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Key Points:
- Evidence for temperature plant growth divergence in boreal forests since mid-1990s
- Rising heat and drought stress due to sustained summer warming are key factors

Supporting Information:
- Figures S1–S9

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Recent shift in Eurasian boreal forest greening response may be associated with warmer and drier summers

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Abstract Terrestrial ecosystems in the northern high latitudes are currently experiencing drastic warming, and recent studies suggest that boreal forests may be increasingly vulnerable to warming-related factors, including temperature-induced drought stress as well as shifts in fire regimes and insect outbreaks. Here we analyze interannual relationships in boreal forest greening and climate over the last three decades using newly available satellite vegetation data. Our results suggest that due to continued summer warming in the absence of sustained increases in precipitation, a turning point has been reached around the mid-1990s that shifted western central Eurasian boreal forests into a warmer and drier regime. This may be the leading cause for the emergence of large-scale negative correlations between summer temperatures and forest greenness. If such a regime shift would be sustained, the dieback of the boreal forest induced by heat and drought stress as predicted by vegetation models may proceed more rapidly than anticipated.

1. Introduction

The circumpolar boreal forest, the second largest terrestrial biome, plays an important role in the climate system and the global carbon cycle and is of considerable socioeconomic importance for northern countries. At regional scales, this biome influences near-surface climates through biophysical factors such as surface albedo, evapotranspiration, and surface roughness [*Chapin et al.*, 2000]. At a global scale, the boreal forests contain about 32% of the world's forest carbon stocks and are considered an important carbon sink [*Pan et al.*, 2011].

The northern high-latitude land regions have experienced variable temperature trends since the beginning of the instrumental record, but have been warming considerably since the early 1970s at rates of ~0.3–1.0°C/decade [*Solomon et al.*, 2007]. Initial results based on satellite vegetation records for the 1980s showed that in response to warmer temperatures, boreal forests experienced longer growing seasons and became more productive, giving rise to the notion of the "greening trend" [*Myneni et al.*, 1997]. However, radial growth and wood density measurements suggest that in recent decades, there has been a "divergence" between warming and tree growth, with localized shifts to a negative relationship between temperature and growth [*D'Arrigo et al.*, 2008; *Porter and Pisaric*, 2011]. Recent analyses of extended satellite vegetation records also indicate that the greening trend has stalled or even reversed, specifically over North America during the 1990s [*Goetz et al.*, 2005; *Xu et al.*, 2013]. Some of these halts and declines in inferred vegetation growth appear to be associated with regional cooling trends [*Wang et al.*, 2011; *Piao et al.*, 2011]. But declines are not restricted to areas of regional cooling, and this previously unexpected adverse response of the boreal forest under warming is consistent with the findings from a number of recent studies, which suggest that this biome is becoming more vulnerable to warming-related factors including temperature induced drought stress [*Barber et al.*, 2000; *P. S. A. Beck et al.*, 2011], shifts in fire regimes [*Kasischke and Turetsky*, 2006; *Rubtsov et al.*, 2011], and insect outbreaks [*Kurz et al.*, 2008].

To date, systematic large-scale studies that explore linkages between vegetation dynamics and hydroclimatic variability in the boreal regions are still severely limited by the paucity of robust data for specific hydroclimatic variables (e.g., soil moisture). In addition, the assessments of the quality of satellite vegetation time series are becoming increasingly important with increasing record length. In this context, the most commonly used satellite-based measure of vegetation activity is the normalized difference vegetation index (NDVI), also known as an indicator of vegetation greenness. Several independent validation efforts based on boreal tree ring measurements [*P. S. A. Beck et al.*, 2011; *Berner et al.*, 2011] and fine-scale satellite imagery [*H. E. Beck et al.*, 2011] have shown high fidelity of the longest (1982–2011) currently available consistent satellite NDVI record: The Global Inventory Monitoring and Modeling Studies (GIMMS)-NDVI data set derived from the measurements of the advanced very high resolution radiometer sensors on board of NOAA's satellite fleet (see Data and Methods). However, despite considerable improvements in the corrections of raw satellite measurements for nonvegetation artifacts, low-frequency variations (e.g., decadal trends) continue to be the least robust signals [*Tucker et al.*, 2005]. This is because data from a number of satellites (e.g., the NOAA fleet) are used to generate a long-term record, and the original measurements have to be corrected for various effects (e.g., satellite orbital drift), which are complex procedures. Yet most of the previous satellite vegetation studies that explored ecosystem responses under climate change have relied on trend analysis.

Here we therefore focus predominantly on interannual variability in the satellite GIMMS-NDVI record across the boreal forest biome for the period 1982–2011 and explore corresponding relationships with high-resolution gridded climate data sets. In particular, we examine whether shifts occurred at regional scales that have produced fundamental changes on how boreal forests respond to variations in climatic drivers.

2. Data and Methods

For satellite vegetation data, we used the improved and extended GIMMS-NDVI version 3g (third generation) data set with a native resolution of 0.084° covering the period 1982–2011 at bimonthly intervals. In the generation of the NDVI3g, which builds on its predecessor NDVIg [*Tucker et al.*, 2005], improved calibration procedures were applied with the goal to enhance data quality specifically over northern lands. The NDVI is computed as the difference between near-infrared and red reflectance of the land surface, normalized by the sum of the reflectances, and is indicative of chlorophyll and therefore of potential photosynthetic activity [*Myneni et al.*, 1995]. Monthly high-resolution (0.5°) gridded temperature, precipitation, and potential evapotranspiration (PET, based on Penman-Monteith) fields were obtained from the Climatic Research Unit Time Series version 3.21 (CRU TS3.21) [*Harris et al.*, 2013]. As an expression of climatic drought, we computed monthly standardized precipitation evapotranspiration index (SPEI) data for 1982–2011 as in *Vicente-Serrano et al.* [2010] (using the *R* code provided in this reference) with CRU precipitation, temperature, and PET data inputs as well as with one alternative PET input (using the Thornthwaite method based on CRU temperature). The SPEI captures the cumulative difference between precipitation and PET over a defined period. For this study, we calculated the SPEI with a 6 month lag (SPEI6) to account for water budgets and effects of soil moisture memory during the course of the growing season.

For this study, all fine scale (e.g., satellite NDVI) and coarse scale (e.g., climate data) were aggregated to a common 0.25° spatial grid, on which the correlation and trend analyses were performed. Circumpolar boreal forests include all regions between 50°N and 70°N with aggregated tree cover $>30\%$, based on the high-resolution (500 m) 2001 Moderate Resolution Imaging Spectroradiometer Vegetation Continuous Field metric (MOD44B) [*Hansen et al.*, 2003]. This "satellite" definition of boreal forests thus includes a relatively small area of more temperate forests in western Europe and western North America. A comparison with a newly available Northern Eurasian Land Cover (NELC) classification [*Sulla-Menashe et al.*, 2011] showed that the forest extent based on the $>30\%$ tree cover threshold is in good agreement with the NELC-based "closed" canopies (Figure S1 in the supporting information). A focus on more closed canopies reduces the contribution of understory vegetation in the satellite NDVI.

In order to explore the links between northern hemispheric (NH) summer vegetation greenness and climate factors (reflecting means of June through August) at more strictly interannual time scales, trends were removed in the original data prior to correlations using two methods that rely on different underlying assumptions regarding trend characteristics [see *Zhou et al.*, 2001]: (i) first differences (change between successive seasonal means) as well as (ii) removal of linear trends (estimated via least squares linear regression) in the original data. Only results that are robust against the methods are discussed. For long-term trend analysis, least squares linear regression was applied. Student's *t* tests were used throughout to evaluate the statistical significance.

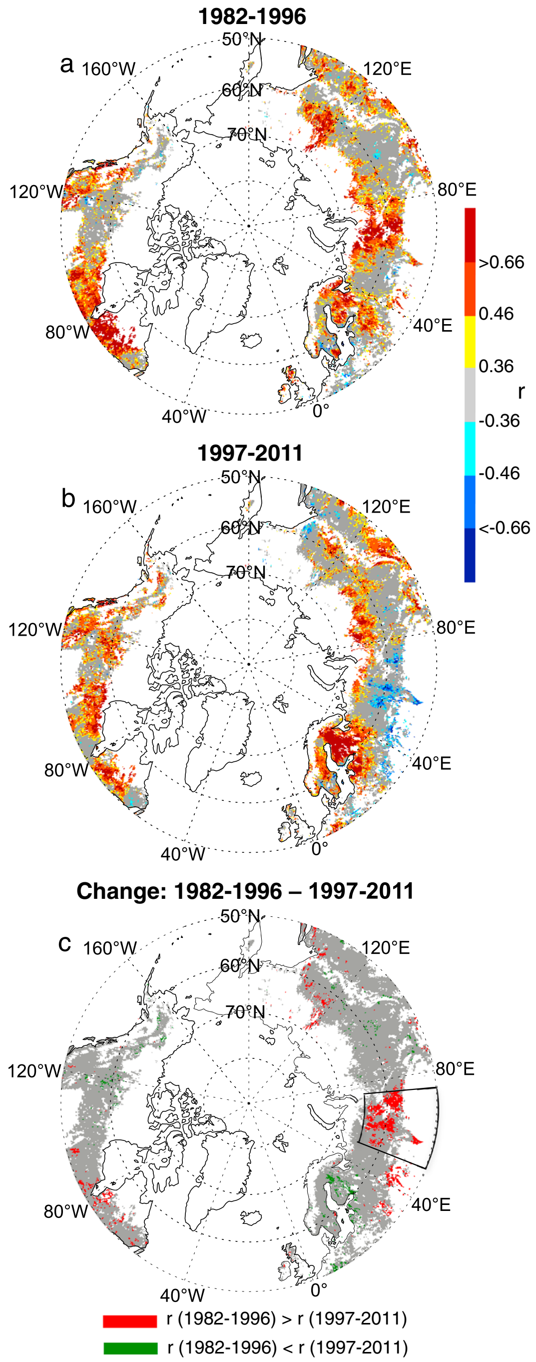

Figure 1. Interannual relationships between summer surface temperature and boreal forest greenness. Maps show grid cell correlations between annual NH summer (JJA) temperature and NDVI for the periods (a) 1982–1996 and (b) 1997–2011, respectively, as well as (c) statistically significant correlation changes ($P < 0.05$) between these two focal periods. Original data were detrended prior to correlations through the first difference method. Absolute r-value categories shown correspond to $P < 0.2$ ($r = 0.36$), $P < 0.1$ ($r = 0.46$), and $P < 0.01$ ($r = 0.66$) significance levels. In Figure 1c, the Ural focus region is outlined, and the area of statistically significant correlation changes between the two focal periods is $\sim 0.45 \times 10^6$ km^2 (bounded between 40°E and 80°E).

3. Results

Exploiting the full 30 year length of the extended satellite vegetation record, we first performed spatially explicit grid point correlations between detrended annual NH summer temperatures and NDVI for the early (1982–1996) and more recent (1997–2011) periods. The results show that the well-established positive relationship between NH summer temperature and NDVI [*Zhou et al.*, 2001] is widespread across the boreal zone, especially during the early focal period (Figure 1a). A new observation is that these positive correlations switch into negative correlations during the later focal period (Figure 1b) over a vast area stretching from the East European Plain to the West Siberian Plain (~40°E–80°E). The shifting correlations appear to be particularly coherent in the vicinity of the Urals (~50°E–75°E), where evergreen needleleaf (north) and mixed (south) forest covers dominate (Figure 1c and Figures S1, S4, and S5 in the supporting information). These results are also closely reproduced with an alternative detrending method (Figure S2 in the supporting information), suggesting that the observed shifts toward inverse summer temperature-NDVI relations across western central Eurasian (EA) boreal forests between the two focal periods are robust.

A key question that follows is why has the drastic change in the summer temperature-NDVI relationship at interannual time scales occurred mainly in western central EA boreal forests and what factors are responsible for this change? One may hypothesize that through continued summer warming, an ecosystem threshold has been crossed, above which the impact of heat and temperature-induced drought stress outweighs the benefits of increasing temperatures on boreal vegetation growth [*Barber et al.*, 2000]. This hypothesis is consistent with the tree ring-based width, density, and stable isotope analyses of the recent divergence between temperature and tree growth in adjacent Siberia, which provide evidence that moisture stress can play a major and widespread role in decreasing tree growth [*Sidorova et al.*, 2010]. To test the veracity of this assertion, we first focus on hydroclimatic conditions during NH peak summer (July and August) and on the region west and east of the Ural Mountains that experienced the most pronounced shift from a positive (1982–1996) to an inverse (1997–2011) relationship in the summer temperature-NDVI (see Figure 1c).

Over the Ural focus region, 14 year moving window correlations between temperatures and NDVI during the peak summer (July and August) display a rather monotonic behavior from positive to negative values

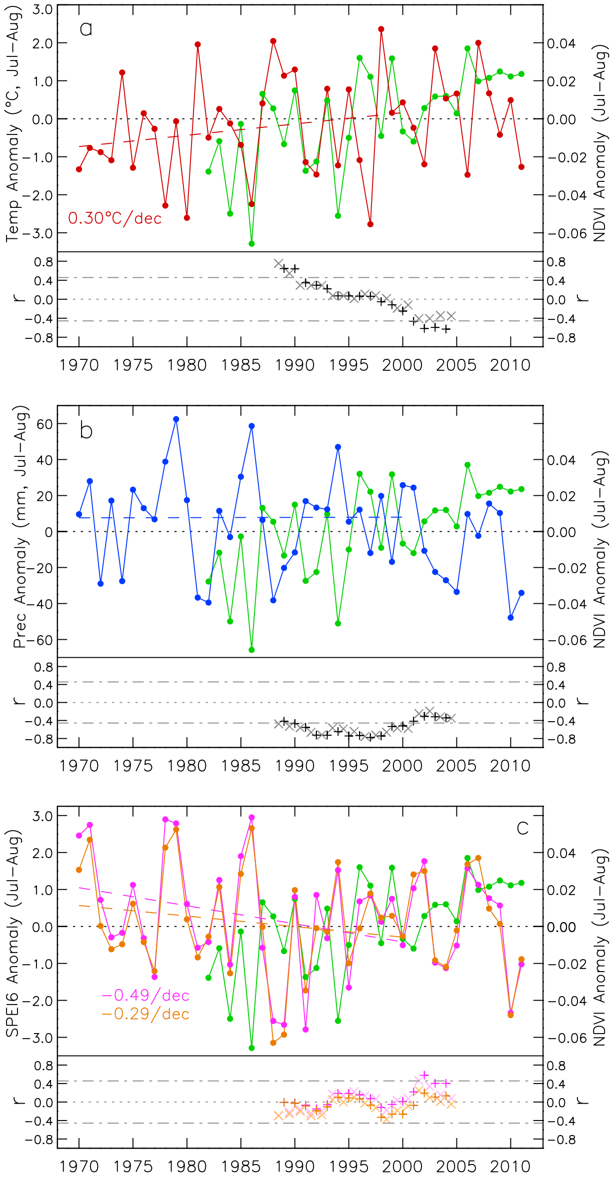

Figure 2. Temporal changes in peak summer boreal forest greenness and climate for the Ural focus region. For peak NH summer (July and August), annual anomalies in spatially averaged NDVI (green) are plotted alongside (a) temperature (dark red), (b) precipitation (blue), and (c) SPEI6 based on the Thornthwaite (pink) and Penman-Monteith (brown) formulations. All anomalies are relative to the period 1982–2011, and long-term trends in climatic drivers shown (dashed lines) are for the period 1970–2000. The Ural focus region encompasses all forested areas within 50°E–75°E and 50°N–65°N that show a significant correlation change ($P < 0.05$) in the NH summer NDVI-temperature links between the focal periods 1982–1996 and 1997–2011 (see Figure 1c). For each plot, moving window correlations based on 14 year periods between corresponding original time series (light crosses) and after removing a trend within each time slice via first differences (dark pluses) are shown in lower panels, whereby the corresponding correlations are plotted in the middle (year 7) of each interval. In Figure 2c, moving window correlations between NDVI and SPEI6 (Thornthwaite) as well as SPEI6 (Penman-Monteith) are plotted in pink and brown, respectively. Correlations above/below the horizontal gray dash-dotted lines are statistically significant (absolute $r \geq 0.46$; $P < 0.1$).

over the period 1982–2011 and suggest that the shift in this link is largely confined to the mid-1990s, the time span when moving window correlations cross the 0 line (Figure 2a). Over this region, NH peak summer precipitation is negatively correlated with NDVI from the early 1980s to the middle-to-late 1990s, but this correlation becomes markedly weaker thereafter (Figure 2b). This negative correlation could be due to the effects of cloud cover on solar radiation since the boreal forests in the Ural region are also considered radiation limited [*Nemani et al.*, 2003]; in other words, less cloudy conditions (and less precipitation) may be associated with enhanced vegetation growth. Suggestive evidence for a shift into a more moisture-limited regime in the Ural focus region from the mid-1990s onward is provided by the SPEI6, an index of climatic drought (see Data and Methods). Increasingly positive correlations between peak summer vegetation greenness and this drought index are observed during the more recent 14 year epochs; however, these correlations approach statistical significance only for the case in which the SPEI has been calculated through the Thornthwaite method (Figure 2c). An accompanied trend analysis for this region and during peak summer shows that temperatures have been consistently increasing from the early 1970s (the onset of recent high-latitude warming) to the late 1990s, whereas precipitation rates did not exhibit any trends (Figures 2a and 2b). This suggests that the observed trend toward drier conditions (as evidenced through a negative trend in SPEI6 over this extended time frame (Figure 2c)) is largely driven by summer warming. Increasing direct high-temperature stress (via increased autotrophic respiration [*McDowell*, 2011] and decreased stomatal conductance resulting from hydraulic [*Flexas et al.*, 2004] or vapor pressure deficit (VPD) [*Lloyd et al.*, 2002] stresses) may also be a contributing factor to the observed shift in the summer temperature-NDVI links during the mid-1990s across the Urals. Our analysis on relatively coarse National Centers for Environmental Prediction reanalysis temperature records provides support for the significance of this factor through both increasingly negative

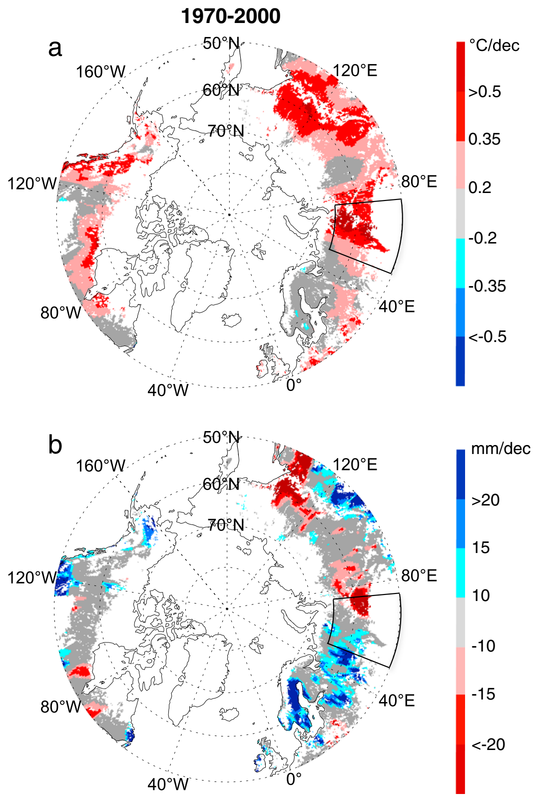

Figure 3. Long-term trends in summer surface temperature and precipitation across boreal forests. Maps depict decadal trends in summer (JJA) (a) temperature and (b) precipitation for the period 1970–2000. Trends are based on linear least squares regression. A large fraction of the trends are larger/smaller than 0.35°C/decade and 20 mm/decade, respectively, are also statistically significant (Figure S6 in the supporting information).

correlations between the number of hot days and NDVI during peak summer during the more recent epochs as well as an increasing trend in the number of hot days over the extended 1970–2000 period (Figure S3 in the supporting information). Taken together, these results are consistent with the notion of a marked change in the factors that limit western central EA boreal plant growth from predominantly low temperature and radiation constraints prior the mid-1990s to more heat and moisture constraints afterward.

Within the western central EA boreal regions, large swaths of forest-bog mosaics are not uncommon (Figure S4 in the supporting information), and if the shift in the summer temperature-NDVI links would be predominantly observed in these regions, our working hypothesis that more arid conditions are a key factor in this transition would be perhaps compromised. A detailed inspection with two newly available high-resolution boreal forest cover classifications show however that most of the correlation change patterns lay in areas characterized by relatively dense forests (Figure S5 in the supporting information). A notable exception is the relatively large coherent correlation change pattern located in the southeast portion of the Ural focus region, which coincides with an area classified as being more a mosaic of forests and bog (Figure 1c and Figure S4 in the supporting information). Further findings of a field-based study on wetland tree responses [*Linderholm et al.*, 2002] show that conifer trees growing in boreal peatlands can have positive growth response to moisture availability indicating that even in these relatively wet locations, trees can suffer drought stress through VPD effects or changes in water table.

To further investigate why the transition toward inverse summer temperature-NDVI relations has occurred predominantly in the western central EA boreal forests, we analyzed trends in NH summer (JJA) temperature and precipitation over the extended period of recent northern high-latitude warming starting from the early 1970s to the late 1990s. Results show that within the boreal zone, the Ural focus region has indeed experienced rather unique rates of summer warming locally exceeding 0.5°C/decade (Figure 3a). At more local scales (e.g., the eastern portion of the Ural focus region), negative summer precipitation trends over this extended time frame (Figure 3b) may also have played a role in this transition toward notably drier conditions (Figure S7 in the supporting information). A recent study suggested that in North American boreal forests, shifts to earlier springs (associated with spring warming) are strongly linked to anomalously low-peak summer productivity, whereby early spring run off and longer evaporative periods lead to lower levels of available moisture later in the growing season [*Buermann et al.*, 2013]. While we find no evidence of unique rates of spring warming from the 1970s to the 1990s in the Ural focus region, it is plausible that warmer spring conditions in the Ural also played a role in this transition into a warmer and drier summer regime (Figure S8 in the supporting information).

Several other potentially interacting factors, including changes in important disturbance regimes associated with fire as well as land use change, may have also contributed to the observed shift toward an inverse relationship between NH summer temperatures and NDVI across western central boreal Eurasia. For example, profound increases in the area burned have been documented for the EA boreal forests in the period 1997–2006 (relative to the period 1961–1990) and attributed to warmer and drier conditions [*Hayes et al.*, 2011]. In addition, large areas have experienced drastic declines in logging activities in the post-Soviet era (from early

1990s onward) and are now in various stages of regrowth [*Achard et al*., 2006]. Our own analysis on the role of fire shows that the burned area at subpixel levels can influence summer NDVI at interannual times scales; however, the effect tends to be more localized across the EA boreal forests (Figure S9 in the supporting information). Further, we do not find significant correlations between summer temperature and burned area in the Ural focus region (Figure S9 in the supporting information), suggesting that fire is not a dominant factor in the observed large-scale shift in the summer temperature-NDVI links. In regards to land use change, relatively large areas in the southern portion of the Ural focus region are currently in a state of regrowth (from intense clear-cutting activities in the former Soviet Union) with accompanied compositional changes toward a greater portion of deciduous trees [*Achard et al*., 2006]. These transitions may have played a role in the observed shifts toward an inverse relationship in the summer temperature-NDVI links from the mid-1990s onward (e.g., through increased sensitivity to moisture stress in more open canopies). However, because we observe these shifts over a significantly larger spatial domain (including disturbed and natural forests) effects of land use change may also not exert a first-order influence on our key findings. It should be noted that at more local levels, any of these alternative mechanisms can be important, but our results suggest that they are not the dominant drivers at the regional scale.

4. Discussion and Conclusions

In both Eurasia and western North America, a number of local boreal stands have shown shifts to negative correlations between summer temperature and radial tree growth coupled with declining annual growth rates over the past few decades [e.g., *Wilmking et al*., 2004; *Lloyd and Bunn*, 2007], and heat and warming-induced drought stresses have often been invoked as dominant mechanisms [e.g., *P .S. A. Beck et al*., 2011]. However, such effects vary in the timing of initiation and have typically been highly localized with stands responding negatively to increasing temperature often found regionally intermixed with stands responding positively. Our new satellite study with a focus on interannual time scales provides the first evidence that this divergence in growth relations and shift to negative response has become increasingly spatially pervasive in western central boreal Eurasia from the mid-1990s onward. Our results further suggest that a unique pattern of accelerated summer warming over western central EA boreal forests starting from the early 1970s onward in the absence of significant increases in precipitation may have played a key role in this transition.

In a previous satellite-based vegetation study that focused on longer time scales, diverging decadal trends in summer temperature (increasing) and vegetation greenness (decreasing) in the period 1997–2006 were reported for several EA temperate and boreal regions, but the western central EA boreal region was not identified as a region of particular change [*Piao et al*., 2011]. This apparent inconsistency may have several explanations (e.g., different record length), but interpretations of long-term trends in satellite-based vegetation data are also more limited since this portion is considered the least robust signal in these data.

Increasing CO_2 might be expected to lead to decreased stomatal density and conductance of water, and this would generate increased water use efficiency (WUE) and a degree of resilience to the impacts of increasing moisture stress [*Keenan et al*., 2013]. However, recent isotopic studies have detected evidence of a plateau in the increasing WUE of some northern and boreal tree species in the 1990s [*Waterhouse et al*., 2004; *Gagen et al*., 2011]. If this phenomenon is widely present in other species, it suggests that plateauing in CO_2-induced WUE may contribute to and further exacerbate in the future the degree of moisture stress-induced widespread decline in boreal vegetation growth and carbon sequestration.

In simulations of biome shifts under future climate change, boreal forests are projected to shift their range northward into current tundra, while being replaced by grasslands or temperate forest at the biome's southern edge [*Sitch et al*., 2008]. Hereby, a key mechanism for boreal forest dieback is increasing heat and drought stress. Our analysis based on three decades of satellite vegetation data may be still too short to draw firm conclusions in regards to having passed an irreversible ecosystem tipping point in response to warming [*Lenton et al*., 2008]. However, our key finding of an apparent shift into a more heat and drought-like regime across parts of the Eurasian boreal forests during the mid-1990s is at least suggestive that we are not far away from this hypothesized transition of biome shift, perhaps somewhat earlier and more rapidly than anticipated. The observed widespread heat and drought-related negative impacts on vegetation greenness during the peak of the growing season over western central Eurasian boreal forests since the mid-1990s may be a part of this and a further important contributing factor to the declines in sequestration of carbon by the boreal forest that are already being observed [*Ma et al*., 2012].

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