Vegetation greening in the canadian arctic related to decadal warming†

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This study is presented within the context that climate warming and sea-ice decline has been occurring throughout much of the Arctic over the past several decades, and that terrestrial ecosystems at high latitudes are sensitive to the resultant alterations in surface temperatures. Results are from analyzing interannual satellite records of vegetation greenness across a bioclimate gradient of the Canadian Arctic over the period of 1982–2006. Here, we combine multi-scale sub-pixel analysis and remote sensing time-series analysis to investigate recent decadal changes in vegetation greenness along spatial gradients of summer temperature and vegetation. Linear autoregression temporal analysis of vegetation greenness was performed with relatively "pure" vegetation pixels of Advanced Very High Resolution Radiometer (AVHRR) data, spanning Low Arctic, High Arctic and polar desert ecosystems. Vegetation greenness generally increased over tundra ecosystems in the past two decades. Peak annual greenness increased 0.49–0.79%/yr over the High Arctic where prostrate dwarf shrubs, forbs, mosses and lichens dominate and 0.46–0.67%/yr over the Low Arctic where erect dwarf shrubs and graminoids dominate. However, magnitudes of vegetation greenness differ with length of time series and periods considered, indicating a nonlinear response of terrestrial ecosystems to climate change. The decadal increases of greenness reflect increasing vegetation production during the peak of the growing season, and were likely driven by the recent warming.

1. Introduction

The Arctic region has experienced a continuous trend of warming during the past 30 years, with a magnitude of approximately 2 °C on average.[1] Meanwhile, since 1979 perennial sea-ice in the Arctic has declined 8.6 ± 2.6% per decade for September sea-ice extent, with a total reduction of 21% by 2005.[2,3] The warming has triggered significant changes of various properties of the Arctic, including warming and thawing of permafrost,[4] reduction of snow cover, and changes in hydrological patterns.[5] Terrestrial ecosystems at high latitudes are warmth-limited and sensitive to alterations in surface temperatures and snow/ice dynamics. They are therefore expected to exhibit substantial changes in terms of structure and productivity in response to recent warming. This is especially the case for the Canadian Arctic, as most of its tundra ecosystems are located either on islands in the Arctic Ocean or less than 100 km from the icy coasts. Long-term tundra observations,[6] open-top chamber experiments,[7,8] and repeat photography[9] have all demonstrated trends of increased vegetation production across various sites over the past several decades. Those fine-scale observations demonstrated site-specific trends and are important for investigating changes over larger areas in the Arctic.

Data from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) are so far the longest continuous global land surface records from satellite and are commonly used to monitor seasonal and inter-annual changes in vegetation greenness at regional, continental, and global scales.[10,11] Several comprehensive remotely-sensed studies based on AVHRR time series over northern high latitudes have shown remarkable decadal changes

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Environmental impact

The Arctic is warming and dwarf shrub dominated tundra is greening, as demonstrated by a 25-yr long continuous satellite observation over the Canadian Arctic. This paper uses long-term satellite data time series to monitor environmental processes under a changing climate in the Arctic, a region that is sensitive to warming and disturbances. It demonstrates a remarkable trend of increase in primary production of tundra vegetation over the last two decades, and identifies the areas and vegetation types with the greatest amount of change. Monitoring tundra vegetation dynamics has important implications for understanding changes in biodiversity, ecosystem services, carbon budgets, and the environment of indigenous people in the region. The study is an in-depth new contribution to a multi-level understanding of environmental phenomena in a polar region.

of vegetation greenness,[12,13] and a number of studies clearly show that positive productivity trends are widespread for the Arctic.[13,14] Previous AVHRR based studies suggest that photosynthesis activities of the North American boreal region have increased by 7–14% from 1981–1991,[15] although there was an overall decline from 1982–2003.[12] Compared to the broader boreal region, areas dominated by Arctic tundra have shown almost a constant increasing trend in photosynthesis activities throughout the 1980s and 1990s.[13,16] However, previous studies have been limited in their ability to resolve mixed signals in heterogeneous landscapes over the Arctic due to the coarse spatial resolution of available satellite imagery. Those studies have generated questions as to how the magnitudes and even trends change as the time series of data extends to a longer period, and how the changes of vegetation greenness differ along climate gradients within the tundra biome. High landscape heterogeneity in the Arctic region where water bodies, glaciers, and frost disturbances are very common, makes it difficult to detect initial changes of tundra vegetation without carefully unmixing the fractional covers of landscapes.

Here, we combine multi-scale sub-pixel analysis and remote sensing time-series analysis to investigate recent decadal changes of greenness over relatively "pure" vegetation canopies along spatial gradients of summer temperature and vegetation in northern Canada. In this study, we sought to investigate interannual changes of vegetation greenness over full latitudinal gradients of Arctic tundra from 1982–2003(6) using the methodologies developed in the studies on Alaskan tundra.[16,17] We were interested in how the vegetation greenness changed during the period after non-vegetated and contaminated pixels are removed from analysis, and how the changes varied along full Arctic bioclimate gradient and in relation to summer warmth. We were also interested in how the fractional land cover and dominant plant functional types control the temporal and spatial patterns of greenness variations.

2. Data and methods

2.1 Data description

We used the time series of the normalized differenced vegetation index (NDVI) derived from NOAA AVHRR meteorological satellites across the Arctic region over 25 years (1982–2006). The NDVI is an index of vegetation greenness calculated from spectral reflectance in red (ρ_{red}, 0.58–0.68 μm) and near infrared (ρ_{nir}, 0.725–1.1 μm) bands (NDVI = $(\rho_{nir}-\rho_{red})/(\rho_{nir}+\rho_{red})$). It is directly related to the photosynthetic capacity and hence energy absorption of plant canopies,[18] *i.e.*, the NDVI of an area containing a denser vegetation canopy will tend to greater positive values. The satellite observation data were post-calibrated and processed by the Global Inventory, Monitoring and Modeling Studies (GIMMS) project at a spatial resolution of 8-km and a 15-day temporal resolution. Mean NDVI values were calculated for each 15-day period using a so-called maximal value composite (MVC) approach, *i.e.*, maximal values for each pixel over the period were selected for the composite to avoid cloud contamination and other errors. The dataset used in this study is an extensively calibrated and adjusted AVHRR time series and currently the best available satellite optical-IR record, which has been improved to further overcome the effects of orbital drift, cloud cover and aerosols, and sensor degradation using the best available algorithms, ground reflectance references, and temporal data derived from new generation sensors.[19] The overall high agreement between this newly calibrated AVHRR data and the more modern sensors with onboard calibration and georeferencing[19] demonstrates that long-term monitoring of vegetation activities and climate dynamics is achievable using the GIMMS time series. Even though, the AVHRR NDVI records are still negatively affected by other limitations that are particularly problematic at high latitudes, including seasonal snow cover variations, extreme solar angles, shadowing and reduced solar illumination, and extensive cloud cover during the growing season. We try to at least partially reduce those effects by masking contaminated pixels and selecting only vegetated areas for analysis.

2.2 Image subset and unmixing

We first processed the North America AVHRR-NDVI time series datasets and converted them into Arc Grid format with Albers Conic Equal Area projection. We then overlaid a 500 m MODIS (The Moderate Resolution Imaging Spectroradiometer) Vegetation Continuous Field[20] (http://glcf.umiacs.umd.edu/data/vcf/) dataset (Collection 4, Version 3) with GIMMS data to analyze the fractional covers of vegetation, bare ground, and lakes in the region, and then selected the most vegetated areas for subsequent temporal analysis. We used the Circumpolar Arctic Vegetation Map (CAVM) bioclimate subzone dataset[21] to define the southern boundary of Arctic tundra and to divide the region into five Arctic bioclimate subzones and adjacent boreal forests that reflect climate and vegetation patterns (Fig. 1, Table 1). For each bioclimate subzone, 20–30% of all pixels containing the least surface water and bare ground were included in subsequent analysis. This process also helped to eliminate the coastal pixels mixed with sea water. Fractional lake cover has a major

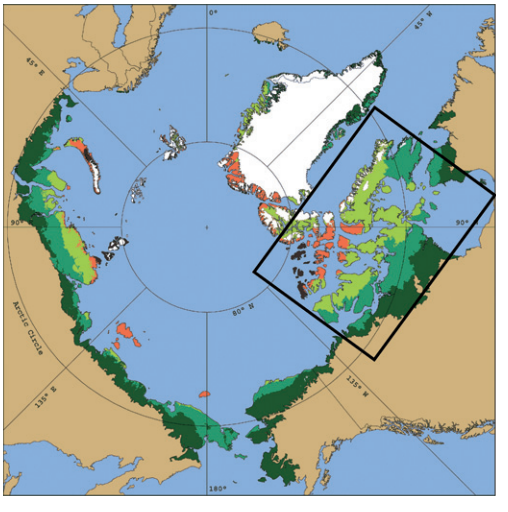

Fig. 1 Location of bioclimate gradient for this study. The southern boundary and five arctic tundra Bioclimate Subzones were defined by summer warmth and dominant plant functional types.[21] From north to south there are Subzone A (black), B, C, D, and E. The black polygon represents the study region.

Table 1 Comparison of major vegetation, climate, and landscape characteristics among five arctic bioclimate subzones. (Data derived from *Walker et al.*, 2005.[21])

Subzone	Mean July temp (°C)	Summer warmth index (°C)	Dominant life forms	Plant cover	Total plant biomass (t/ha)	NPP[a] (t/ha/yr)	Number of vascular plant species
A	0–3	<6	Cushion forbs, mosses, lichens	<5% vascular, <40% moss/lichen	<0.3	<0.3	<50
B	3–5	6–9	Rushes and prostrate dwarf shrubs	5–25% vascular, <60% moss/lichen	0.5–2	0.2–1.9	50–100
C	7–9	9–12	Hemiprostrate and prostrate dwarf shrubs	5–50%	1–3	1.7–2.9	75–150
D	9–11	12–20	Sedges, erect and prostrated dwarf shrubs	50–80%	3–6	2.7–3.9	125–250
E	11–13	20–35	Tussock sedges, low and erect dwarf shrubs	80–100%	5–10	3.3–4.3	200–500

[a] NPP: Net primary production.

contribution to NDVI values within a given pixel. Statistically, NDVI values reach the highest point when lake fractions account for 10–25% of the land cover in the Arctic, largely due to the balance between water availability to the vegetation and the negative contribution of the water signal to the vegetation index. NDVI declines as lake fraction increases and is reduced sharply to approximately one-third of the peak values at 50% lake cover.[22] Similar to water bodies, bare ground also tends to buffer the magnitude of greenness changes in response to climate dynamics. However, as vegetation coverage is generally low in the northern Arctic, we can only remove pixels with large fractions of continuous bare ground such as areas recently deglaciated or areas of extensive frost-related disturbances. The temporal analysis was performed with a subset of the decadal AVHRR dataset, with minimal fractions of lake, bare ground, and cloud contamination. 2183 AVHRR pixels screened with the fractional cover analysis described above were used for the study. We examined the decadal changes of vegetation greenness as indicated by variations of several indices of NDVI, spanning boreal forest, Low Arctic, High Arctic and polar desert ecosystems. Two NDVI indices, Peak-NDVI and TI-NDVI were developed to represent annual characteristics of vegetation greenness. Peak-NDVI is the maximum measurable NDVI recorded during the year and is associated with the peak of greenness during the growing season. TI-NDVI is the cumulative value of NDVI recorded during each growing season; therefore, this index reflects accumulated vegetation activities within a year. The growing season was defined as the period when the NDVI time series curve was above a value of 0.09.[10,16] ArcInfo software was used to calculate mean values and temporal trends of Peak-NDVI and TI-NDVI for the time series, along with seasonal patterns of NDVI. The means and variation datasets were spatially summarized for the five bioclimate subzones along the Arctic transect based on the CVAM bioclimate map.[21]

As a result, we masked off most non-vegetation signals and selected areas with relatively homogeneous vegetation for each Arctic bioclimate subzone. Pixels of water, ice/snow, and contaminated areas were masked and excluded from subsequent analysis, so that we were able to detect "pure" vegetation signals over a highly heterogeneous landscape. For selected areas we calculated the annual peak NDVI for each year to reflect the annual maximum greenness using the maximum value composite (MVC) approach to eliminate cloud contaminated pixels and compose a clear-sky data layer over a given period of time. We analyzed average seasonal curves of vegetation activities for the periods 1982–1992 and 1993–2003 to examine possible changes in growing season phenology under different climatic conditions. Initial analysis showed that vegetation greenness varied across most of 15-day composite periods, especially during the early growing season; length of the growing season varied from year to year as well. We decided that a more integrated index should be used to reflect those intra-annual variations over time. Therefore, time-integrated NDVI (TI-NDVI) was introduced to represent the cumulative signals of vegetation growth for a given year. We summarized each index by Arctic bioclimate subzone.

We recently received the extended time series for 2004–2006. The data have been calibrated and corrected with the same algorithms and procedures as previous years, but data beyond 70° N were not confidently calibrated due to original data errors and lack of reference data for calibration. With this extended dataset, we reanalyzed the pixels south of 70° N over the period of 1982–2006. We expect to gain a more reasonable and predictable long-term trend as AVHRR observations continue in coming years, along with MODIS and upcoming VIIRS (Visible/Infrared Imager Radiometer Suite) records.

We applied linear trend analysis with auto-regression techniques to examine the interannual trends over each Arctic bioclimate subzone as well as the regional tundra biome. Significance tests (t-test) were performed on the trends. We applied image difference analysis and calculated temporal standard deviations to examine spatial patterns of interannual trends and variations.

3. Results

3.1 Increasing vegetation greenness in the tundra biome

Vegetation greenness in arctic tundra generally increased throughout the regional tundra biome over the past 22-year period from 1982–2003. 96.6% of the pixels of tundra used in the analysis show positive trends throughout the period. Annual peak values increased by 0.49–0.79%/yr over the High Arctic

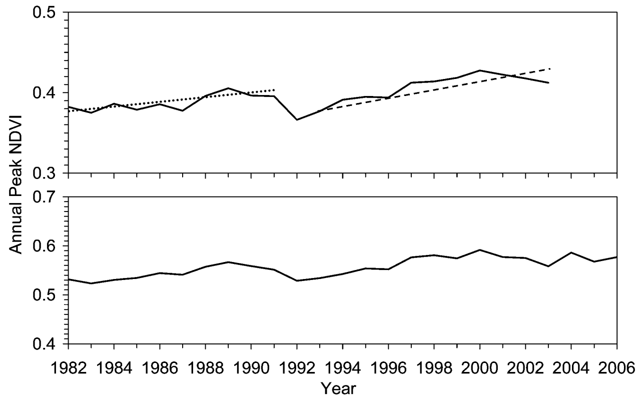

Fig. 2 Changes of annual peak NDVI over tundra biome from 1982–2003 (top) and below 70-degree north from 1982–2006 (bottom). Dotted lines represent linear trends for 1982–1991 and 1993–2003.

where prostrate dwarf shrubs, forbs, mosses and lichens dominate, and by 0.47–0.67%/yr over the Low Arctic where erect dwarf shrubs and graminoids dominate. The overall rate of increase is 0.56%/yr ($r^2 = 0.60$, $p < 0.001$) over the tundra biome (Fig. 2). There were similar interannual trends, years of high greenness, and years of low greenness among the five subzones despite the differences in NDVI magnitudes. Vegetation greenness was lower in the early 1980s and increased slowly but almost systematically over the first ten years. A sharp decline of greenness was observed in 1992, which is largely related to the Mt. Pinatubo eruption in late 1991.[23] Following that decline, the trend of greening continued and even accelerated until 2003 (Fig. 2, 3). When splitting the time series into 1982–1991 and 1993–2003, we see different patterns of trends and magnitudes of changing greenness. The trends of increased greenness showed a non-linear pattern, with a 0.66%/yr ($r^2 = 0.56$, $p < 0.005$) increase over the first period and a 1.03%/yr ($r^2 = 0.71$, $p < 0.001$) increase over the second period (Fig. 2). We excluded 1992 from the split time series due to its nature of being strongly influenced by the Pinatubo effects. There was no significant change ($r^2 = 0.06$, $p = 0.137$) of greening when including 1992 in the first period. The greenest year was in 2000 over the Low Arctic (Subzones D and E) and in 2001 over the High Arctic (Subzones A–C), while the least green year was in 1992, followed by 1987. With the addition of the 2004–2006 data, it is apparent that 2006 was the greenest year in terms of TI-NDVI in the 25-yr record for the Low Arctic (Fig. 3), and that 2004 was slightly less greener than 2003, but still relatively high in peak NDVI (Fig. 2). When adding 2004–2006 to the time series, TI-NDVI increased by 0.71%/yr, 0.03%/yr greater than when using the 1981–2003 time series (Fig. 3).

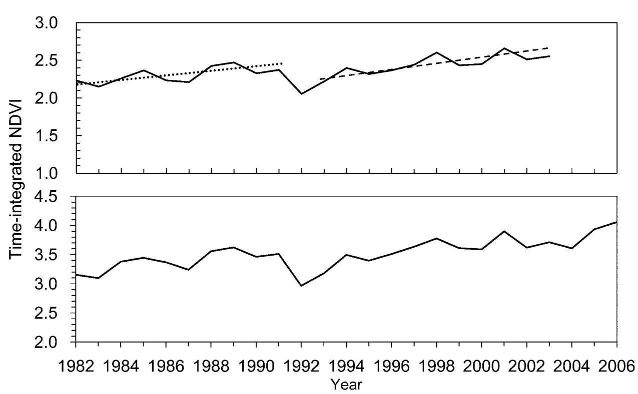

Fig. 3 Changes of time-integrated NDVI over tundra biome from 1982–2003 (top) and below 70-degree north from 1982–2006 (bottom). Dotted lines represent linear trends for 1982–1991 and 1993–2003.

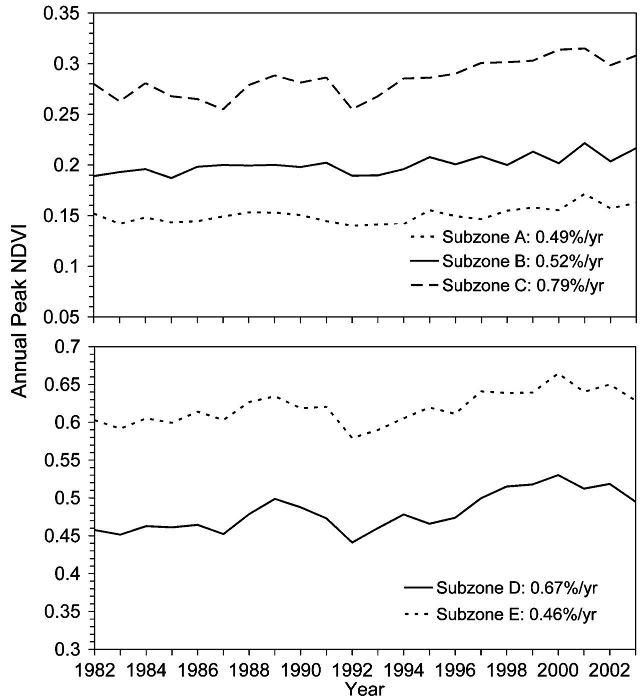

Fig. 4 Interannual trends of peak vegetation greenness for each of the five arctic bioclimate subzones over the Canadian Arctic from 1981–2003. With exclusion of pixels containing high fractions of water, glaciers, and bare ground, relatively homogenously vegetated areas were analyzed for each subzone. Linear autoregression was applied to detect trends.

The greatest rates of greening in peak NDVI were observed in bioclimate Subzones C and D, crossing the transition between High and Low Arctic (Fig. 4). Subzone C had the highest rate of increase of peak vegetation greenness (0.79%/yr, $r^2 = 0.61$, $p < 0.001$), closely followed by Subzone D (0.67%/yr, $r^2 = 0.47$, $p < 0.01$). However, without exclusion of pixels with high fraction of water bodies, *i.e.*, when analyzing all pixels in the subzone, the magnitude of change for Subzone C dropped from 0.74%/yr to 0.51%/yr. With a landscape mosaic of graminoid-dominated vegetation and water bodies, Subzone C has the highest water fractions compared to the four other subzones.[21] This subzone forms a narrow belt along the northern coasts of the Canadian Arctic mainland and islands in the Arctic Ocean (see Fig. 1). Subzone D also has a high rate of increase in peak greenness. This subzone is covered by tussock-sedges and erect dwarf shrubs. The rapid response of tussock-sedges to short-term interannual warming trends[8] and the long-term enhancement of erect dwarf shrubs[9] may have contributed to the greening in this subzone.

The lowest rate of peak greenness change was observed in Subzone E, dominated by dwarf-erect and low deciduous shrubs such as birch (*Betula nana* and *B. glandulosa*), willow (*Salix*

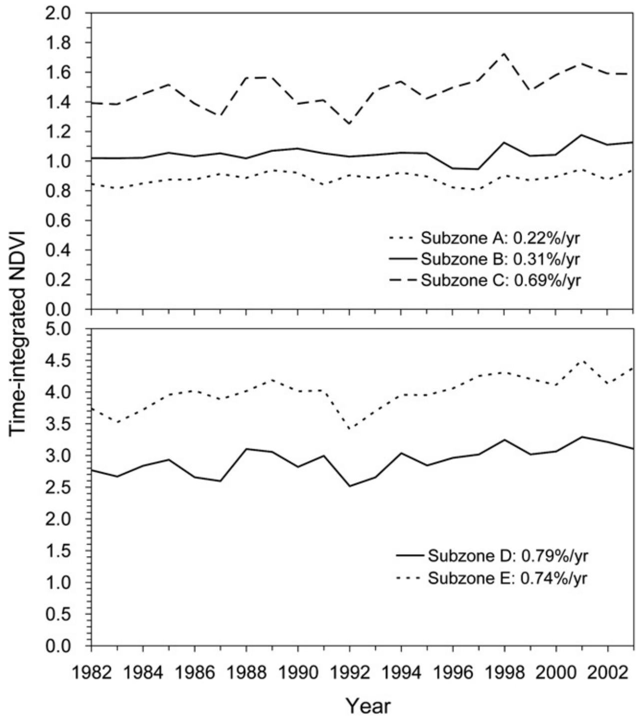

Fig. 5 Interannual trends of time-integrated vegetation greenness for each of the five arctic bioclimate subzones over the Canadian Arctic from 1981–2003. With exclusion of pixels containing high fractions of water, glaciers, and bare ground, relatively homogenously vegetated areas were analyzed for each subzone. Linear autoregression was applied to detect trends.

alexensis, S. pulchra, S. glauca) and alder (*Alnus crispa*), however, the magnitude of change was still as high as 0.46%/yr, and the absolute value of decadal increases in peak NDVI was among the highest (Fig. 4). Located in the southern boundary of the arctic tundra biome, Subzone E has experienced rapid enhancement of shrub cover[9] and slow colonization of tree species (*e.g. Picea mariana*)[24] largely triggered by increased surface temperature and a deeper snow pack, which insulates the soil and increases nutrient mineralization.[25] The increases of fractional cover of shrubs and tree seedlings can potentially lead to higher NDVI values. However, NDVI tends to saturate before reaching values of approximately 0.7–0.8, depending on land cover type. This may leave limited room for the already high peak NDVI in the shrub tundra of Subzone E to have a major detectable increase. However, when we examine time-integrated NDVI, which reflects the cumulative greenness over the entire growing season, the greening trend in Subzone E was the second greatest among the five subzones (Fig. 5), indicating increased vegetation greenness throughout the growing season and possibly a longer growing season.

Subzones A and B, representing the polar desert and northern High Arctic respectively, have very short growing seasons and low vegetation cover (Table 1). Subzone A is characterized by the absence of any woody plants, whereas Subzone B has prostrate dwarf shrubs. Due to the short growing season and sparse vegetation, we did not expect major detectable changes of vegetation greenness in these systems. However, an increase of peak greenness of approximately 0.50%/yr was found there (Fig. 4). Two factors that may have contributed to the greening are: 1) an increase of plant height and coverage due to warming[26] and 2) possibly a faster and earlier growth of tundra plants, as indicated by the earlier peak greenness (Fig. 6). Mosses and lichens are persistent in these harsh environments and may respond to environmental changes more rapidly than vascular plants, and therefore enhance their photosynthesis even during a very short, favorable period.

In summary, vegetation greenness increased systematically in arctic tundra dominated areas (Fig. 2, 3). The changes were also heterogeneous within the tundra biome (Fig. 4, 5). It is apparent that significant greening has been occurring over the tundra biome but not uniformly from one subzone to another. The greatest changes in absolute values of greening were observed in bioclimate Subzone D, followed by Subzone E, while there was less change in the polar desert (Subzone A) in terms of absolute peak values. The spatial patterns of absolute change in greenness are different from those of relative (percent) change, which were the highest in Subzones C and D. Despite the relative changes of peak greenness in shrub tundra (subzone E) being lower than northern tundra types, the increase in time-integrated greenness and therefore also in annual primary production is still among the highest, indicating possible major lengthening of growing season (Fig. 5). Changes were also concentrated in mostly vegetated areas, as there was a significant negative relationship ($r^2 = 0.57$, $p < 0.01$) between change in peak NDVI and fraction of bare ground and lakes. There was a general agreement in spatial patterns of decadal changes between vegetation greenness and surface temperature. The decadal trends of land surface temperature derived from AVHRR thermal bands give a clear picture of warming in the Beaufort Sea area and northern Canada.[27] The increase rate of AVHRR-derived land surface temperatures (LST) was 0.079 ± 0.017 K/yr over the North American Arctic and 0.105 ± 0.019 K/yr over Greenland from 1981–2005.[27] The greenest years in term of time-integrated NDVI were 2006, 1998, and 2005 (Fig. 3, 5), and they appear to be the warmest years with the lowest September sea-ice extents in the Arctic since the early 1980s.[2]

3.2 Changes in phenology

There were changes in phenological patterns of tundra vegetation over the two decades as well. Increases of vegetation greenness were observed throughout most of the growing season for Subzones C–E, yet only during mid-summer for Subzones A and B (Fig. 6). In Subzones D and E, seasonal NDVI values were greater in the second decade than the first one for each 15-day composite period. There was a very clear sequence of onset dates from the colder north to the warmer south, *i.e.*, onset started in Subzone E in approximately the second week of May, then reached Subzone D about 2 weeks later, Subzone C in early June, Subzone B in mid June, and it takes another week to turn Subzone A green (Fig. 6). Vegetation growth in the second decade became more rapid after onset and declined slowly after the peak. Greater greenness values were only observed from late June to early August for Subzone A and slightly longer for Subzone B. Peak greenness occurred earlier in the High Arctic, almost 15 days earlier in the second decade for Subzones A and B, and about 7 days earlier in Subzone C. NDVI remained high

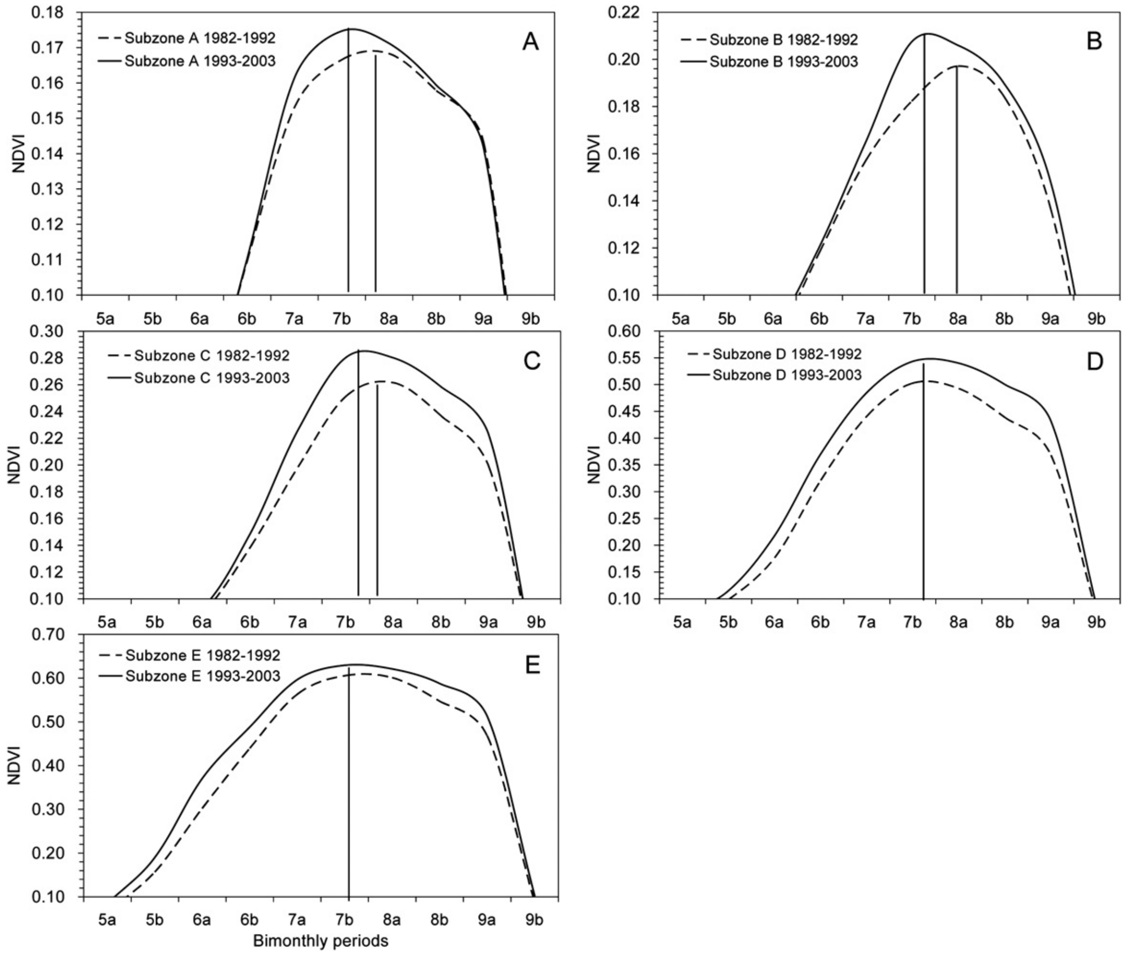

Fig. 6 Seasonal changes of vegetation greenness for each arctic bioclimate subzone. Dashed lines represent average values for the period of 1982–1992, while solid lines are average values for the period of 1993–2003. The x-axis is in bimonthly interval, *e.g.* 5a and 9b represent first half of May and second half of September, respectively. Vertical lines indicate the dates of peak NDVI. (a) Subzone A, (b) Subzone B, (c) Subzone C, (d) Subzone D, (e) Subzone E.

after the growing season peak through September in Subzones C–E. Generally, tundra plants have experienced longer growing seasons and greater peaks in greenness over the past two decades.

As a cumulative greenness index over the entire growing season, time-integrated NDVI represents both seasonal values and phenology features. It therefore provides more information about year round vegetation activities compared to peak NDVI. Greater increases of vegetation activities in the southern tundra biome than in the north were indicated by TI-NDVI (Fig. 3). The inter-annual increase rate was 0.79%/yr and 0.74%/yr over Subzones D and E respectively, while the rate dropped to 0.22%/yr in Subzone A. This indicates a strong cumulative effect in the south.

With a 15-day temporal resolution of the remote sensing data, it is difficult to detect shifts of plant growth onset and in the length of the growing season with high confidence. However, we can still find some interesting trends even over two decades. For example, there was slightly earlier onset of greenness for Subzones C, D, and E (4.1, 7.2, and 6.7 days respectively). However, there was no obvious later senescence observed. The growing season tended to be longer in each subzone except for Subzone A, where the growing season did not exhibit any observable changes within two decades.

4. Discussion

4.1 Greening and ecosystem changes

The spatial patterns of the decadal changes of vegetation can be explained by distributions of arctic tundra plant functional types (PFT) and fractional land cover over the region. For example, relatively rapid responses of tussock and non-tussock sedges may have contributed to the high increase rate of peak NDVI in Subzones C and D; dense dwarf-erect and low shrub dominated Subzone E had a relatively lower increase rate of peak greenness, but is among the highest in amount of absolute greenness change. Higher fractions of barren areas and growing season snow cover in the High Arctic, especially Subzones A and B may have reduced the sensitivity of NDVI signals for these areas at the 8-km pixel level.

The decadal increases of vegetation greenness over the tundra biome in summer periods reflect increasing vegetation production during the growing season. Field studies have observed recent earlier snow melt, earlier active layer thaw,[4] and related changes in plant communities. It is evident that tundra vegetation communities are capable of developing in frost-disturbed areas within a decade, through colonization by annual forbs and other early succession plant types.[6] There is also evidence that fractional cover of low shrubs has increased in the southern tundra over the past 50 years,[9] and that tundra vegetation productivities have increased over various tundra sites throughout the circumpolar Arctic.[7] The trends of greening recorded by satellite reflect those ecological processes on the ground.

4.2 Vegetation greenness and summer warmth

Our previous studies demonstrated that there was a good agreement between NDVI and summer warmth index (SWI – growing degree months) throughout the course of this study, both temporally and spatially.[16,17,21] There is a trend of rising summer warmth throughout the study period as recorded by ground meteorological stations[5] and AVHRR-derived land surface temperatures.[27] Marked high NDVI, high summer warmth, and low sea ice extent were observed in 1998, 2005, and 2006. Spatially, higher NDVI and greater summer warmth were observed to the greatest degree for bioclimate Subzones C and D.

Rapid declining of sea ice extent[3] and earlier snow melt in the spring[28] in the region have increased spring warmth as well as summer maximum air temperature.[2] Meanwhile, declining of near-shore sea ice may lead to increased air temperature and defused solar radiation in spring and early summer,[29] which favors the growth of plant leaves and stems.[30] Warming is occurring below ground as well. Long-term records of the near-surface permafrost temperature show a significant warming trend during past 30 years,[4] associated with increases in soil microbial activity and a higher availability of soil nitrogen, a key limiting factor for plant growth in the Arctic. Long-term experimental studies have demonstrated that net primary productivity and biomass respond positively to soil microbial activity and nitrogen additions more rapidly than expected.[7,8] Other land processes related to increases of vegetation greenness in the Arctic, especially in Subzone C, are draining of lakes and wetlands,[5] and vegetation colonization on previously bare patterned-ground features, caused by annual freeze-thaw cycles. These processes tend to reduce the fractions of water and bare ground and thereby contribute to increasing vegetation greenness.

4.3 Issues regarding period of analysis and length of time series

Length of the NDVI time series can make a difference in the amplitude and the trend of interannual changes, and this has been seen in the trend of increased greenness detected by several studies of arctic tundra.[12,17] There was a significant trend of NDVI increase over northern latitudes in the 1980s as demonstrated in this study and others,[15] but there were different trends between tundra and boreal forest when the time series was extended to 2003, with continuous increases over tundra and a slight decrease over boreal forest regions.[12,13] In this study, we further extended the time series to the end of 2006 and find a slightly higher rate of increase of TI-NDVI over the tundra biome (about 0.05%/yr higher) and the absence of change ($r^2 = 0.04$, $p = 0.192$) over boreal forest. When we compare our results with the 1982–1991 analysis,[15] there are similar trends but quite different amplitudes of change throughout the region. It has been argued that the effect of declining aerosols may have contributed to the post-Pinatubo greening trend for up to four years following the eruption.[23] However, it is unlikely that this effect altered the trends and magnitude of greening considering its short duration of influence, and the fact that the dataset used here has been calibrated to further reduce the aerosol effects.[11]

It has been suggested that a minimum of 30 years of observation is good for reliably discovering trends. The longest continuous global satellite record presented here is 25 years long and is reaching the 30-yr suggested minimum. While we cannot wait until our observations are extensive enough to investigate long-term trends, it is very important to obtain the longest available time series to reduce uncertainty. As discussed above, high greenness values, high summer warmth, and low sea ice extent have been observed in 2004–2006.[27] As a result, the interannual patterns of vegetation greenness changed just by extending the time series for three years to 2006.†

4.4 Implications of increased vegetation greenness over the arctic region

Arctic tundra is dominated by dwarf shrubs, graminoids, mosses, and lichen. Changes of vegetation photosynthesis activities are responses to climatic change and also have the potential to feed back to global climate. First, as a warmth-limited biome and dominated by relatively fast responding plant functional types, the arctic tundra is likely to be quite sensitive to decade-long warming. Therefore, the greening trends demonstrated here are reasonable indicators of the warming over the region. Second, increases in arctic vegetation greenness have broader effects on carbon sequestration, snow cover, and albedo,[25,31] which all have the potential to feed back to the climate.[31,32] Greener tundra will insulate the top soil layers and affect active layer depth and soil temperatures,[25] will increase above and below ground carbon reserves,[33] and will lead to changes of snow distribution, flux of moisture to the atmosphere, and runoff of water into the Arctic Ocean.[5,25] Our results may be particularly valuable for investigating large scale land-climate processes by mean of modeling given their scale and details. The Arctic is home to various indigenous people whose lives largely rely on tundra plants and animals. A greener Arctic could provide higher primary and secondary production for local people, but also could come with other challenges such as introduced diseases, melting permafrost, and possible drier and shrubbier landscapes.[34]

5. Conclusions

Landscape heterogeneity and signal mixture are major biases in detecting initial changes of vegetation greenness in the Arctic. Here, we have further mitigated those biases by applying fractional cover analysis and by excluding pixels of water, snow, bare ground, and contaminated pixels with data errors. Although several remotely sensed studies have demonstrated overall greening trends over northern high latitudes in the past decades, our study gives a more detailed picture of heterogeneous changes of vegetation greenness along the full Arctic bioclimate gradient and among dominant plant functional groups in the Canadian Arctic. The greatest rates of greening were observed in bioclimate Subzones C and D, *i.e.* at the transition between High and Low Arctic. Seasonal curves show that tundra plants have experienced longer growing seasons and greater peaks in greenness over the past two decades. By extending the NDVI time series to 2006, we found a stronger trend of interannual increase in vegetation greenness over the tundra biome and a weaker trend of decrease over boreal forests, showing the importance to include all data available. Changes of vegetation photosynthesis activities are responses to climatic change and also have the potential to feed back to global climate.

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