Circumpolar Relationships Between Permafrost Characteristics, NDVI, and Arctic Vegetation Types

Martha K. Raynolds and Donald A. Walker
University of Alaska Fairbanks

Abstract

An understanding of the distribution and characteristics of vegetation found on different types of permafrost is necessary input for modeling permafrost response to climate change. Interactions between climate and soil thermal regime are modified where vegetation exists, and >75% of permafrost on land in the Arctic is covered by non-barren vegetation types. A circumpolar spatial analysis was conducted to compare mapped permafrost characteristics with the Normalized Difference Vegetation Index (NDVI), mapped vegetation types, and environmental characteristics. A General Linear Model (GLM) analysis found that, when added to a model that included climate and lake cover, permafrost characteristics accounted for an additional 11% of the variation in NDVI. High ice content in permafrost had the strongest effect, lowering NDVI. Over 65% of areas with thin overburden is vegetated by low-stature, low-cover, low-biomass vegetation types that have little impact on thermal regimes. This climbs to >82% for areas that also have high ice content permafrost. Over 83% of areas with thick overburden have vegetation types with denser, taller vegetation, which alters the interaction between climate and permafrost. Including vegetation characteristics in permafrost models will be particularly important in areas with thick overburden and medium or high ice content.

Keywords: arctic vegetation; Circum-Arctic Map of Permafrost and Ground Ice Conditions; Circumpolar Arctic Vegetation Map; NDVI; permafrost.

Introduction

Permafrost, its characteristics, and its vulnerability to change are increasingly in the public eye as a result of attention focused on climate change and the Arctic. Climate change is occurring at a faster rate in the Arctic than other biomes and is resulting in an increase in temperatures in almost all parts of the Arctic (Comiso 2006, Hassol 2004). The effects on the Arctic Ocean have resulted in dramatic loss of summer sea ice, especially in the summer of 2007 (Comiso et al. 2008). The effects on land, both to permafrost and vegetation, are a focus of on going research, particularly during the 2008 International Polar Year.

Most permafrost, even in the Arctic, is covered with vegetation, and the interactions between the permafrost and the vegetation affect both the growing environment for arctic plants and the thermal environment of the permafrost. Permafrost strongly affects vegetation by affecting landscape and soil characteristics. Permafrost underlying the annually-thawed active layer limits soil drainage and results in cryogenic features such as polygons, gelification lobes, circles, and mounds (Washburn 1980). Permafrost ice content can raise surface elevations through aggradation or lower it due to degradation (Jorgenson et al. 2001). Permafrost affects the characteristics of the active layer, such as its depth, soil temperatures, and soil moisture (Schuur et al. 2007).

Vegetation affects permafrost by changing the thermal characteristics of the soil. Vegetation shades and insulates the soil, reducing the transfer of summer warmth (Kade et al. 2006, Shur & Jorgenson 2007). Vegetation also cools the surface through evapotranspiration. Vegetation has the opposite effect in winter; well-vegetated areas are insulated by the plants and the snow they trap, while unvegetated soils are more exposed to winter temperatures (Kade et al. 2006). The types and strength of the effect of vegetation on the climate-soil interactions vary with vegetation type and depend on the amount of total plant biomass, plant lifeforms, and continuity of plant cover (Kade et al. 2006, Walker et al. 2003).

In order to understand the effects of climate change on permafrost, it is important to understand the distribution of vegetation types in permafrost areas and the characteristics of those vegetation types that affect the thermal regime of the soil. This study compares vegetation distribution in the Arctic, the area north of the treeline, with permafrost characteristics. The vegetation was characterized using both a vector vegetation map and satellite raster data of the normalized difference vegetation index (NDVI). This spatial comparison of arctic vegetation types and NDVI with permafrost distribution help define areas where vegetation has the strongest influence on permafrost, with implications for the possible effects of climate change.

Methods

The permafrost map

The extent and ground ice content of permafrost and depth of overburden in the Northern Hemisphere (20°N to 90°N), were mapped on the Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al. 1997, http://nsidc.org/data/ggd318.html), and summarized by Zhang et al. (1999). The map was printed at 1:10,000,000 scale, and the digital format at 12.5-km pixel resolution was used for this study. Permafrost extent was mapped as continuous (94% of Arctic land area), discontinuous (3%), sporadic (2%), or isolated (1%). Ground-ice content was divided into low
The normalized difference vegetation index (NDVI) is a measure of relative greenness calculated as: NDVI = (NIR - R) / (NIR + R), where NIR is the spectral reflectance in the near-infrared where reflectance from the plant canopy is dominant, and R is the reflectance in the red portion of the spectrum where chlorophyll absorbs maximally. NDVI has a theoretical maximum of 1 and its relationship to vegetation characteristics such as biomass, productivity, percent cover, and leaf area index is asymptotically nonlinear as it approaches 1. As a result, NDVI is less sensitive to ground characteristics at higher values and essentially saturates when leaf area index >1 (van Wijk & Williams 2005). This is not a severe problem in the Arctic where vegetation is often sparse and patchy; the mean NDVI for arctic land areas in the data set used in this study was 0.32, well below the saturation value of 1 and its relationship to vegetation characteristics such as biomass, productivity, percent cover, and leaf area index is asymptotically nonlinear as it approaches 1. As a result, NDVI is less sensitive to ground characteristics at higher values and essentially saturates when leaf area index >1 (van Wijk & Williams 2005). This is not a severe problem in the Arctic where vegetation is often sparse and patchy; the mean NDVI for arctic land areas in the data set used in this study was 0.32, well below the saturation point (Raynolds et al. 2006).

NDVI values in the Arctic increase with the amount of vegetation as measured by leaf area index (LAI), phytomass, and productivity (Riedel et al. 2005, Shippert et al. 1995). NDVI values correlate well with ground characteristics of arctic vegetation and can be used to distinguish between vegetation types (Hope et al. 1993, Stow et al. 2004).

A 1-km-resolution maximum-NDVI data set was used for this study. These data were derived from the U.S. Geological Survey EROS AVHRR polar composite of NDVI data for 1993 and 1995 (CAVM Team 2003, Markon et al. 1995). Daily data were collected by AVHRR sensors onboard NOAA satellites for channel 1, red (0.5 to 0.68 µm) and channel 2, near-infrared (0.725–1.1 µm). Satellite measurement of NDVI is affected by a variety of conditions, especially cloud cover, viewing angle and seasonal variation, that can be compensated for by compositing data over time (Goward et al. 1991, Riedel et al. 2005). Daily NDVI values were composited into 10-day maxima. The maximum values of these composited data during two relatively cloud-free summers (11 July–31 August in 1993 and 1995) were used to create an almost cloud-free data set of maximum NDVI for the circumpolar Arctic in the early 1990s.

The vegetation map

The third data set used in this analysis was the Circumpolar Arctic Vegetation Map (CAVM Team 2003, http://www.arcticatlas.org/atlas/cavm). The map extent includes all land areas north of the northern limit of trees. The map was created at 1:7,500,000 scale with minimum polygon diameter of 8 km and is available digitally as a vector map. The integrated vegetation mapping approach used to create the vegetation map was based on the principle that a combination of environmental characteristics controls the distribution of vegetation. Vegetation-type boundaries were based on existing ground data and vegetation maps, bioclimate (Tundra Subzones A–E), floristic regions, landscape categories, elevation, percent lake cover, substrate chemistry, and surficial and bedrock geology, drawn on an AVHRR false-color infrared base map. The distribution of 15 arctic vegetation types (Table 1) was mapped and described on the CAVM, using a unifying circumpolar legend which enables analysis of the entire Arctic (CAVM Team 2003, Walker et al. 2005).

Analysis

In each of the permafrost categories the area of different vegetation types and average NDVI values were tabulated. Spatial-distribution characteristics were analyzed using GIS software. The CAVM was mapped at finer resolution than the permafrost map, so the most common permafrost category for each CAVM polygon was determined. Results of the analysis were summarized graphically, showing vegetation types occurring on different types of permafrost, using symbols proportional to area. The NDVI raster data were analyzed by calculating the average NDVI value for different categories within the permafrost map and summarizing these results using bar graphs. This analysis of over 7 million 1-km² pixels represents the true mean of the classes, so comparative statistical tests based on sampling were not appropriate.

General linear models (GLM) (R Development Core Team 2006) were run to determine the importance of permafrost variables in accounting for variation in NDVI in the Arctic. Attributes mapped as characteristics of the CAVM polygons, weighted by area, were used as input data. A basic model
including variables known to be important in controlling NDVI (Raynolds et al. 2006) was run first, using the CAVM classes for bioclimate zone and percent lake cover. These variables accounted for the latitudinal variation in NDVI due to climate, and for the reduction in NDVI due to cover of water (NDVI of water is essentially zero). Variables from the permafrost map: extent, ice content, overburden, and the combined code (a unique number for each combination of extent, ice content, and overburden) were added to the model one at a time to evaluate their effect on the model. The amount of variation accounted for by the different variables in each model and the significance of the variable in the model were tabulated.

*Interdependence of data sets*

Climate and landscape characteristics including slope, elevation, geologic and glacial history have important effects on all three variables: NDVI, permafrost and vegetation. In some cases these characteristics will vary together, especially in extreme conditions. For example, steep, high elevation mountains will generally have low NDVI, continuous, low ice-content permafrost with little overburden, and barren vegetation types. In more moderate terrain the type of vegetation which will grow on a given type of permafrost varies. In these areas the vegetation map and the NDVI data provide valuable information about the distribution of vegetation on different types of permafrost.

*Results*

Most of the Arctic has continuous permafrost underlying 4.68 million km$^2$ of land surface (excluding ice and water). Arctic areas without continuous permafrost include southern Greenland, European Arctic Russia, and in Alaska the Seward Peninsula and southern parts of the Kuskokwim River Delta. Continuous permafrost in the Arctic supports a mix of vegetation types. Over 83% of areas with thick overburden commonly is vegetated by erect shrub tundras (S1, S2), graminoid-shrub tundra (G3, G4), or low-shrub wetlands (W3) (Fig. 1). All of these vegetation types have relatively high stature, high biomass, and complete cover (Walker et al. 2005). Over 65% of areas with thin overburden have barren vegetation types (B1-B4), sparse graminoid (G1, G2), or prostrate dwarf-shrub (P1, P2) vegetation types with low stature, low biomass, and partial ground cover (Walker et al. 2005). Areas with thin overburden and high ice content are likely to be vegetated with either cryptogam, herb barrens (B1), graminoid, prostrate dwarf-shrub (G2), or prostrate dwarf-shrub herb tundra (P1), with >82% of these areas vegetated by vegetation types that have low stature, low cover, and low biomass.

In areas of discontinuous permafrost, tussock tundra (G4) and erect-shrub (S1, S2) vegetation types are common. Areas with sporadic permafrost support mostly low-shrub vegetation (S2) and sedge, moss, low-shrub wetland (W3). Areas with isolated permafrost are dominated by non-carbonate mountain vegetation complexes (B3).

Low ice-content permafrost is characterized by barren types (B2, B3) and shrub types (S1, S2). Medium ice-content permafrost supports graminoid- (G4) and shrub-dominated (S1, S2) vegetation, as well as wetlands (W3). High ice-content permafrost is most commonly vegetated by graminoid-dominated vegetation types (G2, G3, G4), prostrate dwarf-shrub (P1), or cryptogam barrens (B1).

Examination of the types of permafrost that characterize vegetation types reveals that only three vegetation types have <90% continuous permafrost: non-carbonate mountain complex (B3); low shrub tundra (S2); and sedge, moss, low-shrub wetland (W3). Vegetation types that occur mostly on low ice content permafrost include the barren types (B2,
B3, B4) and types common on the Canadian Shield (P2, S1). Cryptogam herb barrens (B1) characteristic of the High Arctic and wetland vegetation types (W1, W2, W3) occur mostly on medium or high ice content permafrost. Tussock sedge, dwarf-shrub, moss tundra (G4) occurs mostly on areas with thick overburden and medium or high ice content.

NDVI varied inversely with permafrost extent, increasing from continuous to discontinuous to sporadic (Fig. 2), as would be expected, following the climate gradient from colder to warmer (Raynolds et al. 2006). NDVI was lowest for isolated permafrost, which occurred mostly in the mountainous areas of southern Greenland, where steep slopes and exposed bedrock limit plant cover.

The largest differences in NDVI values occurred between overburden categories; NDVI was much greater in areas with thick overburden than with thin (Fig. 3). Thin overburden occurs in glaciated areas such as the Canadian Shield, on mountains, ridges, and plateaus. Thick overburden is less common in the Arctic and occurs at lower elevations and in depressions where sediments can accumulate. Areas with thick overburden are more commonly vegetated by graminoid (G3, G4) or erect-shrub (S1, S2) vegetation types with high NDVI values, while areas with thin overburden often have sparse vegetation with low NDVI values (B1, B2, B3, Fig. 1).

NDVI values varied less by ice content within overburden types (Fig. 3). High and medium-to-high ice-content permafrost had lower NDVI than average. Areas with thick overburden and high ice-content permafrost are more commonly covered by graminoid vegetation types, while medium ice-content permafrost areas are more commonly vegetated by shrub-dominated types (Fig. 1). Areas with thin overburden and medium-to-high ice-content permafrost mostly occur in high-latitude areas (such as the Canadian Arctic Islands), and have barren or sparse, prostrate vegetation (B1, P1, G2).

Permafrost characteristics accounted for 11.9% of the variation in arctic NDVI in a general linear model that included bioclimate zone, percent lake cover, and permafrost characteristics (Table 2). The CAVM variables accounted for 54.9% of the variation, with bioclimate zone responsible for 38.6% and percent lake cover for 16.3%. Permafrost ice content accounted for more of the remaining variation than either extent or depth of overburden.

Discussion

The comparison of the Circum-arctic Map of Permafrost and Ground Ice Conditions, the Circumpolar Arctic Vegetation Map, and satellite NDVI values emphasized the importance of the difference between areas with thick overburden (>5–10 m) and thin overburden (<5–10 m). The thick overburden areas had NDVI values almost twice as high as those of the thin overburden areas, indicating a much greater amount of vegetation cover (Shippert et al. 1995). NDVI would be expected to be lower in areas with thin soils, but the distinction between overburden <5 m and >5 m occurs far below the rooting depth of arctic plants. GLM models showed that once climate and percent lake cover were accounted for, overburden depth was much less important. Areas with thin overburden had more lake cover (especially on the Canadian Shield) and a more northerly distribution than areas with thick overburden, both effects reducing the average NDVI.

The model results showed that ice content correlated with variation in NDVI, and the map summaries showed that medium-high ice-content permafrost with thin overburden has especially low NDVI values. These conditions occurred mainly in the northern areas of the Arctic: the Canadian Arctic Islands and Novaya Zemlya.

About one quarter of the Arctic land area is covered by barren vegetation types. In these areas the vegetation plays a minimal role in the soil thermal regime, and the permafrost is climate-driven. The rest of the continuous permafrost in the Arctic would be considered climate–driven, ecosystem-modified permafrost, according to Shur & Jorgenson (2007). The effect of the vegetation modification is to reduce soil temperatures in summer and to increase them in winter (Kade et al. 2006). Vegetation types that have the most plant cover, thickest moss layers, and deepest organic soils insulate the soil most from summer warming (Kade et al. 2006). Types with the tallest vegetation trap the most snow in winter and
The net effect of vegetation on soil thermal regimes depends largely on the thickness of the moss/peat layer and the height of the vegetation. For example, tussock tundra (G4) at Happy Valley on the North Slope of Alaska has a thick peat layer (12 cm) developed from dead tussocks and mosses, a relatively thick layer of live moss (5 cm), and also a dwarf-shrub layer (25 cm tall) (Walker et al. in press). The vegetative factors in tussock tundra decreasing absorption of summer warmth by the soil outweigh the factors warming the soil in winter, resulting in thinning of the active layer and aggradation of ice at the top of the permafrost (Shur & Jorgenson 2007). This process had been recognized by arctic researchers as paludification, a process whereby soils become progressively wetter and more acidic as reduced thaw depth restricts soil drainage (Mann et al. 2002, Walker et al. 2003). The shallower thaw and saturated soils in turn favor peat-producing species like sphagnum mosses and tussock sedges in a positively reinforcing cycle.

The vegetation types with characteristics resulting in the greatest effect on the soil thermal regime are graminoid-erect dwarf-shrub (G3, G4, W3) and erect-shrub (S1, S2) types (Walker et al. in press). These vegetation types are common in areas with thick overburden and medium or high ice-content permafrost, which occur mostly in the foothills and coastal plains of the southern Arctic. These vegetation types are also common in areas with thin overburden and low ice-content permafrost, which occur mostly on the Canadian Shield and mountainous areas.

Areas with thin overburden and low-ice content permafrost are shown as having mostly low to medium risk of subsidence due to climate change in a study that modeled IPCC climate predictions, soils, and permafrost data (Nelson et al. 2001). Risk of subsidence increases with ice-content, and areas with medium and high ice content permafrost on deep overburden are more commonly mapped as having medium or high risk of subsidence (Nelson et al. 2001).

Medium ice-content permafrost extends into discontinuous and sporadic permafrost where the permafrost is preserved by the effects of the vegetation (climate-driven, ecosystem-protected, Shur & Jorgenson 2007). Although researchers have recognized the importance of predicting the effects of climate change on permafrost in these areas because of the high risk of subsidence (Nelson et al. 2001), the complex interactions between the climate, the vegetation, and the soil are difficult to quantify. Vegetation cover varies from shrub- (42% S2, 13% S1) to graminoid-dominated (14% G4, 5% G3), and 20% of the area is wetlands (W3), in a mosaic of vegetation types with differing thermal attributes. Not surprisingly, different models project either thawing or persistence of this permafrost (Anisimov & Reneva 2006). Spatially detailed models that include vegetation data will be required to understand the effects of climate change on permafrost in these areas.

An additional complicating factor is that vegetation is not a static characteristic but will in many cases change in response to changes in permafrost. Changes in surface elevation and stability due to subsidence and erosion will change vegetation, usually to wetter types (Jorgenson et al. 2006). Increases in active layer depths in southern tundra are likely to increase shrubbiness (Schuur et al. 2007). Complete thawing of permafrost that allows previously saturated soils to drain will improve conditions for tree-line advance (Lloyd et al. 2003).

**Conclusions**

This study highlights both the effects of permafrost on vegetation, and conversely, the effects of vegetation on permafrost. A GLM analysis found that when added to a model that included climate and lake cover, permafrost characteristics accounted for an additional 11% of the variation in NDVI. High ice-content permafrost with shallow overburden was most strongly correlated with lower NDVI.

Over 75% of permafrost on land in the Arctic is covered by non-barren vegetation types, resulting in some degree of ecosystem-modification of the permafrost. Vegetation insulates the soil from both summer warmth and winter cold, with the net effect depending on vegetation characteristics. Thick moss layers and erect shrubs have the greatest effects on soil thermal regimes, and vegetation types with both occur in areas with medium to high ice-content permafrost and in areas of non-continuous permafrost. Including thermal characteristics of vegetation and the spatial distribution of different vegetation types, though complex, will be important for predicting the effects of climate change on permafrost in these areas.

**Acknowledgments**

Research for this publication was supported in part by a Univ. of Alaska International Polar Year (IPY) graduate fellowship through the Cooperative Institute for Arctic Research (CIFAR) with funds from NOAA under cooperative agreement NA17RJ1224, and NSF grants ARC-0531180 and ARC-0425517. Comments from three anonymous reviewers were very helpful in revising and focusing the paper.
References


