperature, regional floras, glacial history, bedrock and soil chemistry, local nutrient availability, and disturbance patterns on NDVI (Walker *et al* 2003, Reynolds *et al* 2006, 2007, Munger *et al* 2008, Reynolds and Walker 2008, 2009). Recently, rapid changes in sea-ice concentrations (Comiso *et al*

2008) have raised the questions regarding the influence of sea-ice changes on land temperatures, permafrost, and associated ecosystem processes (Lawrence *et al* 2008, Bhatt *et al* 2007, 2008, Walker *et al* 2009a). The Yamal offers an opportunity to take a closer look at the spatial and temporal patterns of NDVI in this region and to look at the possible underlying causes of any trends.

A major question in our study is: how do various forms of physical disturbance affect Yamal greening patterns? Many studies of disturbances in the Arctic have shown that plant production often increases on disturbed sites because of the positive influence of increased soil temperatures and enhanced nutrient regimes (Ebersole 1985, Shaver and Chapin III 1995, Walker 1996, Shaver *et al* 1998, Forbes and Sumina 1999, Forbes *et al* 2001, Walker *et al* 2006). For example, landscape-scale studies of vegetation response to climate and disturbances in the Mackenzie River delta region of northwestern Canada, indicate that increased the frequency of disturbances such as fire and landslides results in the introduction of abundant shrubs (Lantz 2008). On the Yamal, we were looking for disturbances that occur at a large enough scale to affect the regional NDVI patterns.

1.2. Physical environment

The Yamal Peninsula (figure 1) is about 250 km wide and is bounded on the west and north by the Kara Sea and on the east by the embayment of the Ob River. The maximum elevations in the interior parts of the Peninsula are only about 45–90 m (Tsibulsky *et al* 1995). The Peninsula was unglaciated during the last glaciation (Forman *et al* 2002). Most of the Peninsula is built of sandy and clayey marine, alluvial and lacustrine sediments deposited during and following the middle and late Quaternary marine transgressions. Most of the deposits are saline within the permafrost, and some are saline in the active layer (the layer of soil above the permafrost that melts annually) (Trofimov 1975). Hilltops in sandy areas are often windblown with sand hollows, some covering large areas. Meandering rivers and streams have cut broad valleys through the terrace deposits creating lowlands that are occupied by polygonal peat lands, thaw lakes and drained thaw-lake basins.

The zonal vegetation ranges from dominantly low-shrub tundra in the south to sedge, prostrate-dwarf-shrub, moss tundra on Belyy Island (Dobrinsky 1975, Ilyina *et al* 1976). The Yamal Peninsula is one of the best places in the Arctic to examine the effects of climate change along the full Arctic climate gradient because it is a relatively flat homogeneous land that traverses four of the five Arctic bioclimate subzones¹¹ (subzones B to E, figure 1) (Yurtsev 1994, CAVM Team 2003).

¹¹ The Arctic bioclimate subzones are defined by key plant growth forms, species limits and mean July temperatures (MJT). Subzone A: cushion-forb, *Saxifraga oppositifolia*, MJT < 3°C. Subzone B: prostrate-dwarf-shrub, *Dryas integrifolia*, 3°C < MJT < 5°C. Subzone C: hemiprostrate-dwarf-shrub, *Cassiope tetragona*, 5°C < MJT < 7°C. Subzone D: erect-dwarf-shrub, *Betula nana/exilis*, 7°C < MJT < 9°C. Subzone E: low-shrub, *Alnus viridis*, 9°C < MJT < 12°C (Walker *et al* 2005).

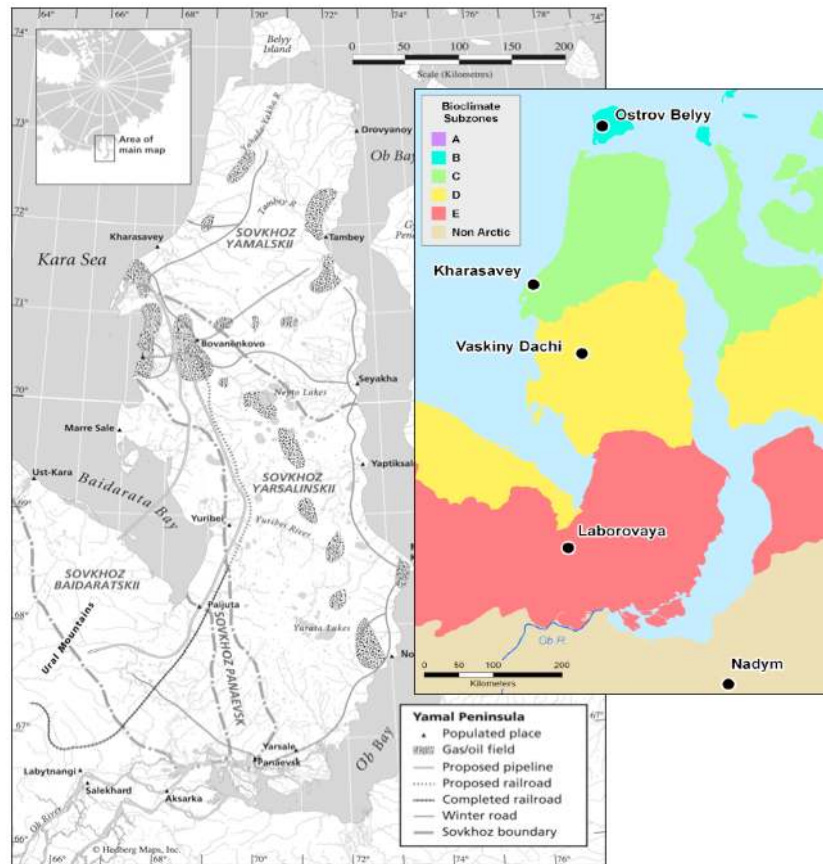


Figure 1. The Yamal Peninsula with locations of existing and proposed infrastructure (modified from Forbes (1999a, 1999b)). Colored inset map shows the bioclimate zonation as shown on the Circumpolar Arctic Vegetation Map (modified from CAVM Team (2003)). See footnote 11 for more details regarding the five Arctic bioclimate subzones.

2. Approach

2.1. Spatial analysis of NDVI

We made an NDVI map of the Yamal Peninsula using the same data that were used to make the circumpolar NDVI data set for the Circumpolar Arctic Vegetation Map (Walker *et al* 2005). The data set was derived from AVHRR (advanced very high resolution radiometer) sensors aboard the NOAA weather satellites and developed by the Alaska USGS Alaska Geographic Science Office. These data were used previously in an analysis of circumpolar NDVI-land-temperature relationships (Raynolds *et al* 2008). The 1 km resolution maximum-NDVI (MaxNDVI) data were averaged within 850 12.5 km pixels that covered the 312876 km² area of the analysis to match the resolution of the land-temperature data set. The MaxNDVI values were maximum values recorded in each pixel during two years of record (1993 and 1995) used in the 1 km database.

Global tundra land-surface temperatures were calculated from AVHRR thermal data (Comiso 2003, 2006). This data set provided the longest satellite temperature record available. The data were geographically mapped to 12.5 km pixels in a north-pole stereographic projection and composited into monthly means from 1982–2003. Daily differencing and moving window techniques were used to eliminate cloud-

contaminated pixels (Comiso 2003, 2006). A constant emissivity value of 0.94 was used to calculate temperature from the thermal-infrared channels. We used a summer warmth index (SWI = sum of monthly mean temperatures that are greater than 0 °C, expressed as °C mo) as an index of the amount of warmth at the ground surface during the thaw season (May–September) in each 12.5 km pixel (Raynolds *et al* 2007). The index combines the effect of both the length and the warmth of summer temperatures, and correlates well with variations in Arctic plant diversity and biomass trends within the Arctic (Young 1971, Rannie 1986, Edlund 1990, Walker *et al* 2005). A linear regression analysis of MaxNDVI as a function of SWI was then performed on the 850 pixel data set for the Yamal Peninsula.

A general linear model (GLM) analysis was conducted to examine which variables in a regional GIS database best explain the variation in the average NDVI within the map polygons on the Circumpolar Arctic Vegetation Map (Grafen and Halls 2002, R Development Core Team 2008). Information regarding the terrain on the Yamal Peninsula was extracted from a circumpolar geographic information system (GIS) database. Much of the GIS map information came from the Earth Cryosphere Institute (Melnikov and Minkin 1998, Minkin *et al* 2001, Drozdov *et al* 2005) and the Circumpolar Arctic Vegetation Map (Walker *et al* 2005). Each map polygon

in the database contained information for dominant vegetation, landscape type and substrate type. Average values for summer land-surface temperatures (SWI described above), per cent lake cover and MaxNDVI were calculated for each polygon using the same data sources as used for the Circumpolar Arctic Vegetation Map (CAVM Team 2003) and added to the list of variables for each polygon (Raynolds *et al* 2007).

2.2. Temporal analysis of NDVI trends

The temporal trends of NDVI were examined along with the 1982–2007 trends in sea-ice concentration, and land-surface temperatures (Bhatt *et al* 2007, 2008). We used ice-cover data derived from historical (1982–2007) 25 km resolution SSM/I passive microwave data (Comiso 1999), AVHRR surface-temperature data (Comiso 2003, 2006), and 8 km AVHRR global inventory modeling and mapping studies (GIMMS) NDVI data (Tucker *et al* 2005). The sea-ice concentrations were examined annually during the period 2–22 July, in a 50 km strip seaward of the Arctic coastline along the Yamal Peninsula. The 2–22 July period is the time of the mean 50% ice concentration and the time of transition to summer ice conditions when sea-ice concentrations have the most variability. The temporal land-temperature data were converted to the summer warmth index (SWI) as for the spatial analysis. The SWI was examined in a 50 km strip landward along the Arctic coast. MaxNDVI and time-integrated NDVI (TI-NDVI) trends were examined for the land area of the Yamal Peninsula south of 72° N. The TI-NDVI is the sum of the biweekly positive NDVI values and is considered a proxy for the total annual primary productivity (Goward *et al* 1985). The NDVI relationships were calculated only south of 72° N because we detected a discontinuity in the GIMMS NDVI data at that latitude. The relationships from the Yamal region were compared with those for Eurasia, North America and the Circumpolar Arctic (Bhatt *et al* 2007, 2008, Walker *et al* 2009a, 2009b, 2009c). Correlations were calculated using linearly detrended time series.

2.3. Aerial and ground observations of vegetation patterns

Aerial and ground observations were conducted during field campaigns in 2007 and 2008 at locations representative of four of the five bioclimate subzones on the Yamal: Kharasavey (subzone C), Vaskiny Dachi (subzone D), Laborovaya (subzone E), and Nadym (northern boreal forest) (figure 1, inset). This Yamal bioclimate transect was similar in concept to trans-Arctic studies of NDVI and biomass conducted in North America (Walker *et al* 2003, 2008, Epstein *et al* 2004, 2008). At most locations we found both sandy and clayey study sites to conduct our observations so as to examine the effects of substrate on the NDVI patterns. We were unable to find sites that were not heavily grazed and trampled by reindeer at any location except Nadym (the forest site). A network of oil pipelines and roads surrounds the Nadym location and has kept reindeer out of that area for several decades, but the vegetation is not comparable to the tundra areas north of tree line where this paper focuses.

Table 1. Results of general linear model analyses showing per cent of deviance explained by each GIS variable for the Yamal Peninsula compared to a similar analysis for the circumpolar Arctic. Circumpolar data are from Raynolds *et al* (2008).

GIS variable	% deviance accounted for	
	Yamal	Circumpolar
Elevation	29.21	0.001
Landscape type	19.72	0.52
Substrate	4.88	3.61
Vegetation type	4.29	0.37
Summer warmth index	1.87	68.46
Lake area	1.57	3.61
Total	61.55	73.57
Significance of all variables:	<0.0009	

A data report summarizing the 2007–08 field information includes general descriptions of each location, photographs, maps of the study sites, summaries of sampling methods, vegetation data (species lists, species cover), leaf-area index (LAI), NDVI, soil data and active layer depth (Walker *et al* 2009a, 2009b, 2009c). Results of the ground measurements of biomass, leaf-area index and NDVI trends along the bioclimate gradient will be published after completion of the transect in 2010. Here we present mainly photographs of the landscapes and vegetation from the tundra sites visited to date. The observations reported here are in reference to major disturbance factors that could conceivably affect regional NDVI patterns.

3. Results

3.1. Spatial distribution of NDVI from satellite data

A strong summer-land-temperature gradient occurs across the Peninsula (figure 2(a)). The summer warmth index varies from 10–15 °C mo at the northeast coast of the Peninsula to greater than 45–50 °C mo in the south. The summer temperature pattern is similar to that portrayed on the bioclimate map (figure 1, inset) but the satellite data more accurately reflect the cooling marine influence near the coast and warmer temperatures inland.

We expected to see a strong positive north-south trend in the MaxNDVI values because circumpolar Arctic MaxNDVI values are strongly correlated with the summer warmth index ($y = 0.0137x - 0.0204$, $R^2 = 0.58$, (Raynolds *et al* 2007)), but the Yamal MaxNDVI patterns (figure 2(b)) do not show much correspondence to the temperature patterns ($y = 0.0036x + 0.356$, $R^2 = 0.2158$). The map of the difference between the observed MaxNDVI values and what was expected based on a circumpolar regression shows that MaxNDVI values are generally higher than expected particularly in areas with colder summer temperatures (figure 2(c)).

The general linear model analysis of the Yamal using variables from a regional GIS (figure 3 and table 1) revealed that the SWI explains less than 2% of the total MaxNDVI deviance. In a comparable GLM analysis using the same variables for the circumpolar NDVI data set, land temperature

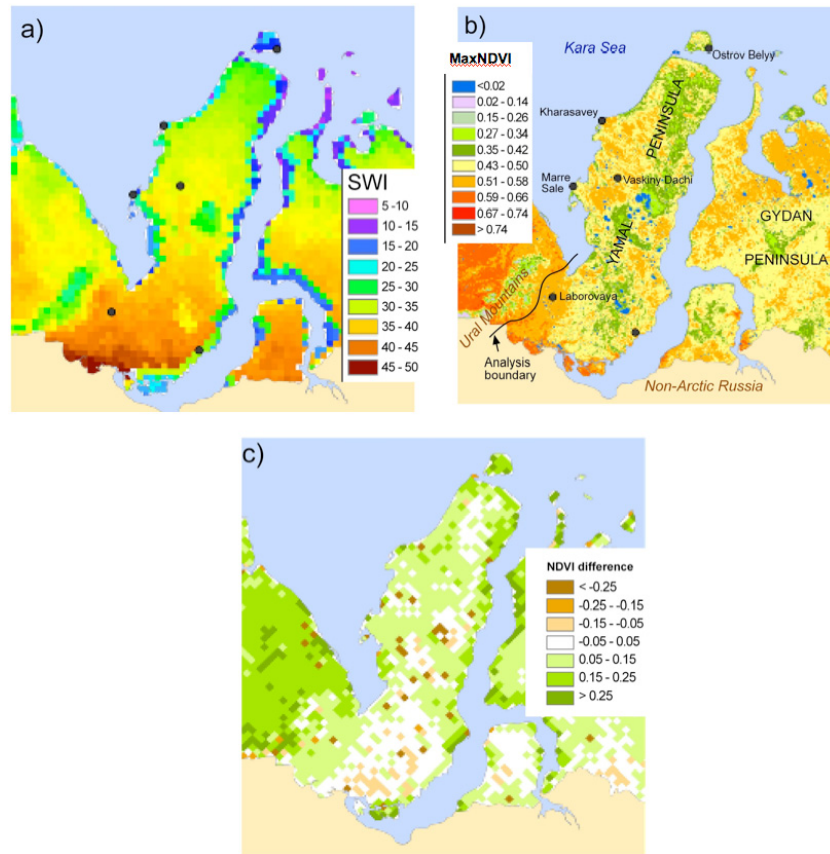


Figure 2. Land-surface temperatures and NDVI on the Yamal Peninsula. (a) Mean summer warmth index (SWI) at the land surface (1982–2003) (SWI = sum of mean monthly temperatures greater than 0 °C (°C mo)). (b) MaxNDVI of the Yamal region (1993 and 1995) (Based on Walker *et al* (2005)). (c) MaxNDVI on Yamal compared with expected values based on global NDVI–surface–temperature relationship. Green areas are warmer than predicted by the global regression model, and brown areas are cooler. High MaxNDVI and large differences west of the Ural Mountains are related to shrubby vegetation and maritime climate in this region.

explained 68.5% of the deviance (Raynolds *et al* 2008). Forty-nine per cent of the Yamal MaxNDVI deviance is explained by a combination of elevation and landscape type (e.g., low plains with marine deposits, low plains with alluvial and lacustrine deposits, high plains with fluvial and lacustrine deposits, foothills, and mountains); another 9% is explained by substrate type (peat, clay, silt, sand) and broad vegetation categories from the Circumpolar Arctic Vegetation Map. Generally, the alluvial valleys have higher MaxNDVI values than the uplands (not shown in these results). The mean MaxNDVI of the valleys across the Yamal Peninsula is 0.455 compared to 0.470 on the uplands despite many more lakes in the valleys, which tend to lower the NDVI. The high amount of MaxNDVI deviance accounted for by elevation in table 1 is due to the geography of the Yamal Peninsula. Normally NDVI decreases with elevation partially in response to cooler temperatures and partially to more exposed bedrock in mountainous areas. Elevations are uniformly low (<90 m) across the Peninsula but increase somewhat toward the warmer southern part of the Peninsula, where the foothills of the Ural Mountains have dwarf birch (*Betula nana*) plant communities with high NDVI values. In summary, NDVI across the Yamal is much less sensitive to variation in temperature than the circumpolar

Arctic. Most of the variation is related to relatively minor differences in elevation and to different terrain types and substrates.

3.2. Temporal trend of NDVI

Between 1982 and 2007, early-summer sea ice in the 50 km coastal strip of the Yamal/Kara Sea area declined 37% (figure 4, top). The SWI within the 50 km coastal zone increased 1.06 °C mo (+0.22 °C mo/decade, 4% overall change). MaxNDVI was nearly flat (+1% overall change), and the time-integrated NDVI (TI-NDVI) increased modestly, (7% overall change) (figure 4 bottom). Only the sea-ice trend was significant at $p = 95\%$.

Yamal (−37%) had a somewhat larger reduction in sea ice compared to all of the Eurasia Arctic (−27%) and the circumpolar Arctic (−25%). The 4% increase in the SWI was one of smallest increases in summer land temperatures of any area in the Arctic (compared to 18% in Eurasia and 24% for the circumpolar Arctic). TI-NDVI increased 7% on the Yamal compared to 8% for Eurasia as a whole and 8% for the circumpolar Arctic (Bhatt *et al* 2007, 2008, Walker *et al* 2009a, 2009b, 2009c). The MaxNDVI and the TI-NDVI trends are not significant at $p = 95\%$.

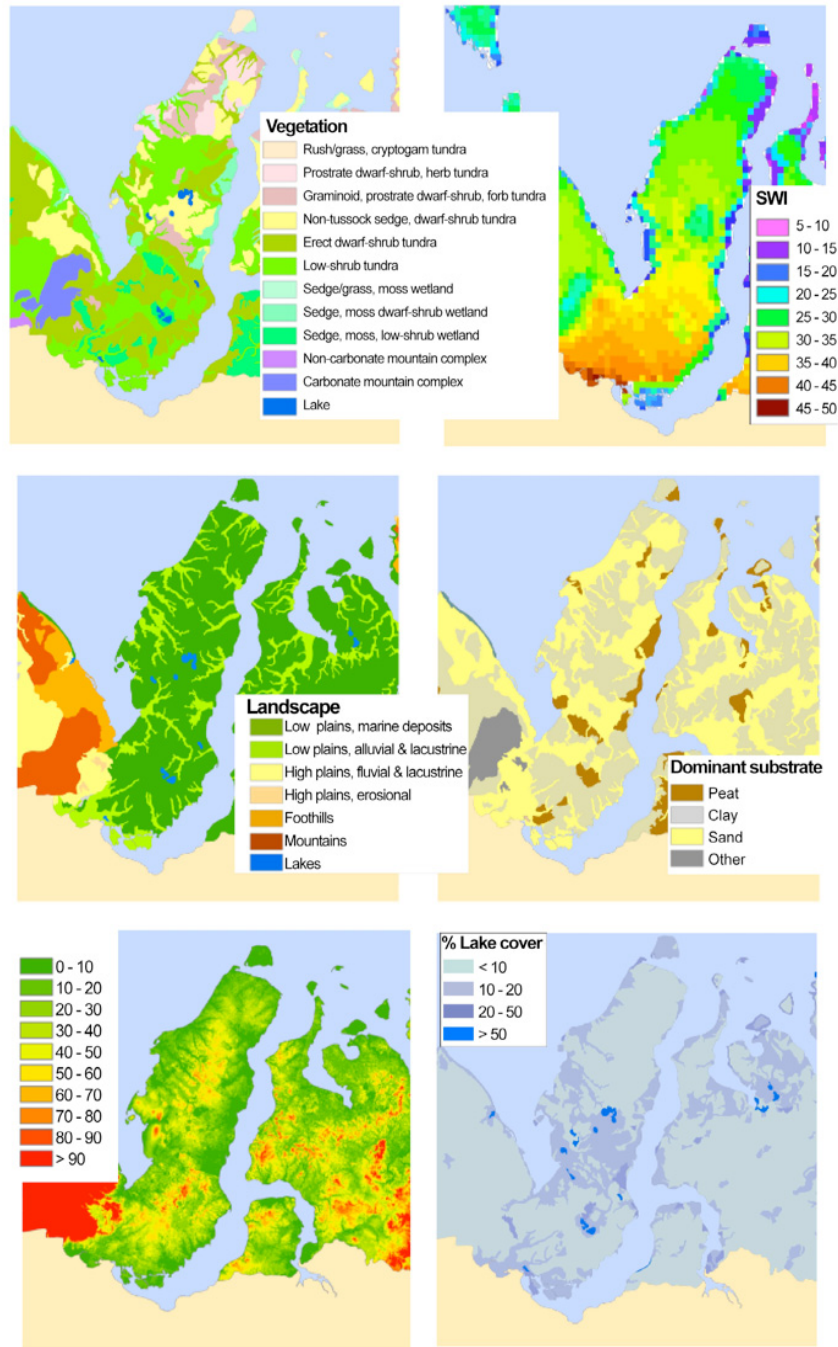


Figure 3. Variables used in the general linear model to examine the MaxNDVI relationships: vegetation, summer warmth index, landscape type, dominant substrate, elevation and lake cover. Based on information from CAVM Team (2003) and Reynolds *et al* (2008).

In the Kara/Yamal region, sea-ice concentrations and SWI were negatively correlated ($r = -0.37, p > 0.1$). Sea ice and TI-NDVI (south of 72°N) were negatively correlated ($r = -0.39, p > 0.05$) and SWI and TI-NDVI (south of 72°N) were positively correlated ($r = 0.52, p > 0.01$). These trends are consistent with other coastal areas studied in the Arctic—i.e., periods of lower sea-ice concentration are correlated with warmer land-surface temperatures and higher NDVI values (Bhatt *et al* 2007, 2008, Walker *et al* 2009a, 2009b, 2009c).

3.3. Aerial and ground observations of greenness patterns

Photographs of the vegetation of zonal upland sites indicate greener vegetation in bioclimate subzone E, where dwarf deciduous shrubs are a dominant part of the plant canopy (figure 5). Average vascular-plant biomass (not including mosses and lichens) from the zonal sites shown in the photos are as follows: Kharasavey, $180 \pm 55.8 \text{ g m}^{-2}$; Vaskiny Dachi, $221 \pm 112.5 \text{ g m}^{-2}$; and Laborovaya $447 \pm 146.6 \text{ g m}^{-2}$ ($\pm \text{s.d.}, n = 5$). Kharasavey has a more open canopy with exposed

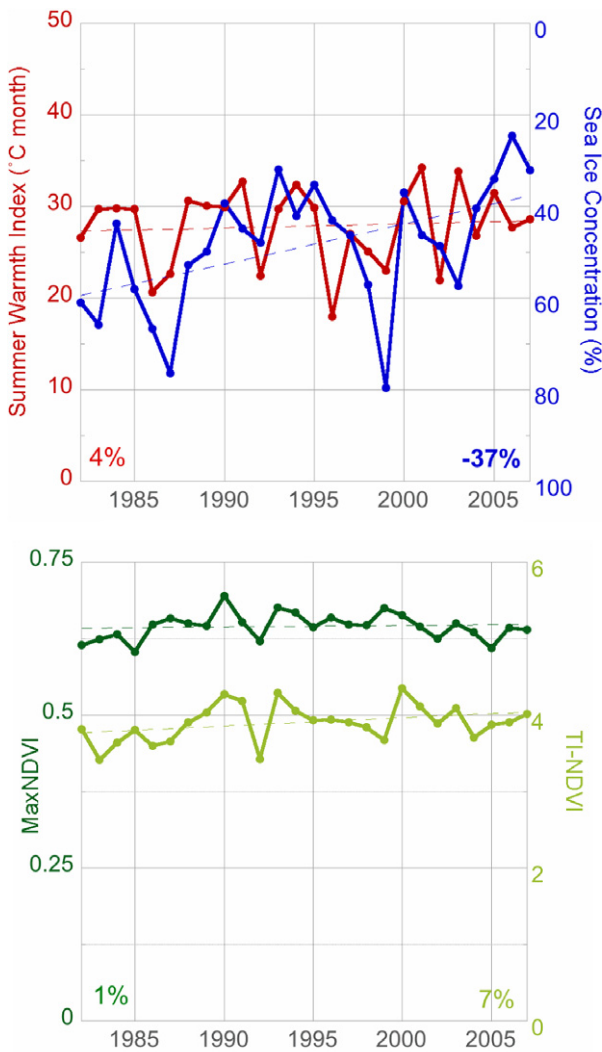


Figure 4. Trends in sea ice, land temperatures and NDVI in W. Kara Sea/Yamal region from 1982 to 2007. Blue line: sea-ice concentration. Red line: summer warmth index (SWI, the sum of mean monthly temperatures above freezing dark green line: MaxNDVI. Light green line: integrated NDVI (see text for explanation). NDVI values were calculated for the region south of 72° N because of a discontinuity in the GIMMS data at that latitude. Per cent change in each variable from 1982 to 2007 (2006) is shown by the numbers in the plots. Only the sea-ice trend is significant at $p = 95\%$. (Modified from Bhatt *et al* 2008.)

mosses. More green dwarf-shrub cover occurred at Vaskiny Dachi, and the greenest site at Laborovaya has high cover and biomass of dwarf birch (*Betula nana*). The general impression is that there is a large difference in biomass and greenness between subzones D and E and relatively little change on zonal sites north of here. Reindeer graze all three locations, but the upland areas at Vaskiny Dachi and Kharasavey have particularly ‘mown’ appearances due to strong grazing and trampling pressure.

Numerous photos were taken from helicopters during transport to and from the study locations. These photographs document some of the effects of various types of disturbance on the regional greenness patterns, particularly those related to permafrost thawing. Some of these photos are presented below in the discussion of the effects of permafrost thawing.

4. Discussion: factors influencing NDVI on the Yamal

4.1. Effects of climate and climate change

Although there is a strong summer temperature gradient on the Yamal Peninsula there is not a strong correlation between NDVI and summer warmth. The GLM analysis revealed that SWI accounted for less than 2% of the variance in MaxNDVI. This is in contrast to the situation for the Arctic as a whole where the SWI accounts for most of the deviance in MaxNDVI values. Photographs of zonal vegetation taken on the ground suggest that greener vegetation does occur in the southern part of the Peninsula as represented by the Laborovaya site in subzone E, but there is not a strong difference in greenness of zonal sites further north. Limited biomass data also support this general conclusion.

The analysis also showed that much of the Yamal has greener vegetation than would be predicted from the circumpolar MaxNDVI–SWI relationships. This is somewhat surprising because of the strong reindeer grazing pressure, which we expected might reduce biomass and NDVI values. Observations from helicopters indicate that vegetation in eroded valleys is much greener than the vegetation on the zonal upland surfaces and this may account for the greener-than-expected vegetation on much of the Yamal. (See discussion below related to effects of thawing permafrost.) The rather coarse scale of the spatial analysis (12.5 km pixels) did not allow us to resolve the differences in NDVI of the intricate networks of small drainages, so the mixed signal in pixels containing both uplands and valleys is likely responsible for the higher-than-expected NDVI values over much of the Peninsula. In the future, a more detailed analysis using higher resolution images from MODIS (250 m pixels), Landsat 7 (30 m pixels) and Quickbird (2.5 m pixels) will help resolve the spatial patterns of NDVI in these complex landscapes.

Although early-summer coastal sea-ice concentrations have declined sharply (–37%), summer land temperatures and TI-NDVI on the Yamal have increased only slightly (1% and 7% respectively) during the 25 years of AVHRR satellite observations. Neither trend is significant. This contrasts with patterns seen in northern Alaska and much of Arctic North America where strong decreases in sea-ice concentrations are linked to strong increases in land temperatures and NDVI (Jia *et al* 2003, Bunn *et al* 2007, Walker *et al* 2009a, 2009b, 2009c).

4.2. Effects of gas-field infrastructure

Infrastructure expansion is a major potential source of future land-cover change on the Yamal. The largest known untapped gas reserves in Russia are currently concentrated on the Yamal Peninsula. The giant Bovanenkovo Gas Field (70°17'N, 68°54'E) is the most developed of about 200 known fields (figure 2). Russia is currently on the verge of approving massive development schemes, but as of yet, none of the gas is being transported. The road and pipeline infrastructure is still small compared to the oil fields in northern Alaska (table 2), but the infrastructure network is expected to expand rapidly when the Yamal is connected to the south by railway, roads and pipelines.

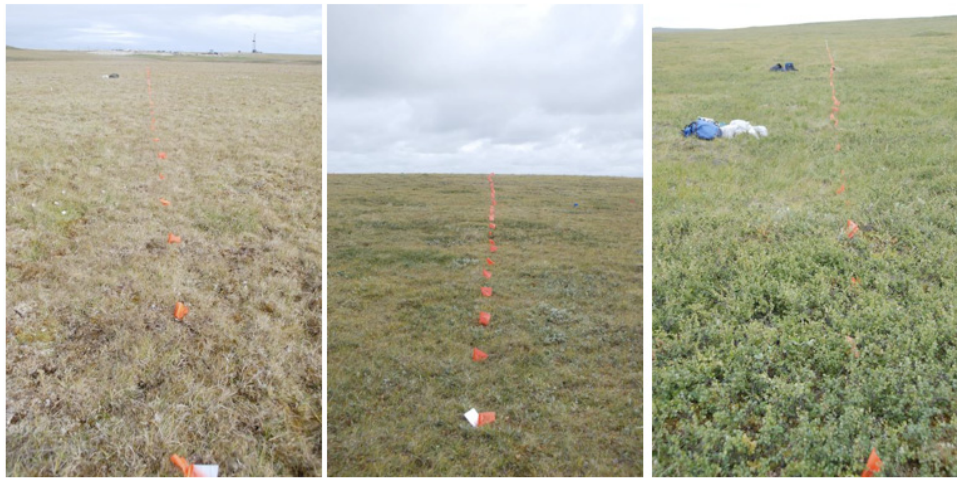


Figure 5. Upland vegetation at three mesic upland sites along the Yamal transect. From north to south: Kharasavey (subzone C) (left); Vaskiny Dachi (subzone D) (middle); and Laborovaya (subzone E) (right). The flags mark transects where biomass, leaf-area index, plant cover, and NDVI measurements were made. Photos by Walker.

Table 2. Area (km²) of infrastructure and related disturbance at Bovanenkovo and North Slope, Alaska. Sources: Bovanenkovo (Kumpula 2008), North Slope (NRC 2003).

Type of impact	Area of impact (km ²)	
	Bovanenkovo, RU	North slope, AK
Construction pads	2.1	24.2
Quarries	4.3	25.8
Roads (all types)	2.9 (79 km)	12.2 (954 km)
Air strips	0	1.2
Total infrastructure	9.3 km ²	63.4 km ²
Other affected areas ^a	24 km ²	7.14 km ²
Total detectable changed area	33.3 km ²	70.5 km ²
Approximate total extent of infrastructure ^b	448 km ²	2600 km ²

^a Includes major ORV trails, debris.

^b Perimeter, including enclosed unimpacted areas, generally not accessible as pasture or other subsistence activities.

Gas development has caused local disturbance to the vegetation in the major gas fields (Vilchek and Bykova 1992, Vilchek 1996, Dobrinsky 1997, Kumpula 2008). For example, within the Bovanenkovo field about 9.3 km² of tundra have been covered in roads, quarries and other infrastructure and another 24 km² have changed vegetation caused mainly by off-road vehicle trails (Dobrinsky 1997, Kumpula 2008, Kumpula *et al* 2008). These disturbances are important to the indigenous Nenets people because they restrict access to about 450 km² of traditional reindeer pasturelands (Kumpula 2008) (table 2).

Presently, the greenness of the vegetation is affected only in the immediate vicinity of roads and off-road vehicle trails and these are not extensive enough to affect the regional NDVI values.

4.3. Effects of reindeer

The Peninsula is home to about 5000 nomadic Yamal Nentsy who migrate with their reindeer up to 1200 km annually

(Stammler 2005). The steady increase of reindeer and humans poses increasing pressures on the tundra vegetation. In 2008, the reindeer population on the Yamal was estimated at 276 200 animals (27 March 2008, message from the chief executive of the Yamalsky District <http://nac.yanao.ru/12/1/419>). The total area of the Yamal reindeer pastures is about 10 600 000 ha. Estimates of total annual consumption per thousand reindeer are: 900 metric tons of lichens, 220 tons of forbs, 600 tons of graminoids, and 679 tons of shrub leaves (Polezhaev 1987). In 2001, when there were 201 000 animals on the Peninsula, it was estimated that the number of animals using the range needed to be reduced by 54% to maintain a healthy range (Morozova and Magomedova 2004). At present it is difficult to assess the effects of reindeer on the regional patterns of NDVI because of the lack of areas where reindeer are excluded that could be compared to the grazed pasturelands. Many upland surfaces across the Peninsula have a mown appearance and there are prevalent trails left by the migrating reindeer.

Additionally, there is some evidence that eolian erosion in sandy parts of the Peninsula is linked to reindeer activities. Although peat accumulation has occurred throughout most of the Holocene, there has been considerable recent reactivation of these sands starting about 1000 yr ¹⁴C BP possibly associated with heavy reindeer grazing starting at about that time (Forman *et al* 2002). Sandy areas are especially sensitive to degradation by reindeer trampling (Forbes and Kumpula 2009). Areas of active eolian activity are concentrated in the windier environments near the coast and where reindeer congregate for relief from insect harassment. In spring when the landscape is still snow covered, animals focus on hilltop areas where lichen cover is the greatest and snow cover is minimal. In their search for lichens, the animals dig into the snow with their hooves and form craters that can also expose the underlying sands. Once exposed by disturbance, the nutrient-poor sands are difficult to revegetate (Forbes and McKendrick 2002).

In the future, the reindeer pasturelands will be increasingly impacted if the reindeer populations continue to increase and if

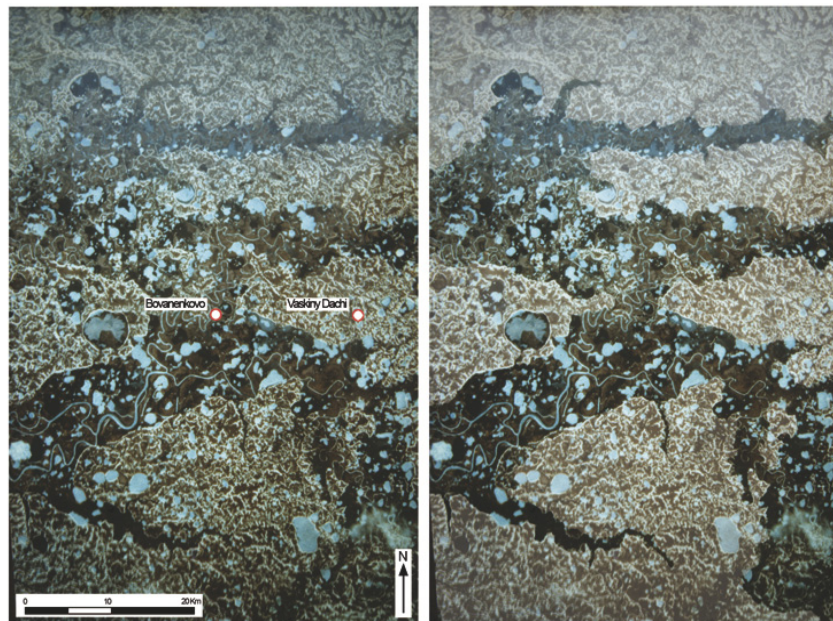


Figure 6. Satellite image of the Bovanenkovo and Vaskiny Dachi region. Meandering rivers on the darker colored floodplains have eroded away the marine terraces that compose the uplands. The right-hand image has the upland areas slightly enhanced to provide more contrast between the broad alluvial valleys and the remnant marine terraces. The lighter colored uplands are highly dissected by mazes of small streams. This early-summer image shows large amounts of snow in the narrow valleys. Abundant landslides occur on the slopes of these small channels (see figures 7–9). The grayish tone of the upper half of the image is due to thin cloud cover. (Derived from a 1991 Walker slide of a hard copy of a RESURS-01 image. The date of the image is unknown, but is likely about 1990–1991 based on extent of gas-field infrastructure.)

access to the pastures are further restricted by the expanding network of roads, railroads, pipelines and other forms of disturbance.

4.4. Effects of thawing permafrost

Ice-rich permafrost underlies much of the Yamal Peninsula. The ice is extensive within the marine terraces and occurs from a few to dozens of meters beneath the surface and varies in thickness from less than a meter to over 40 m (Dubikov 2002, Streletskaia and Leibman 2003). The ice generally lies above salt-rich marine sands deposited during the Late Pleistocene and below marine clays deposited at a later phase of the Late Pleistocene. (See Streletskaia and Leibman (2003) for a description of a sedimentary cross section and history.) One hypothesis for the presence of this ice is that it formed in place through a process of tabular-ice formation (Vtyurin 1975, French and Henry 1990). Following exposure of the sediments to cold temperatures after eustatic or isostatic fall in sea level, water migrated through underlying unfrozen salt-rich marine sands and froze along a boundary beneath overlying marine clays (Dubikov 2002, Leibman *et al* 2003a, 2003b, Streletskaia and Leibman 2003, Streletskaia *et al* 2008). Other hypotheses argue for burial of glacier ice or snow patches (Kaplyanskaya and Tarnogradsky 1982, Moorman and Michel 2000, Svendsen *et al* 2004); however, there is no evidence of glacial ice on the Yamal during the last glaciation, so near-surface massive ice bodies most likely formed through intra-sedimental processes (Streletskaia *et al* 2008).

Thermal erosion of this ice-rich permafrost is occurring at two main scales that are relevant to the analysis of greening patterns on the Yamal. The first is the large-scale erosion associated with big meandering rivers that have eroded broad valleys through the marine terraces (figure 6). Forty-five per cent of the 4406 km² area in figure 6 has been eroded away by the larger rivers during the Holocene. These valleys are up to 10 km wide in the satellite image of figure 6 and much wider near the coast. These valleys are discernable at the 1:7500 000 scale of the Circumpolar Arctic Vegetation Map (CAVM Team 2003) and the 1 km resolution of the AVHRR imagery. In late summer, the valleys are greener than the uplands; the mean AVHRR-derived MaxNDVI of valleys across the Yamal Peninsula is 0.470 compared to 0.455 on the uplands despite many more lakes in the valleys that tend to lower the NDVI (Raynolds *et al* 2008). These valleys were not discernable at the 12.5 and 25 km resolutions of our spatial and temporal NDVI analysis. Satellite views available through Google Earth in late summer (not shown) use Landsat data that show most of the small valleys are much greener than the small hills and interfluvies between the drainages. Finer-scale resolution satellite data will be necessary for future NDVI analysis of these landscapes.

The second relevant scale of erosion is associated with the mazes of smaller drainage networks on the upland marine terraces. These drainage networks are highlighted in figure 6 by white snow that still fills most of the drainages in early summer. The deep snow that accumulates in the concave landslide depressions has large effects on the greenness patterns by providing a summer-long source of moisture.

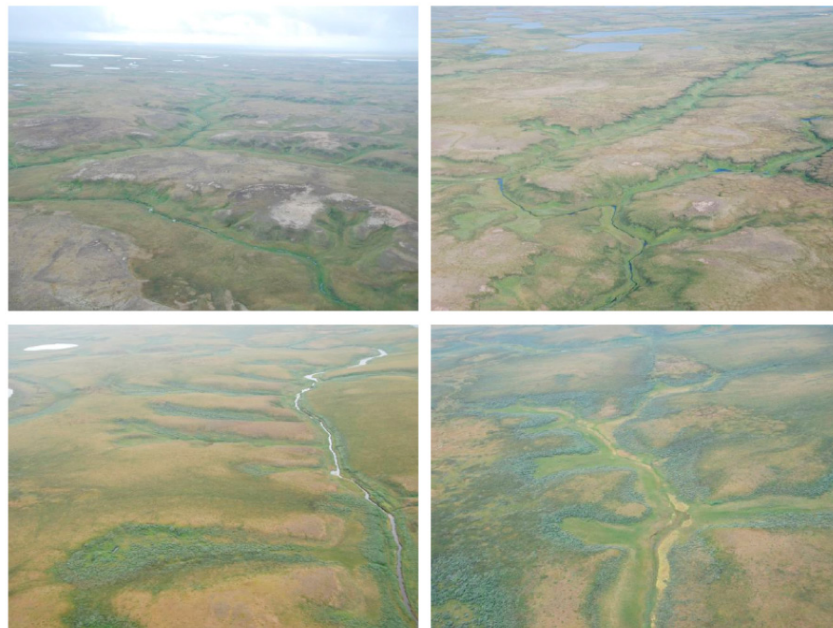


Figure 7. Thermally eroding landscapes on the Yamal Peninsula. Top: areas with sandy uplands. Lightest colored areas on uplands are active areas of wind erosion in sands. Most of the upland vegetation on sandy soil is composed of lichens, prostrate shrubs, grasses and sedges. Green valleys have graminoid, forb meadows. Bottom: several stable landslides along small streams with willow shrubland on relatively stable slopes. Brighter green in valley bottoms are mainly graminoid-forb meadows. Yellow areas are moss-rich sedge meadows. Photos by Walker.

Oblique aerial photos taken from a helicopter illustrate the much greener valleys (figure 7). These small valleys are continually being shaped by landslides (Ukrainitseva and Leibman 2000, Ukrainitseva *et al* 2000). An estimated 70% of the territory around Vaskiny Dachi has been affected by landslides (Ukrainitseva *et al* 2003). Old well-revegetated landslide shear surfaces were dated by radiocarbon from the buried soils to be 300–2200 years old (Leibman *et al* 2003b, 2003a). In August 1989, 400 new landslides occurred within an area of 10 km², where previously there were only three modern landslides (but hundreds of ancient landslides). This was in response to an abnormally wet year when the additional water apparently lubricated the slide surfaces (Leibman and Kizyakov 2007). During the warm summers of 2006–2007 several new areas of tabular ground ice were exposed by landslide activity. In this case, the slides were triggered by increased depth of summer thawing that penetrated into ice-rich sediments. The water from the snow banks that fill the slide depressions also erodes the uplands and further enhances the expansion of the landslides (Leibman 1995, Leibman and Egorov 1996, Leibman *et al* 2003b, 2003a).

Most relevant to the plants and NDVI values are the effects that the landslides have on the substrates available for plants. The landslides affect the thermal, hydrologic, and nutrient regimes of the soils. The slides strip the insulative mat of vegetation from the surface, increasing soil temperatures and active layer thicknesses (Leibman *et al* 2008). The soils on stable hilltops unimpacted by landslides have low acidity (pH 5.5–5.8), very low base saturation (4.5%), low nitrogen content (0.08–0.18%), and rather high organic carbon (1.5–2.3%); whereas, recent landslide surfaces have high soil pH (7.5–8.0), much higher base saturation (50–

100%), and low organic carbon content (0.2–0.7%). On 1000–2000 year old landslides, soils have lower pH (down to 6.5) and base saturation (down to 24.5%) that indicate continuing desalination of the active layer deposits towards the background conditions. Organic carbon and nitrogen concentrations in the older soils were double those of recent landslide surfaces (Ukrainitseva 1998, Ukrainitseva *et al* 2000, 2003, Ukrainitseva and Leibman 2007, Leibman *et al* 2008, Ukrainitseva 2008).

For at least 10 years after the landslides, the shear surfaces are practically bare (Rebristaya *et al* 1997, Leibman and Kizyakov 2007), after which the surfaces are colonized by salt-tolerant species including many grasses (figure 9 top left). Willow thickets occupy older landslide surfaces once the salts have been leached out of the soils (figure 9 top right). Willow thickets (*Salix lanata* and *S. glauca*) cover many hill slopes and valley bottoms where there is enhanced water and nutrient regimes and warmer soils, and especially where there is enhanced (but not the deepest) winter snow cover (Leibman 2004). These willow communities appear to be stable once they are established (Ukrainitseva 2008). Deeper snow areas and concavities of slide areas often have bright green sedge-forb meadows that occupy the continually wet soils (figure 7 bottom right, figure 8 right).

The chemical compositions of the soils and plants are related to the age of the landslide surface. The willows growing on the landslide surfaces have higher nutrient content than plants on stable uplands. Concentrations of C and N increase with age of the landslides, and trace elements in willow branches essentially follow an age sequence—the highest values occur on the modern slides, followed by old and then ancient landslides and finally willows growing on



Figure 8. Landslides in the Yamal region. (Left) active landslide. Note contrast between the older green vegetated landslide slopes and adjacent brown upland above the slope. (Right) eroding landscape with several active landslides near the stream. Upper and more gentle stabilized landslide slopes are covered in low willow shrublands. Browner flat upland surface has tundra with sedges, prostrate-dwarf-shrubs, mosses and lichens. Photos by Walker.



Figure 9. Vegetation on landslides at Vaskiny Dachi, Yamal Peninsula. Left: a recent 1989 landslide shear surface that is naturally revegetated mainly by grasses and forbs (e.g., *Deschampsia sp.*, *Poa Arctica*, *Puccinellia sibirica*, *Phippsia concinna*, *Tripleurospermum hookeri*). Right: Shrubby vegetation (*Salix lanata* and *S. glauca*) on an old landslide surface that flowed from the foreground into the right middle background. Photos by Walker.

stable surfaces (Ukrainitseva and Leibman 2000). The nutrient content of plants growing on landslides may be an important consideration for forage quality for reindeer.

Climatically, Vaskiny Dachi is in bioclimate subzone D on the circumpolar Arctic Vegetation Map (CAVM Team 2003). The typical zonal vegetation of subzone D is low-growing sedges, dwarf shrubs, and mosses (including *Carex bigelowii*, *Vaccinium vitis-idaea*, *Salix polaris*, *S. phylicifolia*, *Betula nana*, *Hylocomium splendens*, *Aulacomnium turgidum*). Normally in subzone D dense shrublands are found only in places where there are abundant nutrients and warmer soils such as along streams and in association with anthropogenically disturbed sites—but not dominating the landscape as they do in many areas of the Yamal. The disturbances associated with landslides leads to a succession of vegetation types that culminates in greener vegetation that is more typical of the shrub tundra found in bioclimate subzone E.

The satellite-derived temperature data (figure 2(a)) and a few air-temperature data available from inland parts of the Yamal Peninsula (Belopukova *et al* 1989) indicate that inland parts of the Peninsula are warmer than portrayed on the bioclimate subzone map. The bioclimate boundaries need to be revised to show cooler temperatures near the coast and warmer temperatures inland and a general shift of the zonal boundaries northward.

4.5. NDVI as an integrator of landscape change

The situation on the Yamal Peninsula illustrates the difficulty of ascribing changing NDVI patterns to any single climate or land-cover-change factor. The diagram in figure 10 summarizes the ecological and social factors that influence the NDVI. Temporal changes to NDVI occur in response to a complex hierarchy of factors that affect the fraction of photosynthetically active radiation absorbed by the vegetation canopy (figure 10).

The most proximate factors affecting NDVI are aspects of the plant canopy itself (e.g., color of the leaves, horizontal and vertical structure, plant health) ('vegetation factors', light green ellipse in figure 10). These are influenced by 'site factors' of the plant environment (Raup 1969), including the microclimate, landforms, hydrology, permafrost, site stability, and soil, which influence the availability of heat, light, water, nutrients and the photosynthetic output of plants (brown ellipse in figure 10). The complex of factors has also been called the 'holocoenotic environmental complex' (Billings 1952).

Changes to the site factors occur in response to 'disturbance factors' (gray ellipse in figure 10) operating at a variety of spatial and temporal scales (Walker and Walker 1991). Slow changes involve landscape evolution, plant succession and changes to the climate. Abrupt changes occur in relation to sudden physical disturbance such as severe weather events, fire, various types of sudden

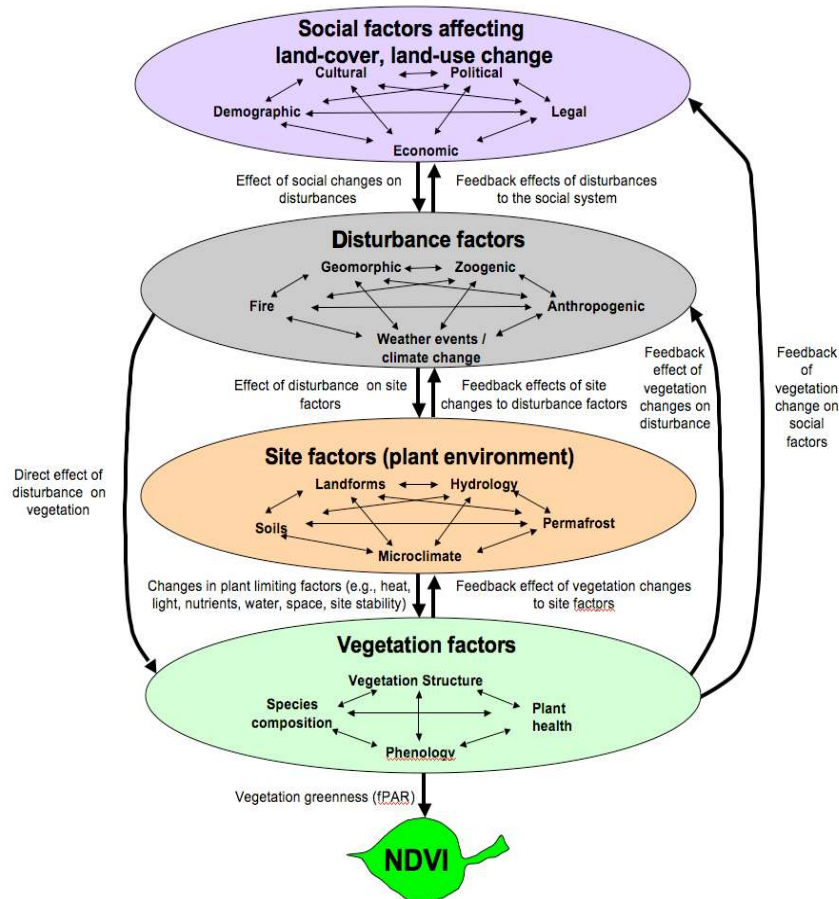


Figure 10. Hierarchy of factors affecting vegetation greenness.

geomorphic change (e.g., landslides, large floods), human-related disturbance, (e.g., infrastructure placement, vehicle trails, dust deposition, and oil spills), or zoogenic disturbances (e.g., trampling and grazing by reindeer or insect infestations)

These disturbances can be caused by natural environmental factors or by events triggered by human activity ('social factors', violet ellipse in figure 10) (Chapin *et al* 2006). Humans have only recently affected large-scale land-cover change in the Arctic. For example, on the Yamal the density of people and their reindeer strongly influence vegetation patterns. Similarly, decisions related to resource development have great potential to affect much a larger area of the Yamal Peninsula in the future.

The early goals of this study were to see if there are disturbance factors that are sufficiently large to contribute to the regional spatial and temporal patterns of NDVI as seen from space. The greening patterns associated with the permafrost thawing and erosion of the uplands are sufficiently large in scale to affect the greenness patterns over large parts of the Peninsula, but it is currently not known if these patterns are changing at a rate that is affecting the regional NDVI patterns. Clearly other disturbance factors are linked to the permafrost issues. For example, a warming climate and enhanced winter snow will likely exacerbate positive feedbacks between climate and permafrost thawing. Further research is needed to determine if erosion is occurring rapidly

enough or at sufficiently large spatial scales to be a factor in future greening trends or in planning needed for infrastructure placement. Also, increased landslides combined with surface warming would likely cause willow shrublands to expand more rapidly northward and this could affect how reindeer utilize the landscapes and the management of reindeer herds. Future studies will examine how the Nentsy and their reindeer interact with the mosaic of landscapes and vegetation on the Yamal.

5. Conclusions

- (1) NDVI patterns on the Yamal are only weakly correlated with the land temperatures and are most strongly related to differences in landscape factors associated with the greener valleys and browner uplands. Satellite-derived land temperatures and available air temperature data indicate that inland areas are warmer than portrayed on the current bioclimate map (figure 1 inset map). The MaxNDVI was expected to increase toward the south with warmer temperatures, but complex eroded landscapes and reindeer yearly graze most surfaces and confound the NDVI patterns.
- (2) MaxNDVI has increased only slightly on the Yamal during the 26 years of satellite observations in strong contrast to patterns observed in Alaska and North America.

- (3) Expanding gas development affects the NDVI patterns at local scales near roads and off-road vehicle trails but currently does not affect the regional NDVI patterns.
- (4) It is presently not possible to determine the effects of reindeer on greening patterns because of the lack of control areas where reindeer are excluded. Long-term experiments using fenced areas to exclude reindeer are needed.
- (5) Satellite images taken in late spring during snowmelt reveal highly dissected uplands that are a result of erosion of massive tabular ice in the uplands. Deep snow collects in the valleys and is responsible for irrigating the hill slopes and leads to further erosion of the slopes. The concavities from the landslides collect moisture, causing the much greener and more nutrient-rich vegetation in the valleys, which undoubtedly contributes to the overall higher-than-expected overall NDVI of the Yamal Peninsula. A warming climate and enhanced winter snow will likely exacerbate positive feedbacks between climate and permafrost thawing. Further research is needed to determine if erosion is occurring rapidly enough or at sufficiently large spatial scales to be a factor in future greening trends. Future studies using higher resolution satellite imagery will help resolve the complex NDVI patterns in these complex landscapes.
- (6) This paper examined NDVI, climate and disturbance on the Yamal to see what factors are affecting the NDVI patterns as seen from space. At the scale of our analysis, it was not possible to detect major changes in NDVI over the period of the satellite record. The ground observations did, however, establish that the NDVI patterns are the result of complex interactions between a variety of different types of ecological and social factors (figure 10). The NDVI should be viewed as powerful tool for monitoring the net cumulative effect of these factors.

Acknowledgments

US support came from NASA Land Cover Land Use Change Program, Grant No. NNG6GE00A, and NSF Grant No. ARC-0531180, part of the Synthesis of Arctic System Science initiative. Finnish participation came from the Environmental and Social Impacts of Industrial Development in Northern Russia (ENSINOR) sponsored by the Russia in Flux program of the Academy of Finland (Decision #208147). The Russian colleagues were supported by the Russian Academy Science through the Earth Cryosphere Institute in Tyumen and Moscow. The project is part of the Greening of the Arctic project of the International Polar Year (IPY) and the Northern Eurasia Earth Science Partnership Initiative (NEESPI). Support from the Institute of Arctic Biology at the University of Alaska is gratefully acknowledged.

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