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Changes in Alaskan Tundra Ecosystems Estimated from MODIS Greenness Trends, 2000 to 2010

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Abstract

Trends in the monthly moderate resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) time-series were analyzed for tundra ecosystems of Alaska over the past decade. Results showed that 10% of all tundra-dominated areas in Alaska were detected with significant (p<0.05) positive or negative MODIS growing season EVI trends from 2000 to 2010. Nearly three-quarters of these pixel areas were detected with significant positive growing season EVI trends. This 3:1 ratio of positive to negative EVI trends was consistent across both wetland and non-wetland tundra cover categories. Ecoregions of Alaska that revealed the highest density of positive areas for tundra growing season EVI slope were along the Pacific coast, namely the western Arctic Foothills, the Seward Peninsula, and the southern coastal plain. Associations between annual temperature and moisture patterns and tundra EVI trends across these regions revealed that change patterns in both the climate moisture index (CMI) and growing degree days (GDD) were related to increasing tundra EVI growing season trends. Results showed a notable association between the largest positive trends in MODIS greenness and annual warming trends of greater than 2 GDD per year.

Keywords: MODIS EVI; Tundra; Wetlands; Wildfire; Alaska

Introduction

Climate is changing worldwide, but Arctic Alaska is warming at a rate almost twice the global average [1]. Changes already observed in Alaskan landscapes include rapidly eroding shorelines, melting ground ice (permafrost), wetland drying, ice wedge degradation, increased shrub growth at high latitudes, and conifer forest decline [2-4]. Sustainable ecological function, community resiliency, and threatened species are all at stake in Alaska [5,6].

Satellite remote sensing has been show to be an accurate method to monitor large-scale regrowth of green vegetation cover and productivity, especially following disturbance [7-10]. There have been numerous previous studies of satellite greenness index patterns in Alaska and arctic North America. For example, Jia et al. [11] analyzed 21 years (1981-2001) of AVHRR-NDVI (Advanced Very High Resolution Radiometer-Normalized Difference Vegetation Index) data for three bio-climatic subzones in northern Alaska and confirmed a long-term trend of increase in vegetation greenness for the Alaskan tundra. This study reported a 17% increase in peak vegetation greenness across the region (corresponding to simultaneous increases in air temperatures), and field sampling throughout the region revealed that NDVI explained over 82% of total above-ground plant biomass. Goetz et al. [12,13] analyzed the seasonal and inter-annual variations of post-fire forest cover by using AVHRR-NDVI time-series across boreal North America and reported vegetation compositional changes consistent with early successional plant species and susceptibility to drought. Beck and Goetz [14] reported that increases in tundra productivity from satellite observations for the North Slope of Alaska do not appear restricted to areas of high shrub cover, and that enhanced productivity was found across mixed vegetation types that include graminoids [15].

Other mechanisms of change in tundra and boreal ecosystems have also been studied with remote sensing. In areas on the North Slope of Alaska where topography strongly controlled the flow and redistribution of surface water, NDVI change was found to be strongly related to the variability in the depth of the active (thawed) soil layers of tundra [16]. Kim et al. [17] further examined changing soil freeze-thaw signal from satellite microwave remote sensing and vegetation greenness patterns for the 9-year (2000-2008) vegetation record from satellites over North America, and reported that the relationship between the non-frozen period (June-August) and mean summer greenness index anomalies was generally positive for tundra and boreal forests areas of Canada.

In this study, we utilized NASA MODerate resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) satellite data in new ways to examine the changes in tundra ecosystems of Alaska over the time period from 2000 to 2010 (Figure 1). We overlaid recently published map data on Alaska wetland cover from [18] to separate (periodically) inundated tundra ecosystems from drier upland tundra cover, and separated burned areas into classes, all to improve interpretations of climate variations associated with changes in growing season EVI.

Methods

Collection 5 MODIS data sets beginning in the year 2000 were obtained from NASA's Land Processes Distributed Active Archive Center site [19]. MODIS EVI values were aggregated to 8-km resolution from MOD13C2 (MODIS/Terra Vegetation Indices) products. MOD13C2 data are cloud-free spatial composites of the gridded 16-day 1-kilometer MOD13A2 product, and were provided monthly as a level-3 product projected on a 0.05 degree (5600-meter) geographic Climate Modeling Grid (CMG). Cloud-free global coverage at 8-km spatial resolution was achieved by replacing clouds with the historical

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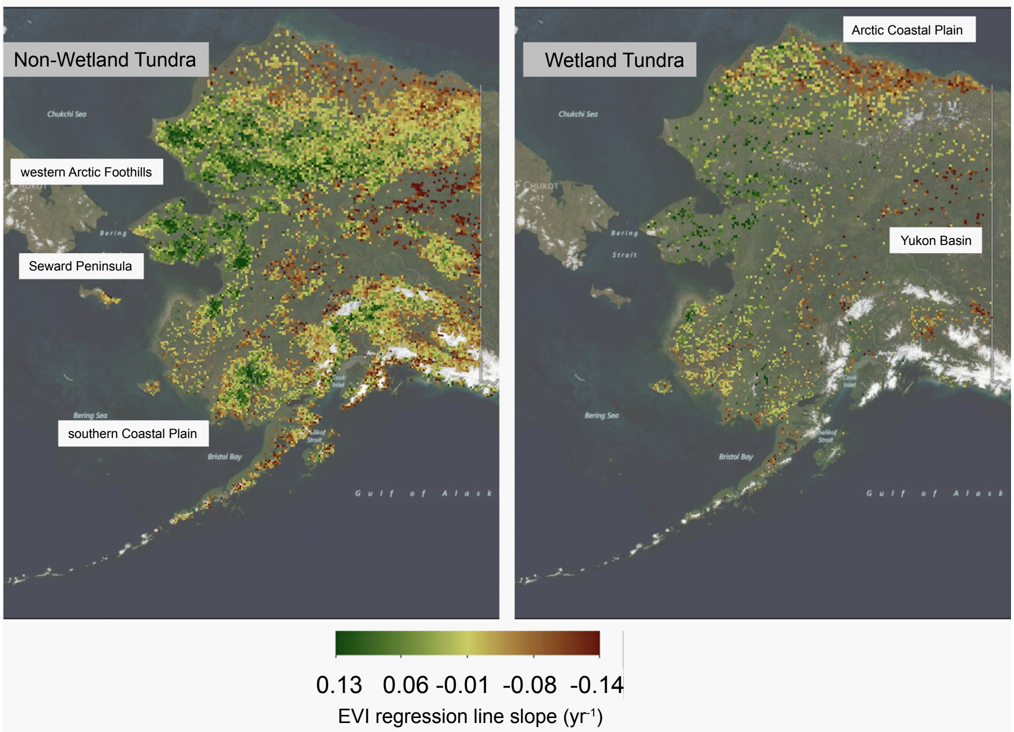

Figure 1: Maps of the regression slopes of summed growing season MODIS EVI (scaled from 0 to 1.0) over the period 2000 to 2010 for nearly 940,000 km² of all unburned (since 1940) tundra ecosystem areas in Alaska. Dark green shades indicate a positive slope of increasing growing season EVI, whereas brown shades indicate a negative slope of decreasing growing season EVI. Non-wetland (left panel) and wetland-dominated (right panel) tundra areas were separated. Ecoregion labels follow Nowacki et al. (2002).

MODIS time-series EVI record. MODIS EVI was calculated from red, blue and NIR bands as described by Huete et al. [20]. Monthly EVI values were summed across each six-month growing season period (May through September) to represent the variability in vegetation productivity for the past 11 years.

MODIS EVI was scaled from its original values to a range of 0 to 1.0 for time-series regression analysis. Slope values indicate the change in summed growing season EVI per year over the period 2000 to 2010. Positive slope values indicate greening over time. According to the values of the slope and the coefficient of determination (R^2) of the EVI time-based regressions, all ecosystem pixels were classified into one of three categories: (1) Pixels with a positive trend, where Slope>0 and a 95% statistical level of significance for a two-tailed *t*-test ($R^2 \geq 0.37$) at a sample size of 10 years; (2) Pixels with a negative trend with a 95% level of significance (where Slope<0 and $R^2 \geq 0.37$); or (3) Pixels with a non-significant trend (R^2<0.37, Slope>0, or Slope<0).

General vegetation cover classes from MODIS 1 km global products (MCD12Q1) were aggregated to 8 km resolution for exclusion of non-tundra (e.g. forest, cropland, or urban) ecosystem areas from the analysis. The Alaska wetland map developed by Whitcomb et al. [18] from satellite radar was also aggregated from its original 100-meter resolution to generate a 8-km resolution statewide layer with a threshold setting of 50% or higher wetland area coverage within each 8x8 km grid cell. Wetland types included in this layer were listed by Whitcomb et al. [18] as combinations of estuarine (tidal inlet), lacustrine (lakes), or palustrine (bogs and fens) with scrub/shrub, emergent, or moss/lichen vegetation cover.

Tundra areas burned by wildfires in Alaska since 1940 were delineated from the polygon boundary files of the Alaska Interagency Coordination Center (AICC). Prior to 1987, only fires in excess of 1000 acres (405 ha) coverage were included in this fire history database, whereas after 1987, all fires in excess of 100 acres (40.5 ha) were included.

We combined MODIS trends with climate datasets from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (R1) database [21]. For the purposes of this study, monthly air temperature (2000-2010; mean, maximum, minimum), and monthly total precipitation (PPT, 1999-2010) were extracted from NCEP R1.

Monthly potential evapotranspiration (PET) from global sources [22] were also prepared for analysis. Annual climate indexes for each year 2000-2010 were calculated from these monthly meteorological datasets to use as independent explanatory variables. The climate index selection was based on previous study results from Potter and Brooks [23], which showed that degree days, annual precipitation totals, and an annual moisture index together can account to 70-80% of the geographical variation in the global vegetation seasonal extremes. Selected indexes in this study included: the climate moisture index [24] and growing degree days (GDD). The CMI indicator ranged from -1 to +1, with negative values for relatively dry years, and positive values for relatively wet years.GDD was computed as the number of days for which mean monthly temperature was greater than 0°C.

The "Breaks for Additive Seasonal and Trend" method [25,26] was further applied to the EVI monthly time series for annual trend characterization. de Jong et al. [27] analyzed trends in normalized difference vegetation index (NDVI) satellite data between 1982 and 2008 using the BFAST procedure and detected both abrupt and gradual

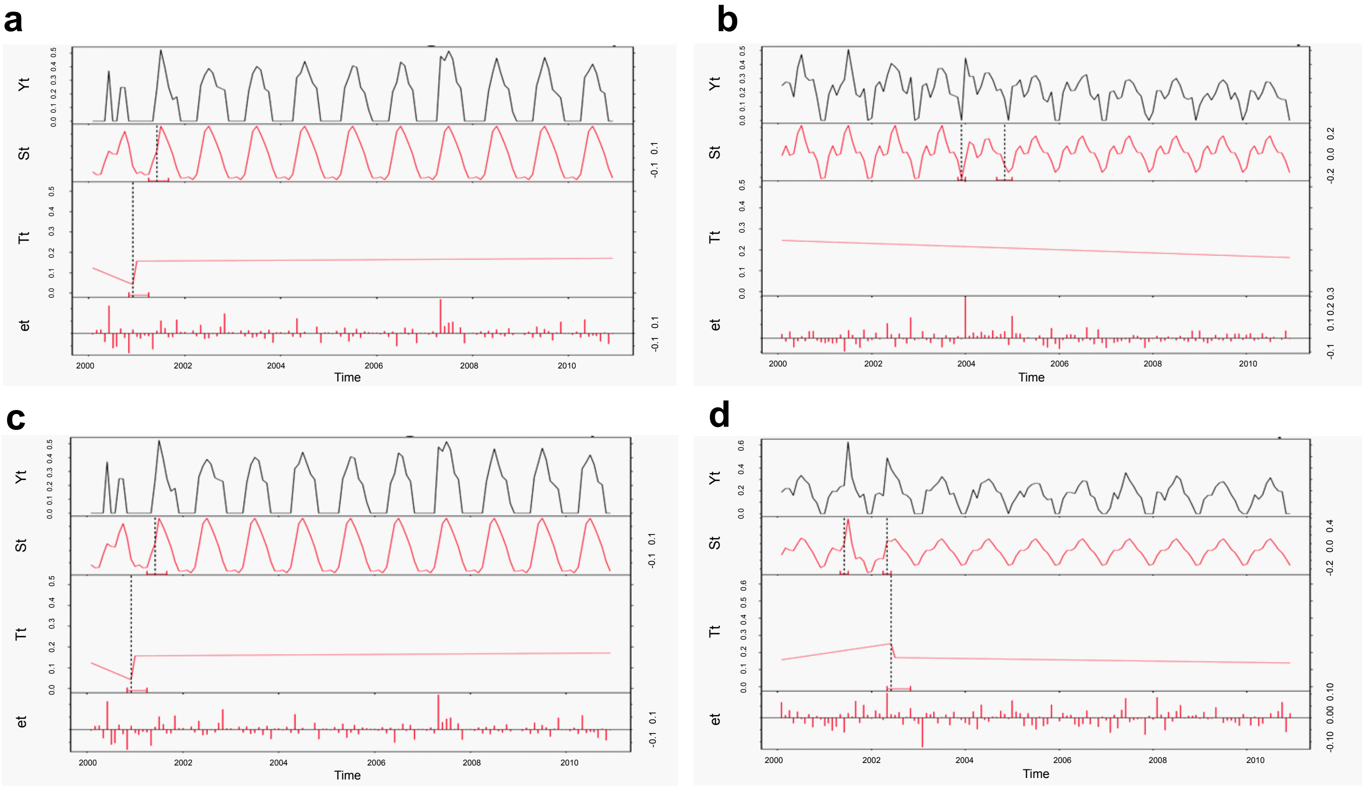

Figure 2: Tundra EVI trends displayed with break points detected by the BFAST methodology. Examples include: (a) non-wetland, positive slope; (b) non-wetland, negative slope; (c) wetland, positive slope; (d) wetland, negative slope. *Yt* is the time-series MODIS EVI value; *St* is the fitted seasonal component; *Tt* is the fitted trend component; *et* is the noise component (Verbesselt *et al*., 2010a). Statistical breakpoints are identified by vertical dashed lines.

	Total Tundra Area Coverage	Burned Area (1940-1979)	Burned Area (1980-Present)	Non-Burned Area
Non-Wetland	829,952	36,736	62,848	730,368
Wetland	247,488	15,808	23,168	208,512
Totals	1,077,440	52,544	86,016	938,880

Table 1: Wetland and burned area coverages for Alaska tundra ecosystems. All values are in km^2 area.

changes in large parts of the world, especially in (semi-arid) shrub land and grassland biomes where abrupt greening was often followed by gradual browning.

Study region attributes

Tundra ecosystems cover just over 1 million km^2 in Alaska (Table 1), 13% of which has been burned by wildfires since 1940 (AICC, 2010).Tundra comes from the Finnish word *tunturi*, meaning treeless plain. Tundra-dominated ecoregions in Alaska are characterized by shrub-sedge-moss vegetation, low temperatures, nutrient-poor and frozen soils, and short growing seasons [28]. Roughly 23% of tundra ecosystem areas statewide have majority wetland coverage, according to the data from Whitcomb et al. [18].

Results

Approximately 10% (or 109,000 km^2) of all tundra ecosystem areas in Alaska were detected with significant (p<0.05) positive or negative MODIS growing season EVI trends from 2000 to 2010. Nearly three-quarters of these pixel areas were detected with significant positive growing season EVI trends (Table 2). This 3:1 ratio of positive to

	EVI Slope	Burned Area (1940-1979)	Burned Area (1980-Present)	Non-Burned Area	Totals
Non-Wetland	Positive	8,128	1,920	51,776	61,824
	Negative	5,312	4,928	10,048	20,288
Wetland	Positive	1,344	3,072	14,848	19,264
	Negative	1,408	1,920	4,288	7,616
Totals		16,192	11,840	80,960	108,992

Table 2: Matrix of MODIS growing season EVI trend results (with significant regression slope, p<0.05, positive or negative from 2000 to 2010) for Alaska tundra areas. All values reported are summed to total km^2 tundra area per category.

negative EVI trends was largely consistent across both wetland and non-wetland tundra cover categories. It is worth noting some exceptions to this general pattern: (1) wetland tundra areas that burned between 1940 and 1979 had a 1:1 ratio of positive-to-negative EVI trends. (2) non-wetland tundra areas that burned between 1980 and 2010 had a 1:2.5 ratio of positive-to-negative EVI trends.

The ecoregions of Alaska that revealed the highest density of positive areas for tundra growing season EVI slope (Figure 1) were generally along the Pacific coast, namely the western Arctic Foothills, the Seward Peninsula, and the southern Coastal Plain (as defined by Nowacki et al.) [28]. Ecoregions that revealed the highest density of negative slope areas for tundra growing season EVI were the northeastern Arctic Coastal Plain, the Brooks Foothills, and the eastern Yukon Basin. Wetland tundra areas in the northeastern Arctic Coastal Plain stand out as ecoregions of clustered negative EVI slopes (Figure 1).

The number of BFAST breakpoints indicated the level of gradual

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Figure 3: Associations of the significant (p<0.05) slope trends (2000-2010) in EVI with annual GDD change for tundra ecosystems across Alaska. All slope values are in index units yr^{-1}.

(0 breakpoints) versus abrupt (>1 breakpoint) change in the EVI time series. Examples of EVI trends (both significant positive and negative slopes) at selected tundra locations were shown by the BFAST method to have been gradual changes over the past decade (Figure 2). Breakpoints, where detected, were found early in the time series, as both the length of the growing season and the peak summer EVI values appeared to change gradually in most ecoregions.

Positive slope values of GDD indicated a warming trend over the past decade. Tundra EVI slope values plotted against slope values for the GDD climate warming index showed an association of the largest positive trends in MODIS greenness with annual warming trends of greater than 2 GDD yr^{-1} (Figure 3). This EVI-GDD positive association was most noticeable for non-burned and older burned (1940-1979) tundra areas, both non-wetland and wetland-dominated.

Tundra EVI slope values plotted against slope values for the CMI drying-wetting index showed an association of the largest positive trends in MODIS greenness with annual decreases (drying trends) in excess of -0.04 CMI units yr^{-1} (Figure 4). This EVI-CMI inverse association was noticeable for all tundra areas in Alaska, both non-wetland and wetland-dominated.

To further examine the climate history of areas with significant (p<0.05) negative growing season EVI slope from 2000 to 2010, we identified all pixel locations of wetland-dominated, unburned (since 1940) tundra cover where the regression slope for the climate warming index was less than 2.5 GDD units yr^{-1}. These locations plotted in figure 5 were mainly clustered in the northeastern Arctic Coastal Plain and the eastern Yukon Basin ecoregions (as labeled in figure 1).

Areas of Alaska mapped with the warming index slope greater that 3 GDD units yr^{-1} (Figure 5) were located mainly in the western Arctic Foothills and the Seward Peninsula ecoregions. As shown also in figure 1, these ecoregions had the highest density of positive growing season EVI slope areas, which supports the association of warming rates in excess of 3 GDD units yr^{-1} with significant tundra greening.

Discussion

The MODIS EVI time-series data used in this study provided consistent large-scale metrics of vegetation growth trends across the arctic region. We hypothesize from the results that temperature warming-induced change and inter-annual variability of evapotranspiration at local and regional scales has altered the rates of tundra growth in Alaska over recent years. In support of this hypothesis, evidence of shrub expansion over the last half century has been documented through repeat photography [29]. Beck and Goetz [14] also postulated that the proportion of North America tundra areas increasing in productivity has steadily grown since 1982, reaching 32% of non-barren areas in 2008. This regional greening trend appeared to be unrelated to shrub density, indicating that primary productivity is increasing across a range of functional vegetation types.

It is worth noting that Wang et al. [30] reported on sensor degradation having had an impact on trend detection in North America boreal and tundra zone NDVI with Collection 5 data from MODIS. The main impacts of gradual blue band (Band 3, 470 nm) degradation on simulated surface reflectance was most pronounced at near-nadir view angles, leading to a small decline (0.001–0.004 yr^{-1}; 5% overall between

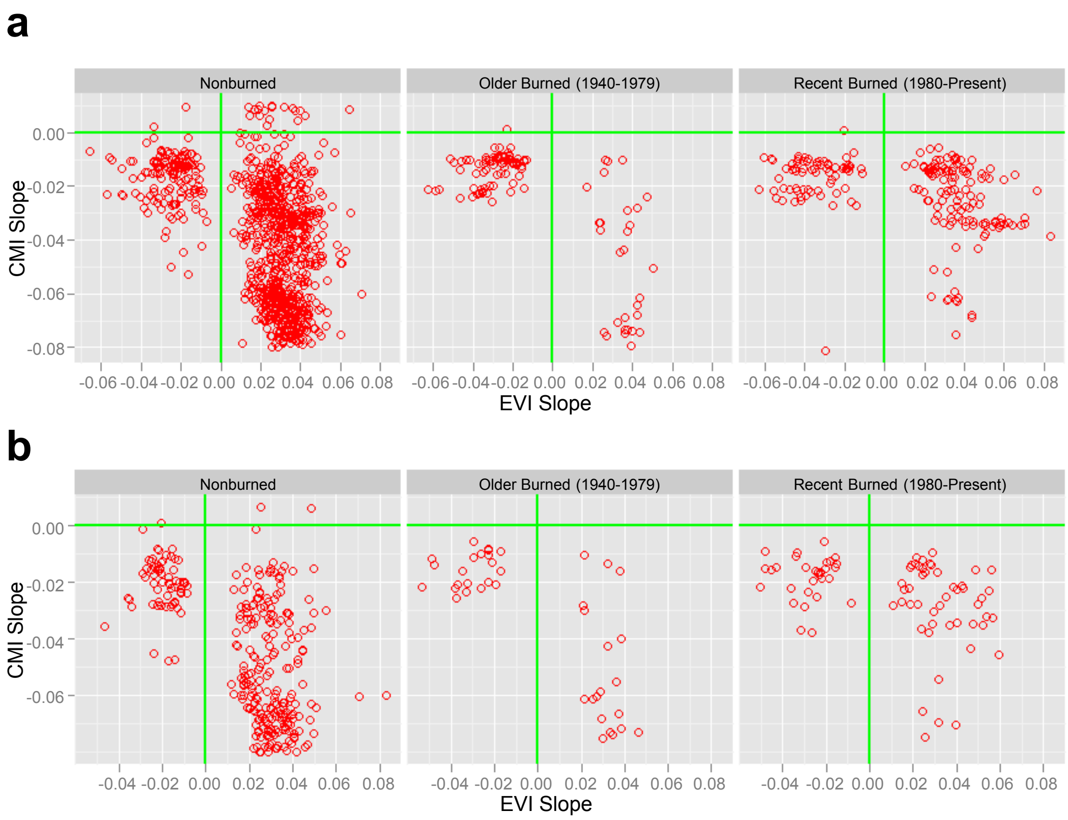

Figure 4: Associations of the significant ($p<0.05$) slope trends (2000-2010) in EVI with annual CMI change for tundra ecosystems across Alaska. All slope values are in index units yr^{-1}.

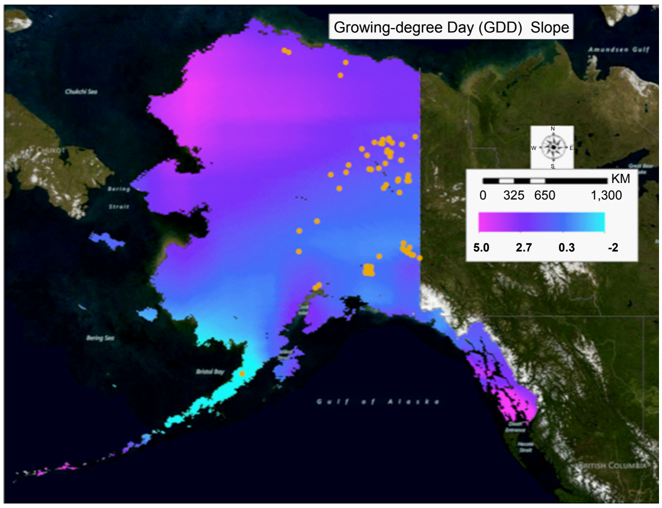

Figure 5: Map of the regression slopes for the GDD warming index in Alaska over the period 2000 to 2010, overlaid with point locations of significant ($p<0.05$) negative EVI slope areas for wetland-dominated, unburned (since 1940) tundra in areas where GDD slope was less than 2.5 yr^{-1}.

2002 and 2010) in NDVI under a range of simulated aerosol conditions and high-latitude surface types. Even if this same sensor degradation problem affected MODIS EVI trends over the period of our analysis from 2000 to 2010, the apparent rate of greening in warming tundra ecosystems of Alaska was not negated by such small, progressive changes in MODIS data quality.

In summary, the methodology developed for mapping and characterization of forest growth trends can be readily extended over the next decade of Collection 6 MODIS EVI data. The results from BFAST break point analysis provides an additional trend decomposition method for local scale studies with higher resolution satellite data. Further research should be pursued in order to elucidate the developing relationship between climate change, tundra growth, and boreal forest decline in Alaska.

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