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Remote sensing of interannual boreal forest NDVI in relation to climatic conditions in interior Alaska

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Abstract
Climate has warmed substantially in interior Alaska and several remote sensing studies have documented a decadal-scale decline in the normalized difference vegetation index (NDVI) termed a ‘browning trend’. Reduced summer soil moisture due to changing climatic factors such as earlier springs, less snowpack, and summer drought may reduce boreal productivity and NDVI. However, the relative importance of these climatic factors is poorly understood in boreal interior Alaska. In this study, I used the remotely sensed peak summer NDVI as an index of boreal productivity at 250 m pixel size from 2000 to 2014. Maximum summer NDVI was related to last day of spring snow, early spring snow water equivalent (SWE), and a summer moisture index. There was no significant correlation between early spring SWE and peak summer NDVI. There was a significant correlation between the last day of spring snow and peak summer NDVI, but only for a few higher elevation stations. This was likely due to snowmelt occurring later at higher elevations, thus having a greater effect on summer soil moisture relative to lower elevation sites. For most of boreal interior Alaska, summer drought was likely the dominant control on peak summer NDVI and this effect may persist for several years. Peak summer NDVI declined at all 26 stations after the 2004 drought, and the decline persisted for 2 years at all stations. Due to the shallow rooting zone of most boreal plants, even cool and moist sites at lower elevations are likely vulnerable to drought. For example the peak summer NDVI response following the 2004 drought was similar for adjacent cold and warm watershed basins. Thus, if frequent and severe summer droughts continue, moisture stress effects are likely to be widespread and prolonged throughout most of interior boreal Alaska, including relatively cool, moist sites regardless of spring snowpack conditions or spring phenology.

1. Introduction
Over the past 50 years, the highest rate of climate warming in North America has occurred in Alaska and Northwest Canada (Clegg and Hu 2010). This warming has led to substantial physical and biological changes in Alaska including record sea-ice retreat and autumn warming (Wendler et al 2010), record summer warmth (Barber et al 2004), record wildfire extent (Kasischke et al 2010) and wildfire frequency (Kelly et al 2013), accelerated permafrost thawing (Jorgenson et al 2010), shrinking boreal lakes (Roach et al 2011, Jepsen et al 2013), shrinking mountain glaciers (Arendt et al 2002, Das et al 2014) and a longer unfrozen period (Wendler and Suhlski 2009).

One consequence of a warming boreal climate has been regional drought stress leading to reduced tree growth (Barber et al 2000), regional tree mortality (Peng et al 2011, Williams et al 2012) and a decline in the remotely sensed normalized difference vegetation index (NDVI), termed a ‘browning trend’ (Goetz et al 2005, Lloyd and Bunn 2007). A prolonged and extensive regional decline in NDVI (browning trend) has occurred in Eastern boreal Alaska and Western boreal Canada (Beck and Goetz 2011). The browning trend may be due to temperature-induced summer drought stress (Barber et al 2000, Lloyd and Bunn 2007) as the optimal temperature for boreal plant growth is exceeded (D’Arrigo et al 2004, Lloyd et al 2013, Juday et al 2014). Based on analysis of NDVI
and tree ring measurements, Beck et al (2011) suggested that water availability has increasingly limited boreal productivity in interior Alaska since the 1980s.

With climate warming, earlier melting of snowpack may also lead to soil moisture deficits occurring earlier in the growing season, resulting in a decline in summer peak NDVI (Grippa et al 2005, Trujillo et al 2012). For example, in a North America boreal study, Buermann et al (2013) found a strong correlation ($R > 0.50$) between date of spring thaw and summer peak NDVI for the Western boreal regions of North America. In a field experiment to exclude summer rain, Yarie (2008) concluded that in low elevation upland sites near Fairbanks, melting snowpack was a major source for tree growth that may have buffered any effect of the exclusion of summer precipitation. Barilihich et al (2014) also claimed that changes in snow dynamics appear to be more important than increased evaporative demand in controlling summer NDVI in moisture-sensitive regions of the circumpolar boreal forest.

In this study, I investigated the interannual pattern of peak summer NDVI in relation to spring snow conditions and summer climatic conditions from 2000 through 2014. Since decline in boreal productivity in this region has been interpreted as sign of widespread drought stress (Beck et al 2011, Juday et al 2014, Walker et al 2014), I expected summer maximum NDVI to have a positive correlation with early spring snow water equivalent (SWE) and with spring date of last snow. I also expected a positive relationship between summer maximum NDVI and a summer moisture index. Since microclimate strongly controls soil moisture, I also investigated the pattern of peak NDVI following a major drought event within a relatively warm nearly permafrost-free basin compared to an adjacent colder basin dominated by permafrost.

2. Materials and methods

2.1. Study area

The study area was interior boreal Alaska where a decadal scale declining NDVI trend has been documented by several studies using several different sensors (Verbyla 2008, Parent and Verbyla 2010, Beck et al 2011, Baird et al 2012). The area is bounded to the North and South by large mountain ranges resulting in a West-to-East maritime-to-continental climate gradient. Eastern and central interior Alaska has a growing season that is warmer and drier relative to much of the North American boreal zone (Juday et al 2014). During summer drought, daily temperatures can exceed 26°C and total summer precipitation can be less than 50 mm, with daytime exceeding 20 h (Wendler and Suhlski 2009) and vapor pressure deficits can exceed 1.5 kPa (Welp et al 2007, Sedano and Randerson 2014).

Near the Western edge of the study area, boreal forest transitions into shrub tundra due to the cooler/moister climate from the coastal marine boundary layer (Simpson et al 2002). Boreal forest tree line occurs at an elevation of approximately 800–900 m (Lloyd and Fastie 2003) with alpine shrub tundra common above treeline. The majority of the study area is characterized by local mountains, large areas of hilly uplands, meandering rivers with broad floodplains and extensive wetland regions. Black spruce forests dominate colder sites, such as valley bottoms and North-facing slopes, and are often underlain by permafrost. White spruce occurs on warmer sites such as active floodplains and South-facing slopes. Deciduous forest (aspen, birch, and balsam poplar) also occur on warmer sites, especially following disturbance. The vegetation mosaic of this region is primarily controlled by disturbance legacies (primarily wildfire and alluvial deposition/erosion) and topographic control of microclimate.

2.2. Climate data

SWE data were available from the Natural Resources Conservation Service (http://wcc.nrcs.usda.gov/snow/) as daily measurements at 21 locations (figure 1(a)) within the study area. These locations were buffered by 10 km, and summer peak NDVI values were extracted from within each buffer to compare with the 1 April (early spring) measured SWE values from 2000 to 2014.

The effect of 1 April SWE on soil moisture was investigated. Soil moisture data at 5–50 cm from Bonanza Creek Experimental Forest, near Fairbanks (http://iter.uaf.edu/data.cfm) were available from 2003 to 2012. These measurements were recorded hourly using a CS615 water content reflectometer and converted to volumetric percent water content using the Topp’s equation. For this study, only measurements with a quality control value of ‘Good’ were used and the daily mean soil volumetric water percent was computed from the hourly measurements from observed day of budburst through the end of August.

Within this region there were 26 climate stations that had precipitation and temperature data for the 2000–2014 period. These stations were buffered by 10 km for this study (figure 1(b)). A buffer size of 10 km was used to represent precipitation which typically varies more than temperature. For example, Fairbanks and Big Delta climate stations both occur on the Tanana River floodplain and are within 100 km of each other. The 1997–2014 correlation between these two stations was stronger for mean summer temperature (Pearson’s $r = 0.95$) relative to total summer precipitation ($r = 0.71$). In boreal Canada, Kljun et al (2006) also found significant variability in precipitation over 80–100 km during a major regional drought period. The 10 km buffers did not overlap, thus each buffer represented different NDVI pixels. The climate
stations included remote automated weather stations and primary weather stations (Western Regional Climate Center, www.wrcc.dri.edu). Summer (June, July, and August) mean temperature and summer total precipitation were obtained for the years 1997–2014. These values were normalized as a difference from the mean, divided by the standard deviation. The normalized summer temperature was then subtracted from the normalized summer precipitation as a moisture index (Barber et al. 2000) for each summer from 1997 to 2014. Negative moisture index values represent warmer/drier summers, while positive values represent cooler/wetter summers relative to the 1997–2014 mean for each climate station.

To examine the effect of microclimate on peak summer NDVI response following the 2004 drought, the maximum NDVI within two adjacent watershed basins were extracted from 2003 through 2008. These 5–6 km² basins are within the Caribou-Poker Creek Research Watershed, 50 km Northeast of Fairbanks. Low sun angle throughout the year results in less energy reaching slopes with North-facing aspects than slopes with South-facing aspects. In this study, the C3 basin is cold predominantly North-facing basin, with black spruce and permafrost dominating, while the C2 basin is relatively warm with aspen-birch forest and is nearly permafrost-free (Petrone et al. 2006). I expected the peak summer NDVI response to differ between these basins, with relatively greater decline in NDVI due to drought effects expected in the warmer basin.

2.3. Processing remotely sensed data
Two MODIS Land Products were used in this study: NDVI and snow extent. These products are available globally from 2000 to present. The MODIS 250 m NDVI product version 5 (Huete 2002) was used in this study, downloaded from http://earthexplorer.usgs.gov. This product is based on the MODIS sensor. 

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**Figure 1.** Study area bounded by Alaska and Brooks Ranges. The MODIS H11V02 is extends South of the Alaska Range. (a) The 21 snow water equivalent (SWE) locations are: (1) Bonanza Creek LTER, (2) Borealis, (3) Boundary, (4) Caribou, (5) Chicken, (6) Fairbanks, (7) Fort Greely, (8) Gerslie River, (9) Jatamund, (10) Kantishna, (11) Lake Michumina, (12) Monument, (13) Mount Fairplay, (14) Nolita, (15) Paradise, (16) Parmigan Creek, (17) Seven Mile, (18) Shaw Creek, (19) Thirty Mile, (20) Tok, (21) Upper Chena. (b) The 26 climate (monthly precipitation and mean temperature) stations are: (1) Alcan, (2) Angel Creek, (3) Big Delta, (4) Caribou Peak, (5) Chatanika, (6) Chicken, (7) Cottonwood, (8) Eagle, (9) Fairbanks, (10) Goodpaster, (11) Hogtsa River, (12) Kanuti, (13) Koyukuk, (14) Lake Michumina, (15) Livengood, (16) Noratak Lake, (17) Northway, (18) Poorman, (19) Round Lake, (20) Salcha, (21) Seven Mile, (22) Tanana, (23) Telida, (24) Tok, (25) Tok River, (26) Wein Lake.
onboard the Terra satellite (MOD1Q1, 2000–2014) and Aqua satellite (MYD1Q1, 2002–2014) as NDVI composites every 8 days. The H11V02 global tile covering interior Alaska (figure 1) was reprojected using nearest neighbor resampling to the Alaska Albers Equal Area NAD83 projection at 250 m pixel size. Only pixels with NDVI product reliability value of zero (good quality) were used in this study. To minimize the effect of unvegetated pixels and partially vegetated pixels, only pixels with an MODIS NDVI of at least 0.4 were used in this study. Forested pixels typically had maximum summer NDVI values above 0.8 for broadleaf forest and above 0.6 for spruce woodland (Parent and Verbyla 2010). To eliminate the effect of wildfire, all pixels that were within 1985–2014 wildfire perimeters (http://fire.ak.blm.gov/) were excluded from the analysis. For each year, the maximum NDVI value was extracted from each pixel from the time series of NDVI values from June through August. The mean maximum summer NDVI was also computed within the warmer C2 basin and the colder C3 basin following the 2004 drought within the Caribou-Poker Creek Research Watershed.

The MODIS 500 m snow extent product version 5 (Hall and Riggs 2007) was downloaded from the National Snow & Ice Data Center (http://nsidc.org/data/) for April through June of 2000–2014. This 8 day composite product (MOD10A2) contains a bit-level grid of each day of snow cover during the 8 day composite period at 500 m pixel size. In this study, the last day of detected spring snow cover was used as an index of the start of spring day of year.

Elevation data were downloaded from the National Elevation Dataset website (http://ned.usgs.gov/) and reprojected into the Alaska Equal Albers projection to match the NDVI and day of last snow pixels. Elevation zones were then delineated in increments of 100 m up to 1000 m which is above tree line for the study area.

Within each 10 km climate station buffer, the mean maximum summer NDVI was computed and related to the moisture index and to spring day of last snow for each year, and as a lagged response of 1, 2 and 3 years. The Pearson’s $r$ correlation coefficient was computed as a one-tail test with the alternative hypothesis of $r > 0$, since there was an expected positive correlation between summer maximum NDVI with summer moisture, spring day of last snow, and spring SWE.

### 3. Results and discussion

#### 3.1. Interannual relationship between maximum summer NDVI and spring snow

In this study there was no significant $(p < 0.10, n = 15$ years) correlation between 1 April SWE and peak summer NDVI (table 1). These results may have been due to snowmelt in April occurring over mostly frozen soils, while variability of May rain events had a greater impact on late spring soil moisture. For example, at Bonanza Creek Experimental Forest, near Fairbanks, there was no significant relationship between 1 April SWE and soil moisture at the beginning of June (figure 2). High spring snowpack may have a negative effect by extending the period that roots remain frozen, while warm spring air temperatures increase evaporative demand of coniferous species (Berg and Chapin 1994). In a carbon isotope study of Alaskan black spruce, Walker et al (2014) found that after winters of high snowpack, black spruce trees were more moisture stressed, particularly on North-facing slopes and they attributed this to high snowpack delaying the start of growing season and impeding photosynthesis due to colder spring soil temperatures.

In the Sierra Nevada Mountains of California, Trujillo et al (2012) found a significant positive relationship between measured SWE and maximum summer NDVI, with the relationship strongest at water-limited mid-elevations. Later snowmelt may have delayed and reduced summer drought effects, because later spring would correspond with lower spring evapotranspiration, and later snowmelt could be an important soil moisture source during the summer drought period.

The boreal soils of interior Alaska differ substantially compared to the Sierra Nevada. At even relatively warm sites, these boreal soils freeze down greater than 1500 cm. Due to cold soils over 85% of fine root biomass is typically in the upper 30 cm of the soil profile (Yuan and Chen 2010). Due to slowly warming soils, there is typically substantial lag between

| Station                  | Elevation (m) | $r$ (p-value) |
|--------------------------|---------------|---------------|
| Bonanza Creek LTER       | 351           | $-0.18$ $(0.73)$ |
| Boreal                  | 405           | $0.14$ $(0.31)$ |
| Boundary                | 1067          | $0.09$ $(0.37)$ |
| Caribou Mine            | 351           | $-0.11$ $(0.64)$ |
| Chicken Airstrip        | 503           | $0.32$ $(0.12)$ |
| Fairbanks               | 137           | $-0.25$ $(0.81)$ |
| Ft. Greely              | 457           | $-0.03$ $(0.54)$ |
| Gerdle River            | 366           | $-0.13$ $(0.67)$ |
| Jatuhambd               | 664           | $0.07$ $(0.40)$ |
| Kantishna               | 472           | $0.17$ $(0.28)$ |
| Lake Michumina          | 222           | $-0.14$ $(0.69)$ |
| Monument                | 564           | $-0.07$ $(0.60)$ |
| Mount Fairplay          | 945           | $0.33$ $(0.12)$ |
| Nolitna                 | 171           | $-0.10$ $(0.65)$ |
| Paradise                | 671           | $0.11$ $(0.34)$ |
| Parmign Creek           | 692           | $-0.17$ $(0.73)$ |
| Seven Mile              | 183           | $-0.30$ $(0.54)$ |
| Shaw Creek              | 299           | $0.03$ $(0.45)$ |
| Thirty Mile             | 411           | $-0.18$ $(0.74)$ |
| Tok                     | 503           | $-0.13$ $(0.67)$ |
| Upper Chena             | 869           | $0.09$ $(0.37)$ |
budburst in mid-May and maximum fine root growth rate in mid-July (Ruess et al 2006).

In a remote sensing study across the North American boreal forest, Buermann et al (2013) identified a dominant adverse influence of earlier spring on peak summer NDVI across drier Western and central regions, including the study area of interior Alaska. In this study, most stations had negative or weak correlations between summer maximum NDVI and spring day of last snow (table 2). The few stations with a significant positive correlation occurred at higher elevations (figure 3). This was likely due to later snowmelt at higher elevations, thus having a greater effect on summer soil moisture relative to lower elevation sites. For elevation zones within the entire study region, the relationship between mean summer maximum NDVI and mean day of last snow was negative for zones below 500 m (>70% of interior boreal Alaska), and positive at higher elevations (figure 4).

To further test that at lower elevations, later springs were not correlated with higher maximum NDVI, spring ice-out records from Nenana, elevation 110 m (Sagarin and Micheli 2001) and observed day of budburst from Fairbanks, elevation 140 m (http://lter.uaf.edu) were obtained and compared with mean summer maximum NDVI from 10 km buffers at these locations. There were no significant correlations between mean summer maximum NDVI and the observed metrics of ice-out or spring budburst (figure 5).

In this study, there was no dominant influence of earlier spring or heavier snowpack on peak summer NDVI at lower elevations. This was likely due to snowpack having limited effect on summer soil moisture. For example, at Bonanza Creek Experimental Forest, near Fairbanks, the 1 June soil moisture at 5–50 cm was not significantly related to date of spring budburst or 1 April SWE (figure 2, figure 6). It is likely that summer drought dominates any effect of increased soil moisture from heavy snowpack (figure 7). However, the effect of snowmelt on soil moisture during summer drought would likely be greater at higher elevations due to snowmelt occurring closer to the

Table 2. Correlation (Pearson’s r) between mean summer maximum NDVI and mean last day of snow within each 10 km climate station buffer (2000–2014). Correlations with p-value <= 0.10 are in bold, n = 15 years. MODIS snow extent pixels were 500 m, n > 1150 pixels within each 10 km buffer.

| Station          | r (p-value) |
|------------------|-------------|
| Alcan            | 0.31 (0.13) |
| Angel Creek      | 0.03 (0.46) |
| Big Delta        | 0.25 (0.19) |
| Caribou Peak     | 0.12 (0.34) |
| Chatanika        | -0.04 (0.56) |
| Chicken          | 0.52 (0.02) |
| Cottonwood       | -0.44 (0.95) |
| Eagle            | 0.58 (0.01) |
| Fairbanks        | -0.12 (0.67) |
| Goodpaster       | 0.10 (0.36) |
| Hogtsa River     | -0.15 (0.70) |
| Kanuti           | -0.26 (0.83) |
| Koyukuk          | -0.27 (0.84) |
| Lake Michumina   | -0.08 (0.62) |
| Livengood        | 0.29 (0.14) |
| Noratak Lake     | -0.43 (0.94) |
| Northway         | 0.45 (0.04) |
| Poorman          | -0.02 (0.52) |
| Round Lake       | -0.12 (0.67) |
| Salcha           | 0.14 (0.32) |
| Seven Mile       | 0.18 (0.26) |
| Tanana           | 0.07 (0.41) |
| Telida           | -0.11 (0.65) |
| Tok              | 0.38 (0.08) |
| Tok River        | 0.43 (0.05) |
| Wein Lake        | 0.09 (0.38) |
Figure 3. Correlations of mean summer maximum NDVI and mean day of last snow (Pearson’s $r$) within station 10 km buffers by station elevation.

Figure 4. Correlations of mean summer maximum NDVI and mean day of last snow (Pearson’s $r$) within each elevation zone throughout entire study area. ($n = 15$ years, 2000–2014)

Figure 5. 2000–2014 start of spring field observations and mean maximum summer NDVI within 10 km buffers at Fairbanks (spring budburst) and Nenana (spring ice-out), Alaska.
summer drought period at higher elevations. In this study there was a strong correlation (Pearson’s $r$ exceeding 0.90) between day of last snow and elevation for each spring 2000–2014.

3.2. Interannual relationship between maximum NDVI and moisture index
Climate station buffers with a significant positive correlation to the summer moisture index occurred in central and Eastern interior Alaska (figure 8). This was likely due to the East–West climatic gradient with warmer and drier growing seasons occurring in central and Eastern Alaska. This regional pattern is consistent with boreal Alaska tree-ring studies (Lloyd and Fastie 2002, Juday et al 2014) and remote sensing studies (Goetz et al 2005, Verbyla 2008, Beck et al 2011).

All 26 stations had a non-significant ($p > 50$) correlation between maximum summer NDVI and summer moisture index (table 3). This was likely due to a lagged response of NDVI to growing season climate. The stations with significant correlations ($p <= 0.10$) had a NDVI lag of 1 or 2 years (table 3). This lag is consistent with tree-ring study results in boreal Alaska with a 1–2 year lagged response of ring growth to temperature and precipitation (Barber et al 2000, Lloyd et al 2013, Juday et al 2014, Walker and Johnstone 2014). The NDVI lag could have been due to crown and tree mortality following drought events (Michaelian et al 2010, Anderegg et al 2012, Bond-Lamberty et al 2014). The lag could have also been decreased above ground carbon allocation in response to drought events (Barr et al 2004, Welp et al 2007).
a circumpolar study, Bond-Lamberty et al (2012) found significant multi-year lags between soil respiration and NDVI, likely due to effects of widespread drought stress.

A major drought occurred in 2004, with all 26 stations having a 2004 moisture index at least two standard deviations below the 2000–2014 mean. The climate station buffers had a consistent decline in mean maximum NDVI following this drought event; all 26 station buffers had a lower mean NDVI relative to 2004 in 2005 and 2006.

Following the 2004 drought, the interannual pattern of mean maximum NDVI was remarkably similar within the within the colder C3 (permafrost-dominated) basin and the warmer C2 (mostly permafrost-free) basin of the Caribou-Poker Creek Research Watershed (figure 9). This was likely due to the effect of regional temperature-induced drought stress.

Table 3. Correlation (Pearson’s r) between 2000 and 2014 summer moisture index within maximum NDVI each 10 km station buffer (n > 1500 pixels). Correlations with p-value ≤0.10 are in bold, n = 15 years.

| Station           | Current year r (p-value) | 1 year lag r (p-value) | 2 year lag r (p-value) | 3 year lag r (p-value) |
|-------------------|--------------------------|------------------------|------------------------|------------------------|
| Alcan             | −0.06 (0.59)             | 0.23 (0.21)            | 0.52 (0.02)            | 0.14 (0.30)            |
| Angel Creek       | −0.39 (0.93)             | 0.34 (0.12)            | 0.39 (0.09)            | −0.80 (0.99)           |
| Big Delta         | −0.22 (0.78)             | 0.28 (0.16)            | 0.43 (0.05)            | −0.13 (0.68)           |
| Caribou Peak      | −0.22 (0.79)             | 0.26 (0.18)            | 0.45 (0.05)            | −0.29 (0.84)           |
| Chatanika         | −0.24 (0.80)             | 0.33 (0.11)            | 0.40 (0.07)            | −0.21 (0.77)           |
| Chicken           | −0.44 (0.95)             | 0.11 (0.35)            | 0.41 (0.07)            | −0.15 (0.69)           |
| Cottonwood        | −0.53 (0.98)             | 0.02 (0.47)            | −0.02 (0.53)           | 0.14 (0.31)            |
| Eagle             | −0.24 (0.81)             | **0.57 (0.01)**        | −0.36 (0.10)           | 0.25 (0.19)            |
| Fairbanks         | −0.18 (0.75)             | **0.49 (0.03)**        | −0.08 (0.38)           | 0.20 (0.23)            |
| Goodpaster        | −0.38 (0.92)             | 0.38 (0.08)            | **0.61 (0.01)**        | −0.06 (0.58)           |
| Hogtai River      | −0.42 (0.94)             | 0.30 (0.14)            | −0.39 (0.92)           | −0.11 (0.65)           |
| Kanuti            | −0.57 (0.99)             | −0.21 (0.77)           | 0.31 (0.13)            | −0.38 (0.92)           |
| Koyukuk           | −0.20 (0.76)             | −0.21 (0.77)           | −0.09 (0.62)           | −0.11 (0.66)           |
| Lake Michumina    | −0.37 (0.91)             | −0.27 (0.84)           | −0.28 (0.84)           | −0.08 (0.61)           |
| Livengood         | −0.04 (0.55)             | 0.28 (0.16)            | −0.04 (0.56)           | 0.01 (0.48)            |
| Noratak Lake      | −0.37 (0.91)             | 0.04 (0.45)            | 0.19 (0.25)            | −0.64 (0.99)           |
| Northway          | −0.08 (0.62)             | 0.33 (0.11)            | **0.35 (0.10)**        | 0.07 (0.40)            |
| Poorman           | −0.38 (0.92)             | −0.22 (0.79)           | −0.02 (0.53)           | −0.07 (0.60)           |
| Round Lake        | −0.22 (0.78)             | 0.26 (0.18)            | 0.29 (0.85)            | −0.36 (0.10)           |
| Salcha            | −0.28 (0.84)             | 0.42 (0.06)            | **0.46 (0.04)**        | −0.17 (0.73)           |
| Seven Mile        | −0.08 (0.61)             | 0.72 (0.001)           | **0.62 (0.01)**        | 0.13 (0.32)            |
| Tanana            | 0.00 (0.50)              | 0.27 (0.17)            | 0.34 (0.10)            | −0.03 (0.54)           |
| Telida            | −0.60 (0.99)             | 0.20 (0.77)            | 0.03 (0.46)            | −0.19 (0.25)           |
| Tok               | −0.34 (0.89)             | **0.34 (0.10)**        | 0.21 (0.22)            | −0.10 (0.63)           |
| Tok River         | −0.23 (0.80)             | 0.14 (0.31)            | **0.46 (0.06)**        | −0.11 (0.63)           |
| Wein Lake         | −0.28 (0.84)             | 0.10 (0.36)            | 0.09 (0.38)            | −0.25 (0.82)           |
Walker and Johnstone (2014) found a negative correlation between black spruce tree-ring growth and air temperature across a variety of microclimates including cool, moist sites suggesting that drought stress may be widespread throughout interior boreal Alaska. Based on a time-series of Landsat sensor NDVI, Baird et al. (2012) found a similar pattern of NDVI trends on adjacent upland, lowland, and floodplain landscapes and on South-versus North-facing slopes.

Based on tree-ring studies (Wilmking et al. 2004, Juday and Alix 2012, Lloyd et al. 2013) white spruce growth in boreal Alaska declines above a July threshold of about 12–14 °C. Thus on warm sites, warm summers likely have a direct effect due to temperature-induced drought stress (Beck et al. 2011). On cold, wet sites due to cold soils, roots are limited to shallow surface layers and reduced water and nutrient uptake may occur when water tables drop during drought events (Kljun et al. 2006, Walker and Johnstone 2014). Based on a carbon isotope study in boreal Alaska, Walker et al. (2014) hypothesized that due to shallow rooting structures on colder sites, these sites may be even more vulnerable to drought stress than black spruce forests on warmer microsites.

Summer drought events have increased in boreal interior Alaska. For example, July of 2007, 2009, and 2013 ranked 2nd, 13th and 15th warmest in the 109 year record at Fairbanks (Juday et al. 2014). The years of 2004, 2005, and 2015 ranked 1st, 3rd, and 2th in terms of area burned in Alaska by wildfires since 1940. If the frequency and magnitude of droughts continue to increase, there are likely many future consequences including increased frequency and severity of wildfires (Xiao and Zhuang 2007, Kasischke et al. 2010), decreased boreal production (Ma et al. 2012), and at lower elevations in interior boreal Alaska potentially widespread mortality of birch and spruce species (Juday et al. 2014).

4. Conclusion

Consistent with previous tree ring studies in interior Alaska, there was a consistent NDVI lag of 1 to 2 years in response to a summer climatic moisture index, and to an extreme drought of 2004. Temperature-induced drought stress is likely a dominant factor controlling interannual peak NDVI throughout most of interior boreal Alaska. The effect of extreme droughts such as 2004 likely persists for several years, even on cool and moist sites at lower elevations. At higher elevations, the later spring snowmelt may influence peak summer NDVI, possibly due to snowmelt occurring closer to the summer period at higher elevations. Over 70% of interior boreal Alaska occurs at elevations below 500 m, and peak summer NDVI is likely more affected by summer climate than spring snow conditions in these areas. In this study, at elevations below 500 m, there was no significant correlation between maximum summer NDVI and spring phenology metrics, spring SWE, or day of last spring snow.

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