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LETTER

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David Verbyla

Department of Natural Resources Management, University of Alaska Fairbanks, Fairbanks, AK, USA

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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. Barhovich *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 daylight exceeding 20 h (Wendler and Suhliski 2009) and vapor pressure deficits can exceed 1.5 kPa (Welp *et al* 2007, Sedano and Randerson 2014).

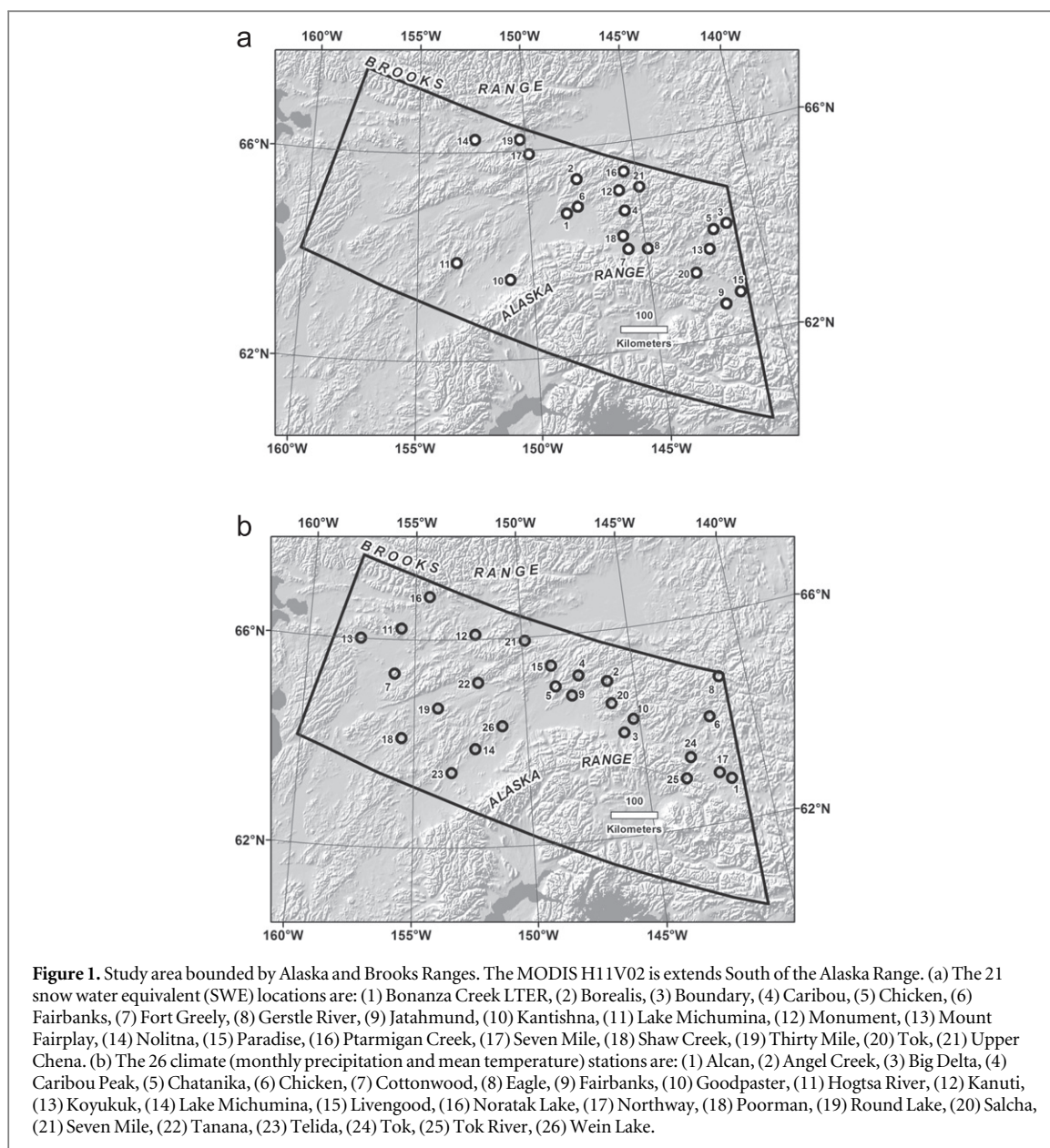
Near the Western edge of the study area, boreal forest transitions into shrub tundra due to the cooler/moister climate from the coastal marine boundary layer (Simpson *et al* 2002). Boreal forest tree line occurs at an elevation of approximately 800–900 m (Lloyd and Fastie 2003) with alpine shrub tundra 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://lter.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 (Petroni *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

onboard the Terra satellite (MOD13Q1, 2000–2014) and Aqua satellite (MYD13Q1, 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 broad-leaf 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

Table 1. Correlation (Pearson's r) between mean summer maximum NDVI within 10 km buffer ($n > 1300$ pixels) and measured early spring (1 April) snow water equivalent at the center of each buffer (2000–2014) $n = 15$ years.

Station	Elevation (m)	r (p -value)
Bonanza Creek LTER	351	-0.18 (0.73)
Borealis	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)
Gerstle River	366	-0.13 (0.67)
Jatahmund	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 (0.63)
Paradise	671	0.11 (0.34)
Ptarmigan 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)

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

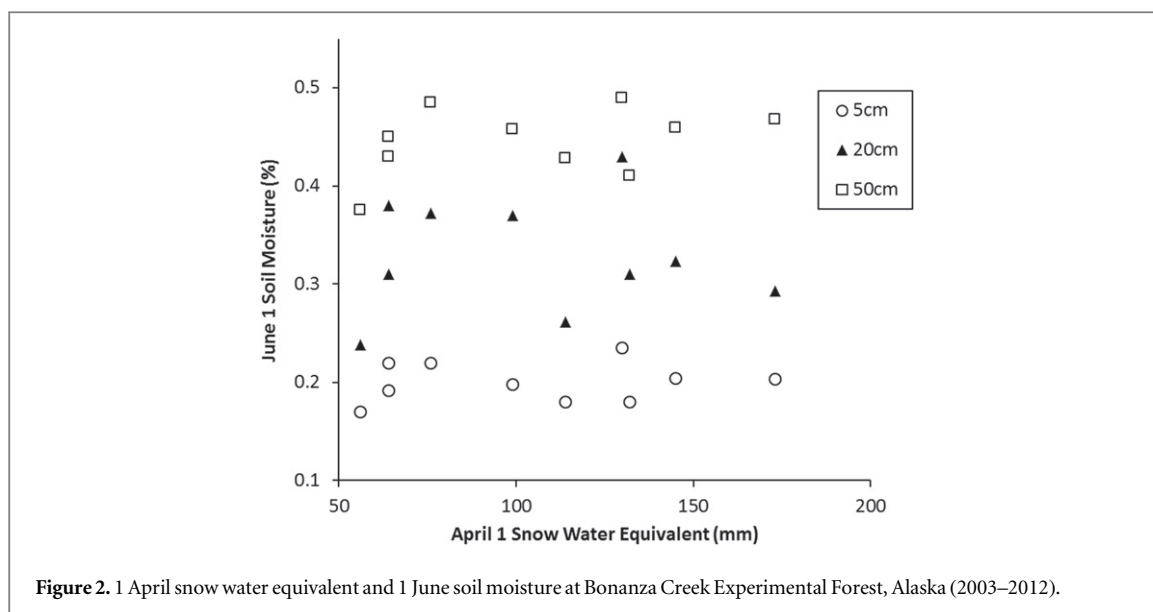


Figure 2. 1 April snow water equivalent and 1 June soil moisture at Bonanza Creek Experimental Forest, Alaska (2003–2012).

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).

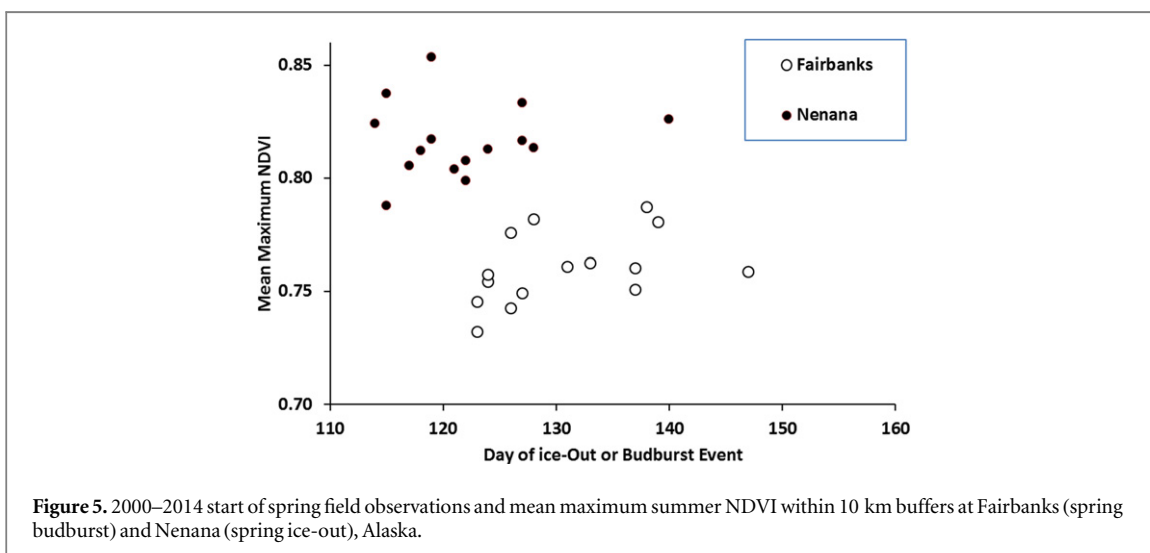
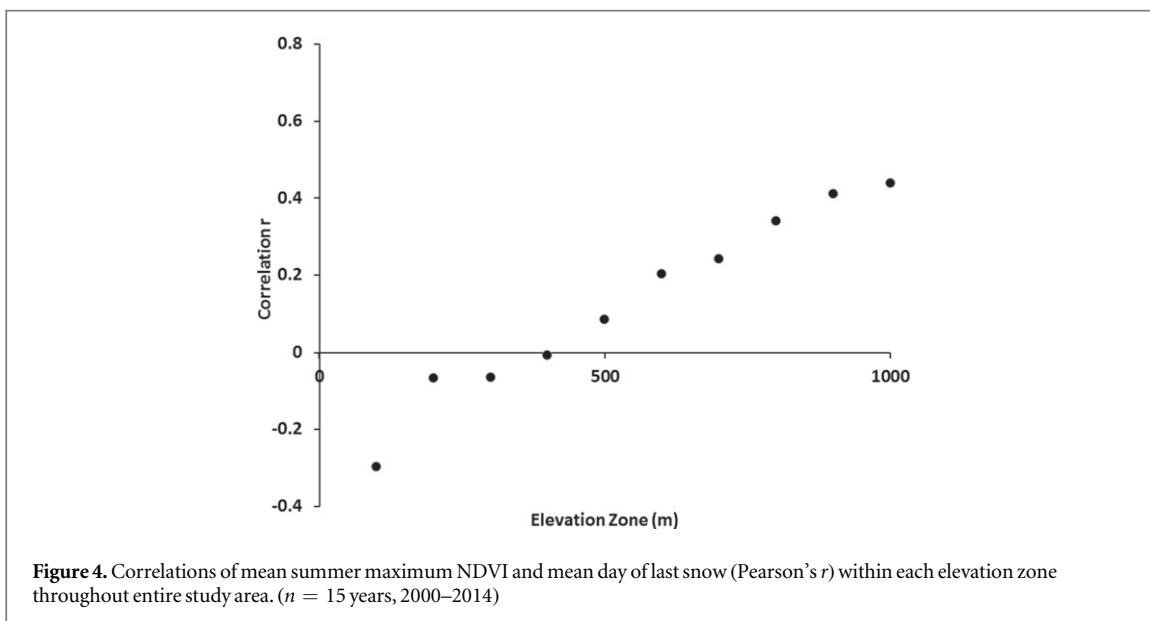
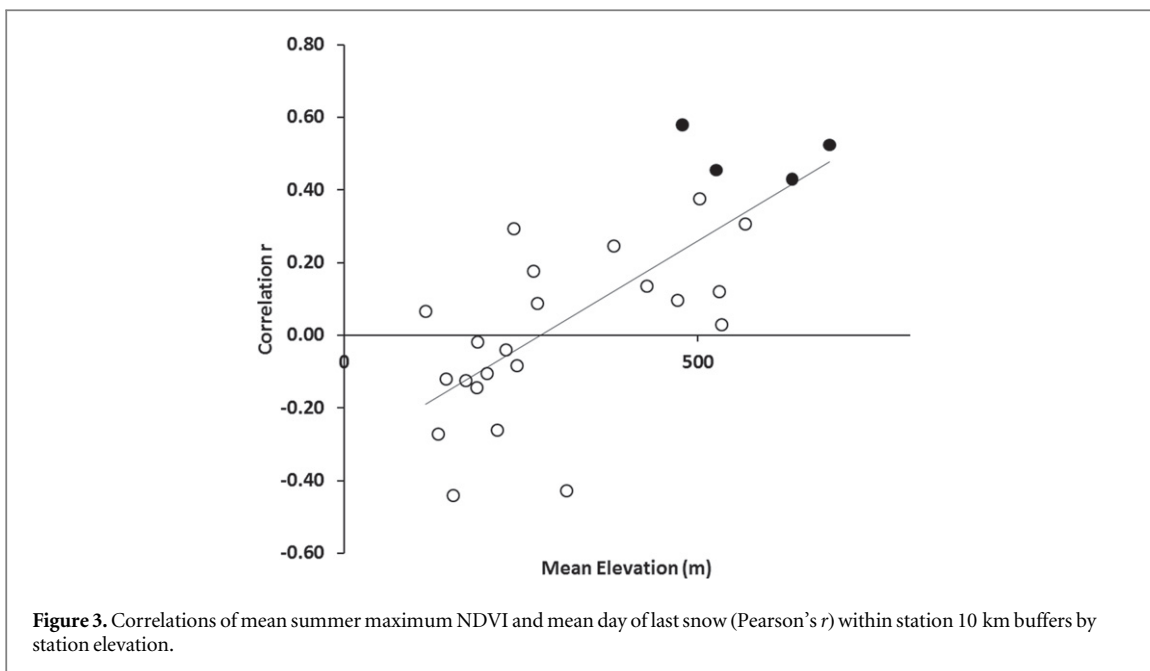
To further test that at lower elevations, later springs were not correlated with higher maximum NDVI, spring ice-out records from Nenana, elevation 110 m (Sagarin and Micheli 2001) and observed day of budburst from Fairbanks, elevation 140 m (<http://lter.uaf.edu>) were obtained and compared with mean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

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)

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



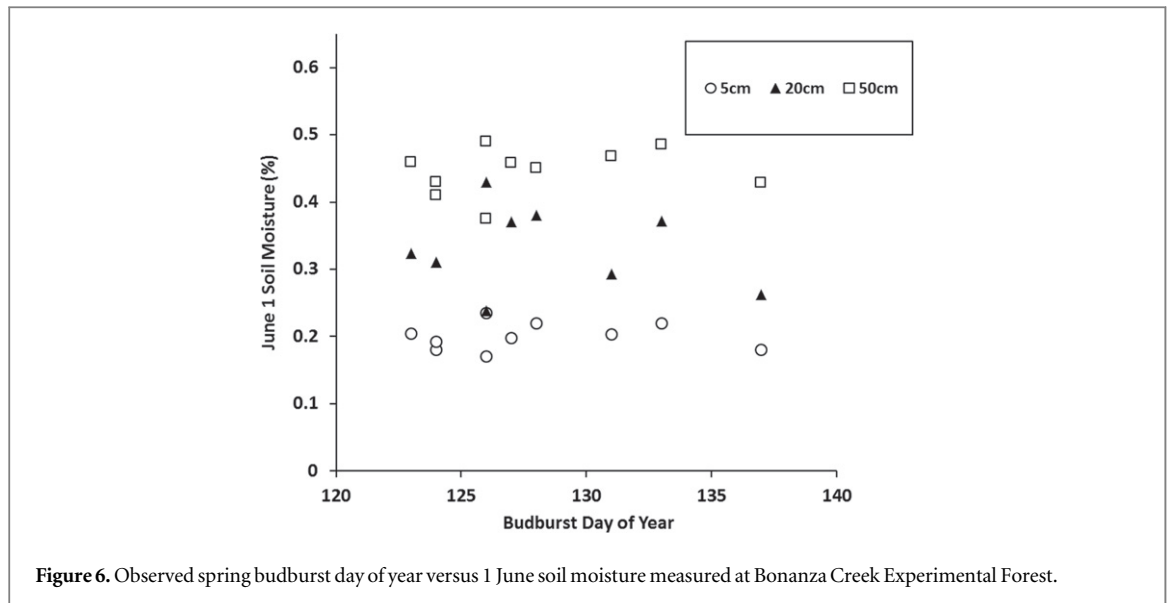


Figure 6. Observed spring budburst day of year versus 1 June soil moisture measured at Bonanza Creek Experimental Forest.

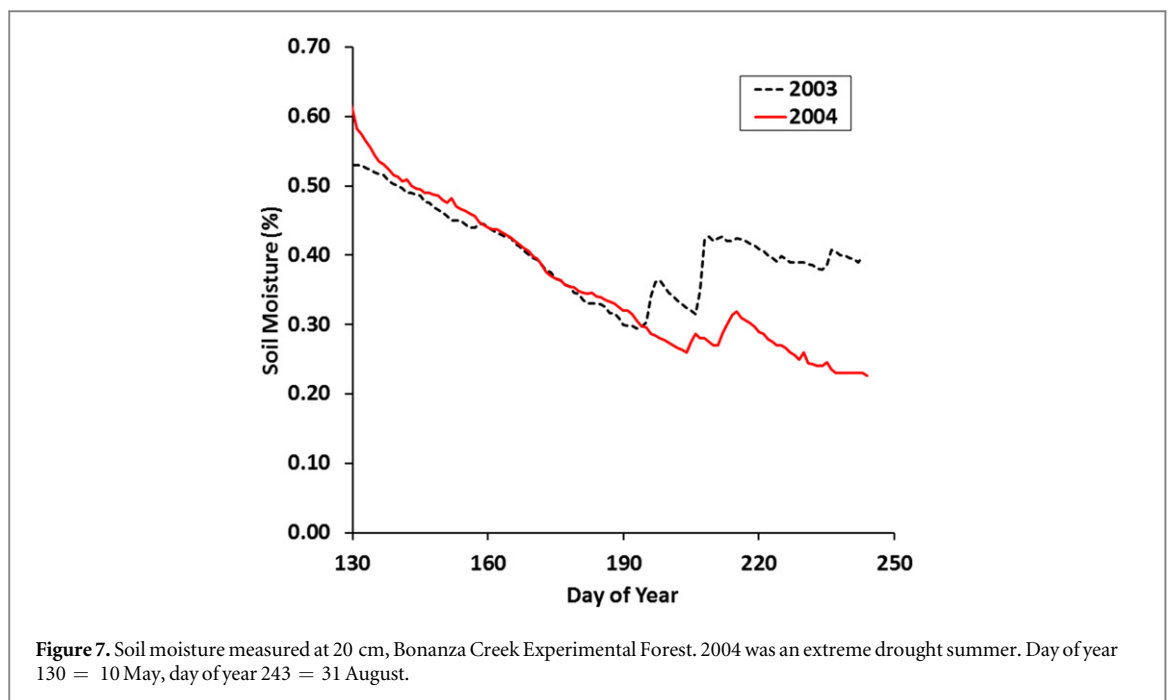


Figure 7. Soil moisture measured at 20 cm, Bonanza Creek Experimental Forest. 2004 was an extreme drought summer. Day of year 130 = 10 May, day of year 243 = 31 August.

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 ($p > 0.05$) 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 ($p \leq 0.10$) 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). In

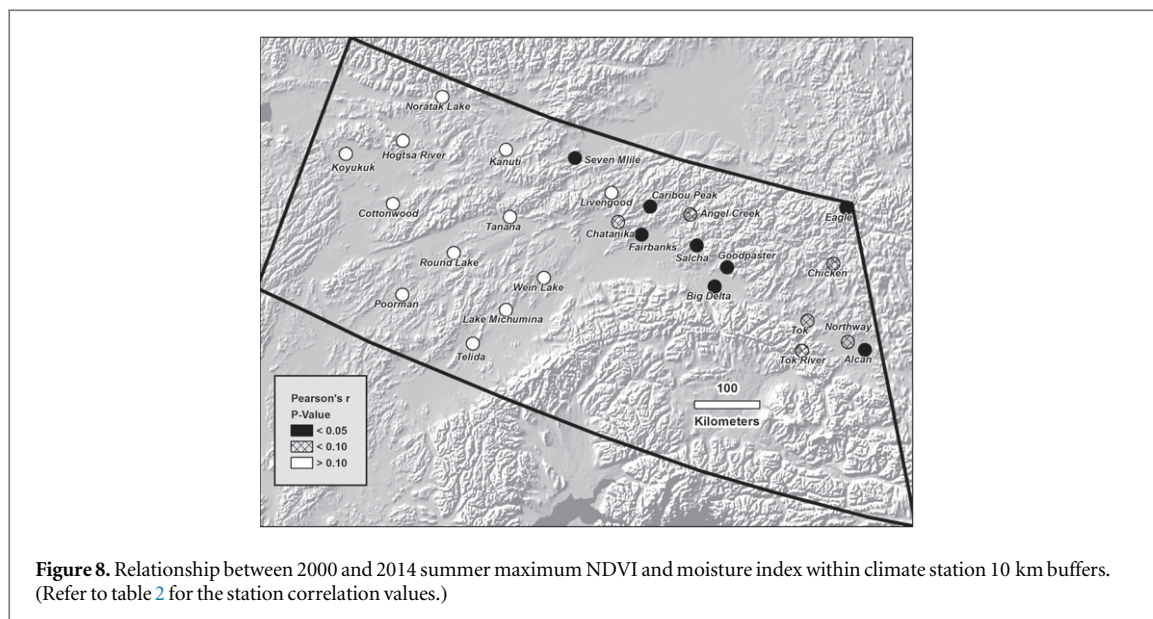


Figure 8. Relationship between 2000 and 2014 summer maximum NDVI and moisture index within climate station 10 km buffers. (Refer to table 2 for the station correlation values.)

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.

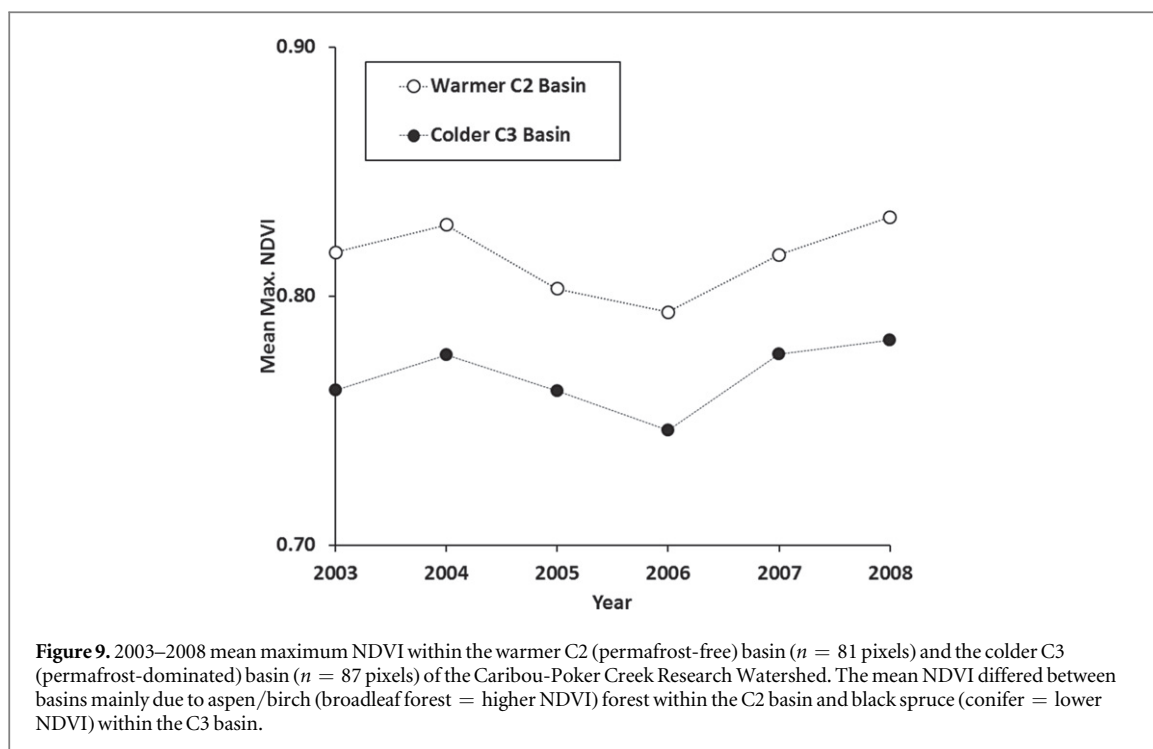
Station	Current year <i>r</i> (<i>p</i> -value)	1 year lag <i>r</i> (<i>p</i> -value)	2 year lag <i>r</i> (<i>p</i> -value)	3 year lag <i>r</i> (<i>p</i> -value)
Alcan	-0.06 (0.59)	0.23 (0.21)	0.52 (0.02)	0.14 (0.30)
Angel Creek	-0.39 (0.93)	0.34 (0.12)	0.39 (0.09)	-0.80 (0.99)
Big Delta	-0.22 (0.78)	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)
Hogtsa 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)

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 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.



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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