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Key Points:
- Arctic tundra vegetation “greening” (since 1982), as assessed by the Normalized Difference Vegetation Index (NDVI), increases from north to south
- The greatest interannual variability in tundra vegetation (NDVI) occurs in the midlatitudes of the tundra biome
- The annual relationship between summer warmth and tundra vegetation (NDVI) is strongest also in the midlatitudes of the tundra biome.

Supporting Information:
- Figure S1
- Figure S2
- Figure S3

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# Spatial Heterogeneity of the Temporal Dynamics of Arctic Tundra Vegetation

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**Abstract** Arctic tundra vegetation has largely been “greening” in recent decades, resulting in major changes to terrestrial ecosystems, with implications for surface energy balance, permafrost, carbon and water cycling, herbivore populations, and human land use. While general greening trends have been well-studied, more specific vegetation-temperature dynamics are spatially and temporally heterogeneous and currently not well understood. This study uses Normalized Difference Vegetation Index (NDVI) and Summer Warmth Index (SWI) data to investigate patterns of arctic tundra vegetation and temperature dynamics over North American and Eurasian continents and by Arctic bioclimate subzones (essentially latitudinal-based). Relative vegetation increases in northern subzones were muted compared to temperature increases, whereas relative vegetation increases in southern subzones were consistent with, or greater than, relative temperature changes. Detrended, interannual NDVI variances were greatest in middle and southern subzones, whereas interannual SWI variances were greatest in southern subzones. Annual SWI and NDVI relationships were strongest in midlatitude subzones.

**Plain Language Summary** Arctic tundra vegetation has generally been increasing in biomass and productivity in recent decades. This paper uses 34 years of satellite data to investigate more thoroughly the relationships between temperature and vegetation in the tundra over time and space. We found that in the southern part of the tundra biome, the vegetation (as indicated by the satellite data) increased at the same rate as, or faster than, temperature, whereas northern tundra vegetation increased more slowly than temperature. The variation in tundra vegetation from year to year was greatest in the middle and southern parts of the Arctic tundra biome, whereas temperature variation from year to year increased from north to south. On an annual basis, the strongest relationships between temperature and vegetation occurred in the midlatitudes of the tundra biome.

## 1. Introduction

The Arctic has experienced increasing temperatures at an accelerated rate in recent decades, and this trend is expected to continue throughout this century (Kirtman et al., 2014; Overland et al., 2016; Stocker, 2014). Warming has been observed up to 2–3 times greater in the Arctic compared to average global temperature increases (Kaufman et al., 2009). Consequences of warming in the Arctic include loss of sea ice and changes to permafrost, land surface hydrology, vegetation, and biodiversity, as well as alterations of human land use (e.g., ACIA, 2004; Richter-Menge et al., 2017; Richter-Menge & Mathis, 2017). The Arctic has already experienced major vegetation changes, including a general “greening” (increased vegetation productivity) of the arctic tundra (e.g., Bhatt et al., 2010, 2013; Goetz et al., 2005; Jia et al., 2003). Dynamics in vegetation have commonly been observed using the Normalized Difference Vegetation Index (NDVI), a satellite-derived index of green vegetation (Tucker & Sellers, 1986). Satellite-derived NDVI is determined based on the solar radiation absorbed by the process of photosynthesis (predominantly red wavelengths) and that reflected by leaf structural and chemical components (near infrared) and provides a reliable index for the quantity of green vegetation. $NDVI = \frac{\text{NIR}-\text{Red}}{\text{NIR}+\text{Red}}$, where NIR is reflectance in near infrared radiation (725–1,000 nm), and Red is reflectance in visible red radiation (580–680 nm).

Recent studies have evaluated dynamics of coastally influenced, circumpolar arctic tundra vegetation. Bhatt et al. (2013) examined NDVI, Summer Warmth Index (SWI, sum of mean monthly temperatures >0 °C), and coastal sea ice (among other variables) of the Arctic from 1982–2011. The Eurasian Arctic experienced a 10% increase in MaxNDVI (peak annual value) from 1982 to 2011, whereas time-integrated NDVI (TI-NDVI;

time-integrated summer values) increased 10% from 1982 to 2005, before it began declining. The eastern North American Arctic experienced slight increases in MaxNDVI from 1982 to 2009 and greater increases from 2009 to 2011 for an overall 15% increase; TI-NDVI in eastern North America increased overall by 8%. The western North American Arctic experienced a steady increase in TI-NDVI (overall 8% increase) and an accelerated increase in MaxNDVI since 2005 (18% increase from 1986 to 2011; Bhatt et al., 2013).

Despite these and other observation of changes in tundra (Bhatt et al., 2017; Ju & Masek, 2016; Xu et al., 2013), the environmental controls on tundra vegetation dynamics (e.g., NDVI) are still not very well understood, although certain potential driving variables have been explored. Bhatt et al. (2010, 2013) found negative correlations between NDVI and Arctic sea ice extent (i.e., less sea ice was related to greater NDVI). Macias-Fauria et al. (2012) found that vegetation growth during the peak growing season responded strongly to the position of continental air mass in the Eurasian Arctic. Bieniek et al. (2015) investigated biweekly NDVI values of the Alaskan tundra in three locations (coastal areas of the Beaufort, East Chukchi, and East Bering Seas) from 1982 to 2013. In all three regions, lower NDVI values during the early growing season were related to increasing spring snow depth and potentially later snowmelt (Bieniek et al., 2015). Another study investigating long-term NDVI trends in Alaskan tundra found a strong correlation between NDVI and the SWI from the previous year (Verbyla, 2008).

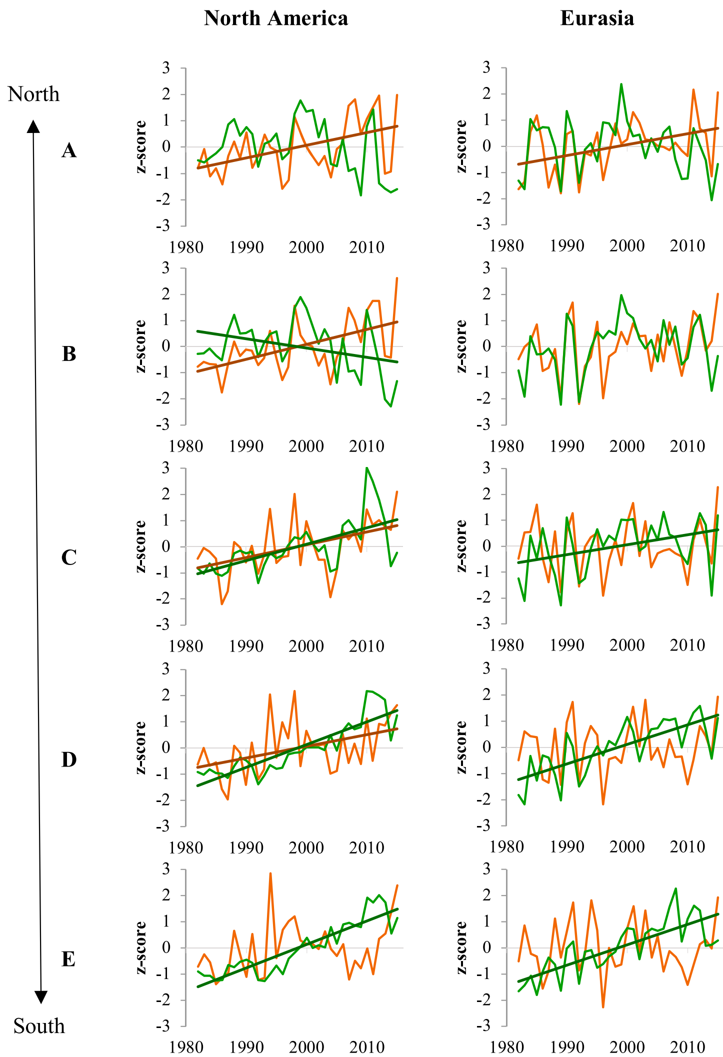
Previous studies on tundra vegetation dynamics have illustrated the substantial spatial (and temporal) heterogeneity of arctic tundra greening trends. Earlier studies of tundra greening suggested that this phenomenon was largely due to tall shrub expansion in riparian areas (Sturm et al., 2001). However, Frost and Epstein (2014) found greening in Siberia to be occurring in upland areas as well, also as a result of tall shrub (alder) expansion. The greening (NDVI increases) observed was occurring more rapidly in areas of expanding shrublands than those of existing shrub tundra (Frost et al., 2014), facilitated by disturbances to other vegetation, such as fires, landslides, and frost heave (Frost et al., 2013). A study of the Canadian Arctic over recent decades related spatiotemporal NDVI trends to plant functional type composition. The greatest greening occurred in tundra subzones C and D (midsouthern tundra; based on the Circumpolar Arctic Vegetation Map, CAVM Team 1995), where dominant sedges may have responded rapidly to interannual warming (Jia et al., 2009).

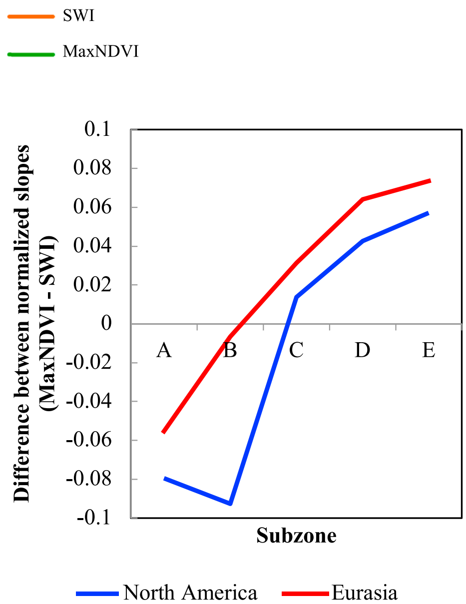
While arctic tundra greening patterns (e.g., NDVI trends) as a whole have been widely investigated, few studies have rigorously evaluated in detail the spatial and temporal heterogeneity of temperature-vegetation relationships throughout the circumpolar Arctic. An understanding of how these patterns of greening vary systematically with latitude and by continent is a next step in determining the spatial variability in tundra vegetation dynamics and perhaps elucidating different environmental controls on tundra vegetation productivity. This study investigates long-term trends in SWI and NDVI over the length of the remote sensing record (1982–2015) and how they vary by tundra bioclimate subzone and continent (North America and Eurasia). It also explores interannual variabilities of SWI and NDVI by tundra bioclimate subzone and continent. In addition, possible controls of arctic tundra NDVI are evaluated through investigating annual relationships between SWI and NDVI.

## 2. Materials and Methods

Satellite-derived, biweekly composited NDVI data were acquired from the NASA GIMMS3g data set developed largely from Advance Very High Resolution Radiometer sensors flown on National Oceanic and Atmospheric Administration satellites (Pinzon & Tucker, 2014). Two NDVI-related variables were calculated as indices for vegetation activity: MaxNDVI and TI-NDVI. MaxNDVI is the maximum annual NDVI value (essentially the summer peak), thereby depicting peak photosynthetic capacity. TI-NDVI is the sum of biweekly NDVI values greater than 0.05 from May to September, thereby depicting the total vegetation activity and indicative of net primary production throughout the growing season. All analyses described herein referring to NDVI were done for both MaxNDVI and TI-NDVI. SWI data were determined from remotely sensed Land Surface Temperature data (also from the Advance Very High Resolution Radiometer record; Comiso, 2003) as the sum of mean monthly surface temperatures greater than 0 °C (°C months). Data were separated by continent and Arctic bioclimate subzone (A-E) from 1982 to 2015. The bioclimate subzones of the Circumpolar Arctic Vegetation Map categorize the tundra essentially latitudinally, with Subzone A being the coldest, highest latitude and Subzone E being the warmest, lowest latitude nonalpine tundra (Walker et al., 2005).

To compare the temporal trends between temperature and vegetation change, SWI and NDVI values for each pixel were averaged for each year by bioclimate subzone and continent, and then trends were calculated.




p-value

| | North America | | Eurasia | |
|---|---|---|---|---|
| | SWI | MaxNDVI | SWI | MaxNDVI |
| A | 0.004 | 0.072 | 0.015 | 0.443 |
| B | <0.001 | 0.040 | 0.098 | 0.204 |
| C | 0.003 | <0.001 | 0.690 | 0.025 |
| D | 0.009 | <0.001 | 0.544 | <0.001 |
| E | 0.059 | <0.001 | 0.802 | <0.001 |

slope

| | North America | | Eurasia | |
|---|---|---|---|---|
| | SWI | MaxNDVI | SWI | MaxNDVI |
| A | 0.048 | -0.031 | 0.042 | -0.014 |
| B | 0.057 | -0.036 | 0.029 | 0.023 |
| C | 0.049 | 0.063 | 0.007 | 0.038 |
| D | 0.045 | 0.087 | 0.012 | 0.075 |
| E | 0.033 | 0.090 | 0.005 | 0.078 |

**Figure 1.** Summary of MaxNDVI and Summer Warmth Index (SWI) *z* scores by bioclimate subzone (A through E) for North America and Eurasia (only significant regression lines plotted); summary graph of regression slopes (the positive values indicate that MaxNDVI is increasing relatively faster than SWI; the negative values indicate that SWI is increasing relatively faster than MaxNDVI); tables of *P* values and slopes of linear regressions by bioclimate subzone and continent.

Linear regression analyses compared normalized SWI and NDVI values over time for the various spatial classifications of tundra (subzone and continent). Data were normalized using *z* scores, allowing for more direct comparison of temporal trends in NDVI and SWI, which vary in units, magnitudes, and starting values. This approach also minimized the effect of possibly anomalous starting values. The difference between slopes (*m* values) of these trend lines (NDVIm − SWIm) indicated whether vegetation (NDVI) or temperature (SWI) was increasing (or decreasing) by larger relative magnitudes. Positive values of slope differences indicated that NDVI increased relatively faster than SWI over the 34-year period, whereas negative values indicated that SWI increased relatively faster than NDVI (Figure 1).

To examine interannual variability of SWI and NDVI by subzone and continent irrespective of the trends, first, the raw data were detrended. Residuals were calculated as the difference between the annual linear trend values and the actual data points for both SWI and NDVI. Variances of residuals were used to compare interannual variabilities of SWI and NDVI across bioclimate subzones and continents, irrespective of any directional trend. Coefficients of variation were also calculated to compare relative variabilities, accounting for differences in mean values.

Finally, several analyses were conducted to examine possible controls of NDVI in any given year or what controls NDVI change from year to year. First, a general linear regression of NDVI as a function of SWI was conducted to determine direct controls of cumulative summer warmth on NDVI by bioclimate subzone and continent. Second, to examine the extent to which the temperature of a given year correlated with vegetation change from the prior year, a linear regression analysis between SWI and the difference between the NDVI of that year and the NDVI of the prior year was conducted for each bioclimate subzone and continent. A third analysis compared annual changes in SWI and NDVI. Differences between the SWI of 1 year and the SWI of the prior year were regressed against the differences between the NDVI of 1 year and the NDVI of the prior year. Slopes of these regressions were used to evaluate the responses of NDVI to SWI by bioclimate subzones and continents. A final linear regression analysis evaluated the detrended NDVI of 1 year as a function of the NDVI of the previous year for each bioclimate subzone and continent, demonstrating to what degree the vegetation of 1 year was correlated with the vegetation of the prior year, irrespective of any trend. $P$ values are calculated for all regressions, and only trend lines of significant regressions ($P$ values $< 0.05$) were displayed in figures.

## 3. Results

Regressions of the detrended MaxNDVI/TI-NDVI of 1 year and the MaxNDVI/TI-NDVI of the next year showed no significant relationships for any subzone/continent combination. Therefore, irrespective of any trend, there is no relationship between NDVI in a given year and NDVI of the following year, and therefore, the individual years may be considered as independent samples.

The differences between normalized MaxNDVI changes and SWI changes were lowest (most negative) in subzone A for Eurasia and in subzone B for North America (Figure 1). In subzone A of both North America and Eurasia, there were significant positive trends in SWI, but no significant trend in MaxNDVI. Differences between the normalized changes in MaxNDVI and SWI increased (and switched from negative to positive) with decreasing latitude (with the exception of subzone B in North America). Thus, at high latitudes (subzones A and B), the SWI normalized changes were greater than those for MaxNDVI for both continents. At lower latitudes (subzones D and E), the MaxNDVI normalized changes were greater than those for SWI for both continents (differences between MaxNDVI and SWI regression slopes range from 0.01 to 0.09). In contrast to what was observed for subzone A, both North America and Eurasia demonstrate significant positive trends in MaxNDVI for subzone E, but no significant trends in SWI. The Eurasian continent had more positive differences between the slopes of MaxNDVI and SWI relative change across all subzones and fewer significant trends in SWI compared to North America (Figure 1).

Most TI-NDVI trends were consistent with MaxNDVI relative changes. The most notable disparity was the overall more negative difference between regression slopes of normalized TI-NDVI and SWI compared to MaxNDVI (i.e., SWI increasing to a greater extent relative to TI-NDVI; Figure S1 in the supporting information). Further, North America demonstrated more positive differences between regression slopes of TI-NDVI and SWI compared to Eurasia (with the exception of subzone B), which contrasts the pattern seen in MaxNDVI. Subzone B of North America experienced the most negative difference between regression slopes of TI-NDVI and SWI relative change. Additionally, there were fewer significant trends in TI-NDVI compared to MaxNDVI, especially in Eurasia (significantly negative trend only for subzone A).

Summer Warmth Index generally had greater detrended variances in southern subzones, which were greater for North America than Eurasia (Figure 2a). However, because of the greater magnitude of SWI variances, there were no statistically different values across bioclimate subzones and continents ($P > 0.05$). MaxNDVI variances were greatest in midsubzones, with both Eurasia and North America experiencing the greatest variances in subzone C. Eurasia had much higher variation in subzones B and C, slightly lower variation in subzone D, and very similar variation in subzones A and E compared to North America. For TI-NDVI, Eurasia variances were much greater than those for North America, except for subzone A, where they were similar. In both continents, the variance increased through subzones A, B, and C. In Eurasia, variances were slightly lower in subzones D and E compared to the rest of the continent. In North America, variance remained relatively constant through subzones C, D, and E.

The coefficients of variation of SWI, MaxNDVI, and TI-NDVI generally decreased from north to south. North America had greater coefficients of variation than Eurasia in both subzones A and B for SWI, MaxNDVI, and TI-NDVI, but not all of these differences were significant ($P > 0.05$). MaxNDVI and TI-NDVI had very similar values for coefficients of variation across all subzones, especially for North America (Figure 3).

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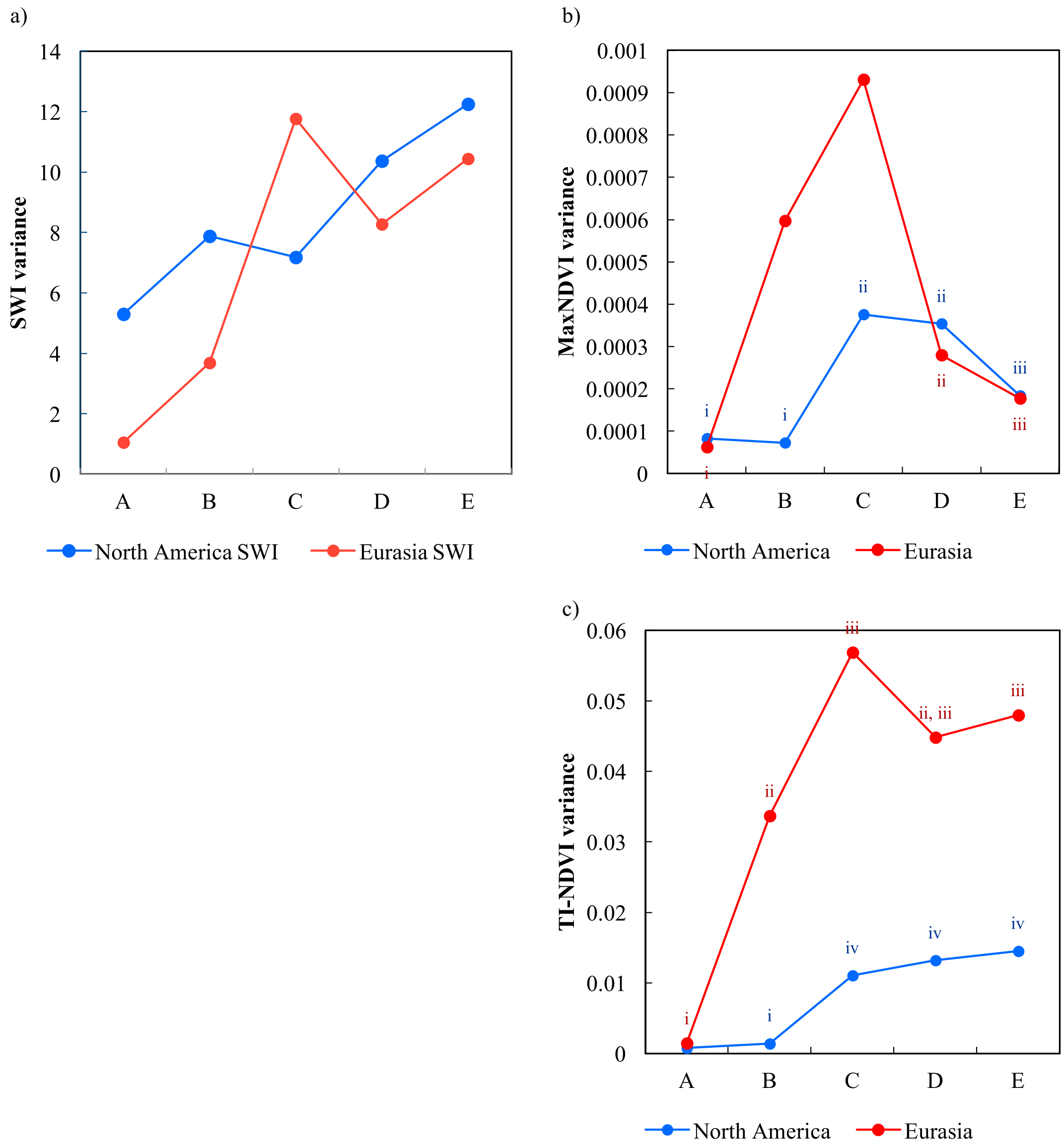


**Figure 2.** Summary of residual variances of (a) Summer Warmth Index (SWI), (b) MaxNDVI, and (c) time-integrated Normalized Difference Vegetation Index from 1982 to 2015 by bioclimate subzone (A through E); the roman numerals indicate variances that are not significantly different ($P > 0.05$) on (b) and (c); there were no significant differences between SWI variances.

The regressions of SWI and MaxNDVI by subzone and continent were strongest with significant, positive relationships in the mid subzones, whereas more northern and southern subzones showed weaker, less significant relationships. There is essentially no relationship between SWI and MaxNDVI in subzones A, B, and E of North America. However, there is a positive, significant correlation in subzone C ($r^2$ = 0.36) and a weaker, but still significant, positive correlation in subzone D ($r^2$ = 0.15) over the 34-year period. There is also no significant relationship between SWI and MaxNDVI in subzones D and E of Eurasia. The strongest and most positive correlation between SWI and MaxNDVI in Eurasia occurs in subzone B ($r^2$ = 0.23). Subzones A and C of Eurasia show weaker, but significant, positive correlations ($r^2$ = 0.18 and 0.16, respectively; Figure 4).

Regressions of SWI and TI-NDVI exhibited strong, positive relationships in midsouthern subzones. There were no significant correlations in subzones A, B, and E on either continent. In Eurasia, subzone D had a weak, but significant, positive correlation ($r^2$ = 0.13). Subzone C had a slightly stronger significant positive correlation

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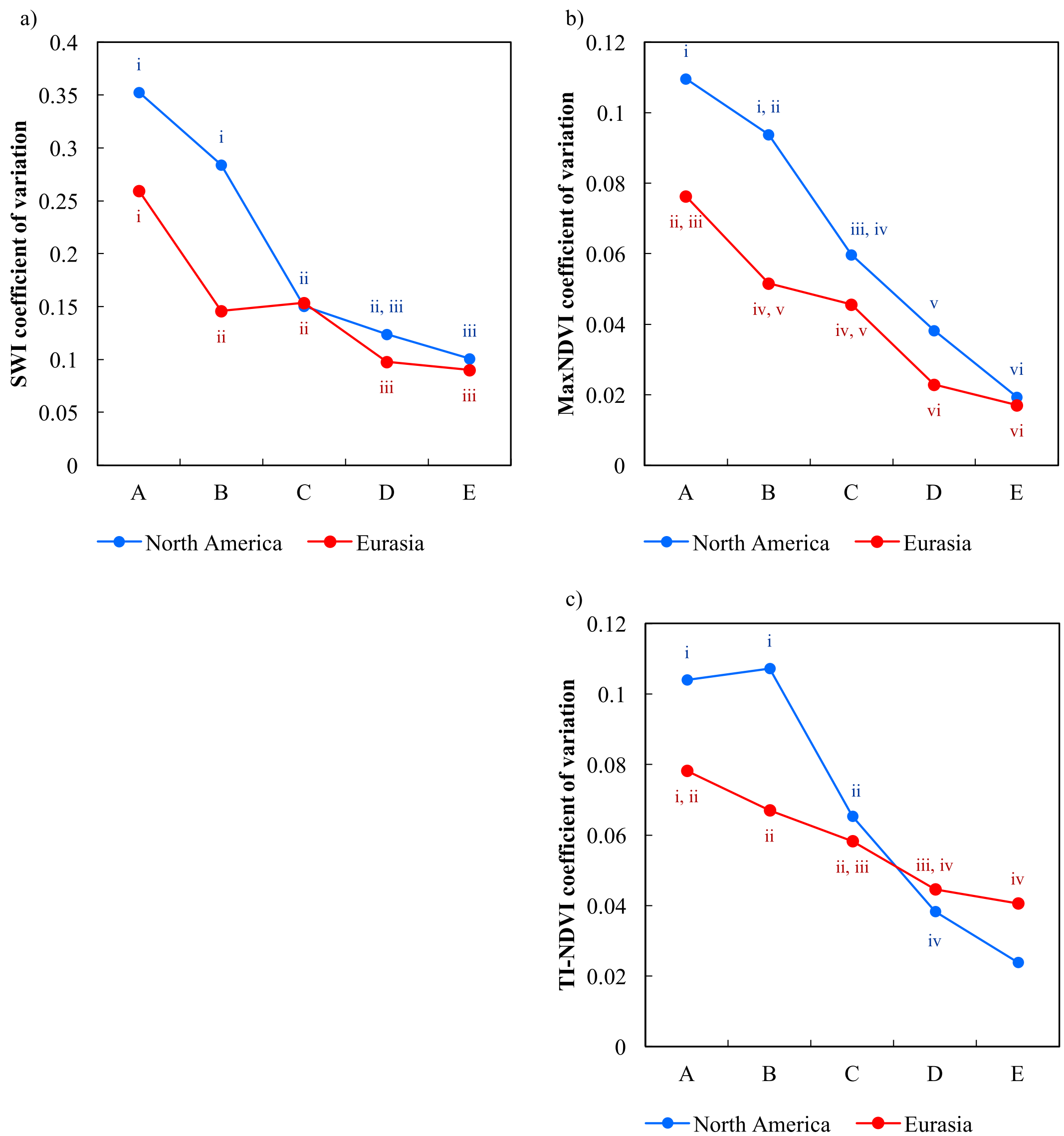


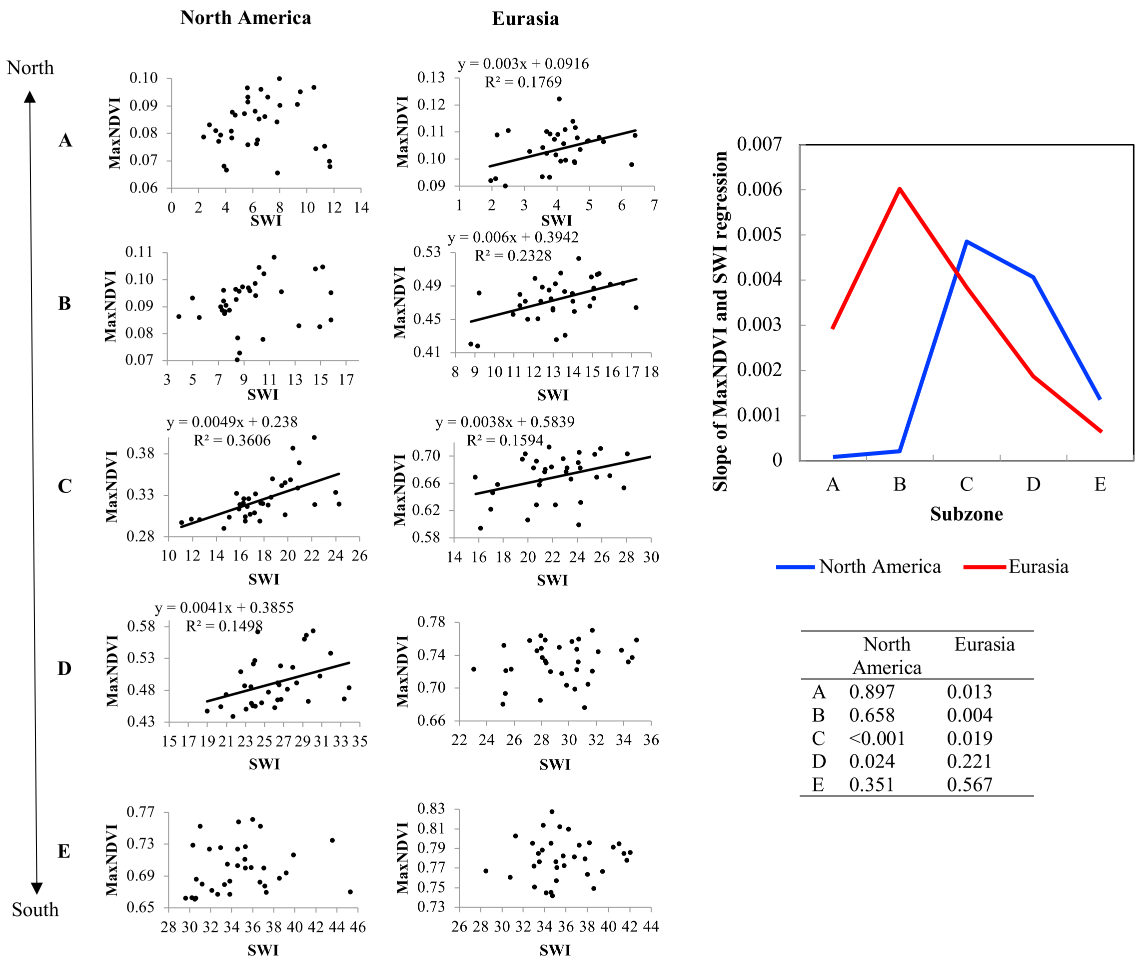

**Figure 3.** Summary of residual coefficients of variation of (a) Summer Warmth Index, (b) MaxNDVI, and (c) Normalized Difference Vegetation Index from 1982 to 2015 by bioclimate subzone (A through E); the roman numerals indicate coefficients of variation that are not significantly different ($P > 0.05$).

($r^2 = 0.17$). In North America, subzones C and D had relatively strong significant positive correlations ($r^2 = 0.23$ and 0.21, respectively; Figure S2).

These general trends were consistent with regressions of SWI and the difference between MaxNDVI/TI-NDVI of 1 year and MaxNDVI/TI-NDVI of the prior year. The strongest, most positive relationships in Eurasia occurred in subzone B, and these declined in the more southern subzones. The strongest, most positive relationships in North America occurred in subzone C, and these declined in more northern and southern subzones. Eurasia also had overall more positive relationships. These trends also were consistent with regressions of the difference between SWI of 1 year and the prior year versus the difference between MaxNDVI/TI-NDVI of one year and the prior year (results not shown).

## 4. Discussion

The temporal dynamics of vegetation across Arctic latitudes and continents could provide essential information for understanding the processes driving current tundra greening/browning patterns, as well as being able




| | North America | Eurasia |
|---|---|---|
| A | 0.897 | 0.013 |
| B | 0.658 | 0.004 |
| C | <0.001 | 0.019 |
| D | 0.024 | 0.221 |
| E | 0.351 | 0.567 |

**Figure 4.** Regression of Summer Warmth Index and MaxNDVI for each bioclimate subzone (A through E) for North America and Eurasia (only significant trends plotted); summary graph of the regression slopes; table of *P* values of linear regressions by bioclimate and subzone.

to predict future trends. Vegetation changes affect land-surface albedo, permafrost thaw, animal migration patterns, carbon sequestration, human activities, and more (e.g., Fauchald et al., 2017; Frost et al., 2017; Horstkotte et al., 2017; Kępski et al., 2017). This study has identified (1) the dynamic patterns of arctic tundra vegetation and (2) the degree to which summer warmth drives tundra vegetation change, and results will provide inputs to analyses that evaluate vegetation change effects on other tundra properties.

From a spatial perspective, throughout the arctic tundra, there is a strong positive relationship between summer temperatures and both NDVI and aboveground tundra biomass (Epstein et al., 2008; Raynolds et al., 2012; Walker et al., 2012), and therefore, a positive temporal correlation between SWI and NDVI may be expected. However, the temporal relationship between summer temperatures and vegetation productivity in arctic tundra is likely complex, with mixed findings in the literature. Numerous field studies suggest that interannual variability in tundra productivity is generally constrained and not strongly linked to summer temperatures (e.g., Chapin III & Shaver, 1985; Hudson & Henry, 2010), although others show positive relationships between summer temperatures and tundra plant growth (Callaghan et al., 1989; Van der Wal & Stien, 2014). In our coarse-scale remote sensing analysis, we did not find consistent relationships between NDVI and SWI (integrated summer warmth), and there are potentially several reasons why increasing SWI over time might not lead to concomitant increases in NDVI. One reason is that increasing summer warmth could lead to melting of ground ice and/or thawing of permafrost, the development of thermokarst, and the ponding of surface water, which would decrease the landscape NDVI signal (at least at the resolutions of many current satellite sensors; Liljedahl et al., 2016; Raynolds et al., 2014). Increases in fall and winter temperatures (likely correlated with SWI) can potentially lead to increases in snow depth, a later melt of the deeper snowpack, and a reduced spring NDVI (Bhatt et al., 2017). Additionally, the melting of coastal sea ice with increases in SWI will reduce the degree of continentality of the adjacent landmasses, with complex indirect effects on regional temperatures and the productivity of vegetation (Macias-Fauria et al., 2017).

The results of this study indicate that temporal relationships between SWI and NDVI are strongest in middle and more southern subzones of the Arctic. In northern subzones, SWI increases to a relatively greater degree than both MaxNDVI and TI-NDVI over the 34-year period (Figures 1 and 2). The muted increase in NDVI compared to SWI seen in northern latitudes is consistent with other Arctic remote sensing (Vickers et al., 2016) and field (Bjorkman et al., 2017; Edwards et al., 2016) studies. There is less vascular vegetation biomass and greater relative nonvascular vegetation biomass as latitude increases (Epstein et al., 2008), and these types are likely to exhibit different responses to changing temperatures. In addition, delays in vegetation response are due to growth constraints of the existing small, cold-adapted plants, as well as limits on reproduction and colonization by new species from warmer areas. In more southern subzones, experiencing equivalent or greater increases in NDVI than SWI, vegetation increase is potentially the effect of positive feedback mechanisms (e.g., more vegetation leads to greater growth). Additionally, increased vegetation decreases albedo (particularly in the spring), which leads to an increase in sensible heat flux and warmer near-surface air temperatures (Chapin III et al., 2005; Lawrence & Swenson, 2011), promoting vegetation growth. Greater vegetation increases relative to SWI increases can also be the result of climate-related disturbances, such as fire, and landslides, which expose substrate for shrub expansion (e.g., Jin et al., 2012; Lantz et al., 2013; Liebman et al., 2015).

Elmendorf et al. (2012) found that tall shrubs (characteristic of southern subzones) increased in warming experiments, while dwarf shrubs (more characteristic of midlatitude tundra subzones) decreased under experimental warming. Thus, it was predicted that most shrub expansion would occur in subzones D and E, while higher latitude regions would be resistant to shrub expansion. Tall shrub expansion has been observed to occur throughout the southern tundra subzones (e.g., Frost & Epstein, 2014; Myers-Smith et al., 2011; Sturm et al., 2001). These results, along with other studies finding increasing NDVI and "greening" with temperature in southern subzones (Epstein et al., 2012; Forbes et al., 2010; Pouliot et al., 2009), are consistent with our results. Interestingly, Lloyd et al. (2011) found increased productivity with warming only in northern Siberian taiga rather than more southern taiga regions. Thus, increasing NDVI in response to warming temperatures may be most prominent in southern tundra, northern taiga, and their ecotone.

Regressions of SWI and NDVI indicate that midsubzone (B and C) vegetation is more highly correlated with SWI than higher and lower latitudes on an annual scale. Further, our data demonstrate that NDVI generally correlates to a greater extent with SWI in Eurasia compared to North America. Similar conclusions were made by Myers-Smith et al. (2015), who found climate sensitivity of shrub growth heterogeneous, with greater sensitivity in northern Eurasian sites and sites with higher soil moisture. Myers-Smith et al. (2015) further found that, by latitude, climate sensitivity of growth was greatest at the boundary between the Low and High Arctic. Prevéy et al. (2017), on the other hand, found that flowering and leaf emergence were more sensitive to temperature in colder, more northern latitudes than warmer Arctic sites on an annual basis. However, temperature sensitivity in the date of a phenological event may not be related to the sensitivity of an index of vegetation quantity (e.g., NDVI). Finally, the lack of any correlation between detrended NDVI and the prior year values shows that vegetation quantity in a given year does not affect vegetation in the following year beyond the current directional trend; in other words, there is minimal, if any, temporal autocorrelation (1-year lag) in the detrended NDVI. Examining the 1-year lag autocorrelation in the NDVI data, including any trend, shows no evidence of any accelerating trends; in fact, many of the subzone-continent combinations indicated potential negative feedbacks (results not shown).

In summary, vegetation (NDVI) and temperature (SWI) trends from 1982 to 2015 differed substantially with latitude (and somewhat with continent); relative temperature increases were much greater than relative vegetation increases in the northernmost tundra regions (subzone A), and this difference decreased with decreasing latitude (i.e., further south), even to the extent where NDVI had a greater relative increase than SWI. Relative interannual variabilities in NDVI and the interannual responses of NDVI to SWI were greatest in midtundra subzones (e.g., subzones B–D), compared to the furthest north and furthest south tundra regions. These results are extremely valuable for understanding how a heterogeneous arctic tundra biome is responding to climate dynamics, and for how these systems might continue to change in the future.

**Acknowledgments**
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