

Article

Does Earlier and Increased Spring Plant Growth Lead to Reduced Summer Soil Moisture and Plant Growth on Landscapes Typical of Tundra-Taiga Interface?

Alemu Gonsamo ^{1,2,*} , Michael T. Ter-Mikaelian ³, Jing M. Chen ¹ and Jiaxin Chen ³ ¹ Department of Geography and Planning, University of Toronto, Toronto, ON M5S 3G3, Canada² School of Geography and Earth Sciences, McMaster University, Hamilton, ON L8S 4L8, Canada³ Ontario Forest Research Institute, Ontario Ministry of Natural Resources and Forestry, Sault Ste. Marie, ON P6A 2E5, Canada

* Correspondence: gonsamoa@geog.utoronto.ca

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Abstract: Over the past four decades, satellite observations have shown intensified global greening. At the same time, widespread browning and reversal of or stalled greening have been reported at high latitudes. One of the main reasons for this browning/lack of greening is thought to be warming-induced water stress, i.e., soil moisture depletion caused by earlier spring growth and increased summer evapotranspiration. To investigate these phenomena, we use MODIS collection 6, Global Inventory Modeling and Mapping Studies third-generation (GIMMS) normalized difference vegetation index (NDVI3g), and Global Land Evaporation Amsterdam Model (GLEAM) satellite-based root-zone soil moisture data. The study area was the Far North of Ontario (FNO), 453,788 km² of heterogeneous landscape typical of the tundra-taiga interface, consisting of unmanaged boreal forests growing on mineral and peat soils, wetlands, and the most southerly area of tundra. The results indicate that the increased plant growth in spring leads to decreased summer growth. Lower summer soil moisture is related to increased spring plant growth in areas with lower soil moisture content. We also found that earlier start of growing season leads to decreased summer and peak season maximum plant growth. In conclusion, increased spring plant growth and earlier start of growing season deplete summer soil moisture and decrease the overall summer plant growth even in temperature-limited high latitude ecosystems. Our findings contribute to evolving understanding of changes in vegetation dynamics in relation to climate in northern high latitude terrestrial ecosystems.

Keywords: boreal forest; browning; Far North of Ontario; greening; Hudson Bay; soil moisture; tundra

1. Introduction

High latitude ecosystems are responding more rapidly [1,2] and consistently [3] to climate warming than other terrestrial ecosystems. Several recent satellite-based studies [4–7] have shown that plant growth is increasing in response to changes in Earth's climate system and atmospheric chemistry. This increase is higher in temperature-limited ecosystems and seasons [1,2,4,5,8–10]. Warming-induced advances in spring vegetation activity [11–13], increased peak productivity [14–16], and enhanced carbon (C) uptake [2,8–10,17–19] in high latitude ecosystems are all well-documented and indicate intensified greening. Yet, the trends to be expected in the future are uncertain.

Emerging evidence shows browning, reversal of greening, and stalled plant growth response to increased temperature at high latitudes. For example, widespread browning has been reported from satellite studies in areas where warming-induced greening was expected to continue [20–27]. Indirect evidence also indicates that substantial area in northern heterogeneous landscapes is browning. This

indirect evidence includes slower leaf unfolding response to temperature increase [28,29] indicating saturation of the rate of bud ontogenesis during warm springs. Additionally, weakened plant growth [30,31] and C uptake [32] responses to temperature by high latitude ecosystems have also been reported. Local scale analyses suggest that warming-induced plant growth is weakening in part due to increased water stress [19,33–35]. Particularly in summer months, water stress could result from earlier arrival of spring, warming-induced increases in summer evapotranspiration, and soil moisture depletion by plants caused by spring-ward shift of peak growth [14,15,36–41]. Empirical evidence for this, however, is inadequate due to lack of systematic assessment of relationships among spring and summer plant growth and soil moisture status. Far North of Ontario (FNO) provides ideal experimental area with vast forested areas on mineral and peat soils, and heterogeneous landscapes typical of tundra-taiga interface.

In this study, we use satellite observations independently recorded by multiple sensors to study the relationships among spring and summer plant growth and soil moisture status on heterogeneous landscapes typical of the tundra-taiga interface. We particularly focused on the influence of spring plant growth on summer soil moisture content and plant growth in FNO ecosystems, comprising boreal forest, wetlands, and the most southerly area of tundra.

2. Methods

2.1. Study Area

We study the FNO, which has heterogeneous landscapes typical of the tundra-taiga interface consisting of unmanaged boreal forests in the south and southwest, the world's third largest area of wetlands (281,439 km²), and the most southerly area of tundra (Figure 1). The FNO is a 453,788 km² area in Ontario, Canada, that represents two ecozones, Boreal Shield and Hudson Plains. In the Boreal Shield, trees generally grow on drier elevated ground or lower latitude areas, while the poor drainage and flat terrain in the Hudson Plains ecozone have resulted in continuous wetland. Forest composition, typical of the tundra-taiga interface, consists of mostly black spruce (*Picea mariana* (Mill.) BSP) on lowland sites, with white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* Michx.), tamarack (*Larix laricina* (Du Roi) K. Koch), and white birch (*Betula papyrifera* Marsh.) [42]. Based on the Ontario Ministry of Natural Resources and Forestry Version 1.4 Far North Land Cover, the forested area on mineral soils comprises conifer (104,426 km²), broadleaf (5,770 km²), and mixed (10,438 km²) forests, the area of which differs slightly from estimates derived from earlier land cover data [43]. Treed- and shrub wetlands (184,783 km²) and other treeless vegetated land (heath, peats, and bogs) (97,321 km²) are also prevalent in the study area (Figure 1), while permafrost is estimated to occur only on ~1% of the entire Hudson Bay Lowland, mostly along the Hudson Bay coast [44]. Although much of the study area is characterized as having the largest organic soil C storage anywhere in the world [45], FNO has the lowest aboveground biomass and productivity of any forested region in Canada [46]. The 1982–2015 FNO average (standard deviation) temperature for December–March is −17.2 °C (±4.9), April–June is 5.8 °C (±6.6), July–September is 13.9 °C (±3.3), and October–November −2.4 °C (±5.4).

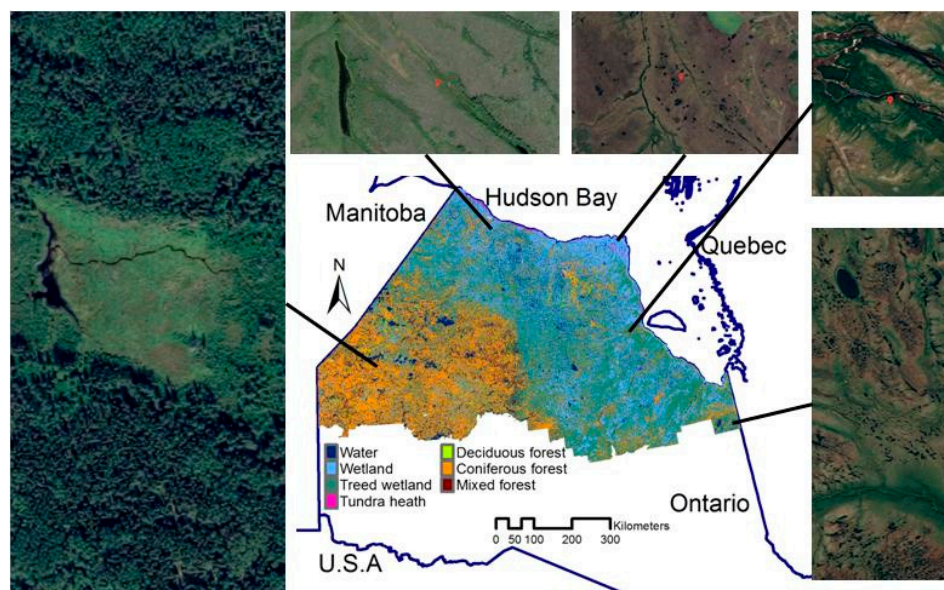


Figure 1. A 30 m land cover map and images of landscape characteristics typical of ecosystems of the Far North of Ontario. Land cover data courtesy of Ontario Ministry of Natural Resources and Forestry, Version 1.4 (year 2014), Far North Land Cover; landscape scenes courtesy of Google Maps (www.google.ca/maps).

2.1.1. Data

We use the following satellite datasets: (i) MODIS collection 6 enhanced vegetation index (EVI), (ii) normalized difference vegetation index (NDVI) and (iii) vegetation continuous field; (iv) NDVI from Global Inventory Modeling and Mapping Studies third-generation (GIMMS NDVI3g); and (v) root-zone soil moisture from Global Land Evaporation Amsterdam Model (GLEAM). Satellite records of NDVI and EVI capture both structural (e.g., leaf area index, LAI) and physiological (e.g., leaf chlorophyll content) attributes of terrestrial ecosystems and thus are proxies of plant growth and productivity.

MODIS EVI and NDVI: The collection 6 (V006) 16-day MODIS NDVI and EVI [47] composites (MOD13Q1) at a spatial resolution of 250 m were obtained for 2000–2017 from Earthdata (<https://search.earthdata.nasa.gov/>). The MODIS NDVI and EVI products are computed from surface reflectance corrected for molecular and aerosol scattering and ozone absorption [48]. Compared to NDVI, EVI is less sensitive to soil background variations and maintains sensitivity over dense vegetation conditions [47]. Both NDVI and EVI pixels corresponding to NDVI values less than 0.15 were interpreted as non-vegetated land pixels and were assigned a value of 0.

MODIS Vegetation Continuous Fields: The fractional tree cover data is obtained from MODIS Vegetation Continuous Field 250 m product V006 (MOD44B) consisting a sub-pixel information on percent tree cover. The data layers in the MOD44B product are generated on an annual basis from monthly composites of surface reflectance data. We downloaded the MOD44B data for the study area for year 2008, the median year of the entire MODIS time series in this study.

GIMMS NDVI3g: The GIMMS NDVI data for 1982–2011 were obtained from bi-weekly 8 km Global Inventory Modeling and Mapping Studies third-generation observations that are derived from satellite-based surface reflectance from the Advanced Very High Resolution Radiometer (AVHRR) series of sensors [49]. The GIMMS NDVI3g product was assembled from different AVHRR sensors and corrected for effects such as sensor degradation, orbit drift, and volcanic eruption. In our study, NDVI values less than 0.1, interpreted as non-vegetated land pixels, were assigned a value of 0.

GLEAM root-zone soil moisture: The daily GLEAM root-zone soil moisture [50], version 3.1 (GLEAM_v3.1a), calculated by combining satellite measurements of soil moisture in the top layer with a simple empirical drainage algorithm to estimate water content in the complete root zone at a

spatial resolution of 0.25° , was obtained for 1982–2016 from the GLEAM archive (www.gleam.eu). The root-zone soil moisture calculation uses observed multi-source precipitation records as input with satellite-observed soil moisture, vegetation optical depth and snow-water equivalent, and reanalysis air temperature and radiation [50]. The multilayer water balance module in version 3.1 has been adapted to represent the continuous drainage of precipitation through the vertical profile. Root zone depth is defined as a function of land-cover type and comprises three model layers for the fraction of tall vegetation (0–10, 10–100, and 100–250 cm), two for the fraction of low vegetation (0–10, 10–100 cm), and only one for the fraction of bare soil (0–10 cm). Validations of GLEAM_v3.1a against measured soil moisture data resulted in $R = 0.67$ and root mean square difference of $0.057 \text{ m}^3/\text{m}^3$ [50]. We have further validated the GLEAM root-zone soil moisture against the satellite observed Climate Change Initiative (CCI) soil moisture data [51] using all available observations. We find statistically significant relationship between the GLEAM root-zone and the CCI total soil moisture values (Figure 2). It should be noted that, at the latitudes of our study area, there are only few valid satellite soil moisture observations from CCI. The CCI soil moisture shows larger values and dynamic ranges than the GLEAM product (Figure 2). This is expected as CCI measures the soil moisture at 0.5–2-cm depth where high variability is expected while GLEAM product is for the entire root zone depth that ranges from 0–10 cm for bare soil to 250 cm for tall vegetation.

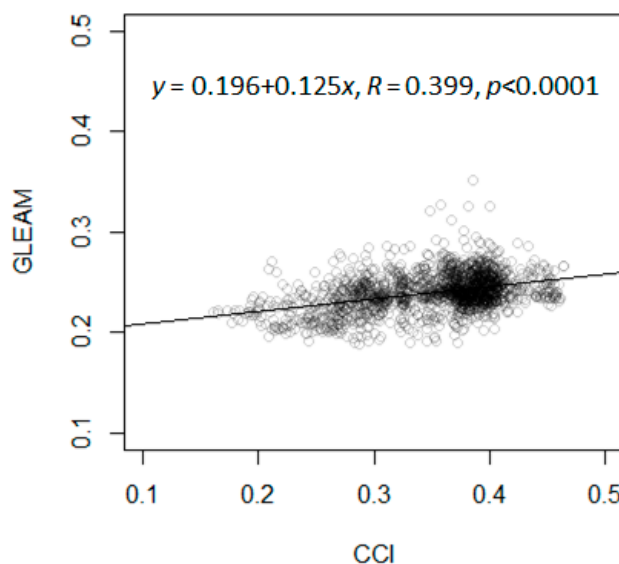


Figure 2. Comparison between summer-time data-model estimate of root-zone soil moisture (GLEAM) and satellite observed Climate Change Initiative (CCI) soil moisture, both in m^3/m^3 . The scatter points include all $0.25^\circ \times 0.25^\circ$ Latitude-Longitude grid cells which have June–August datasets between 1982 and 2015.

2.1.2. Analysis

After aggregating the entire land cover map (Figure 1) other than open water from 30 m to 250 m of MODIS pixel size using a majority rule, we analyzed the relationships between spring and summer vegetation activities per land cover types. Averaged across the study area, the growing season begins in May and ends in November [14,52], so we defined the seasons to reflect the vegetation dynamics as spring = April–June and summer = July–September. NDVI and EVI pixels from MODIS corresponding to $\text{NDVI} < 0.15$ and pixels with $\text{NDVI} < 0.1$ for GIMMS were assigned a value of 0. The NDVI and EVI values are then aggregated into seasonal values using the average of all observations. We use different thresholds to differentiate vegetated and non-vegetated pixels as AVHRR series of sensors used for GIMMS and MODIS NDVI have different spectral response functions [53]. In addition to seasonal values, we also extract start of growing season (SOS), and peak season maximum NDVI value.

To extract SOS, the following seven-parameter logistic function [14] is fitted to bi-weekly GIMMS NDVI3g and 8-day MODIS NDVI data records after assigning 0 to NDVI < 0.1 and < 0.15 for GIMMS and MODIS, respectively:

$$Y(t) = \alpha_1 + \frac{\alpha_2}{1 + e^{-\partial_1(t-\beta_1)}} - \frac{\alpha_3}{1 + e^{-\partial_2(t-\beta_2)}} \quad (1)$$

where $Y(t)$ is the observed data value at a day of year (DOY) t ; α_1 is the winter dormant period value; $\alpha_2 - \alpha_1$ is the amplitude between the winter dormant period, and the spring and early summer plateau; and $\alpha_3 - \alpha_1$ is the amplitude between the winter dormant period, and the late summer and autumn plateau. ∂_1 and ∂_2 are the transition in slope coefficients, while β_1 and β_2 are the mid-points in DOY of these transitions for green-up and senescence/abscission, respectively. Data were fitted to the logistic function with the first guess values of the seven parameters ($\alpha_1 = 0.1$, $\alpha_2 = 1$, $\alpha_3 = 1$, $\partial_1 = 0.04$, $\partial_2 = 0.04$, $\beta_1 = 112$, $\beta_2 = 218$) and solved with maximum of 2000 iterations. SOS is estimated as β_1 value in Equation (1) for both GIMMS NDVI3g and MODIS NDVI. Satellite-based NDVI values are known to be affected by atmospheric perturbation; therefore, we use two methods to estimate the peak season maximum NDVI value. Firstly, we directly extract the maximum annual value (max) for each pixel from the raw bi-weekly GIMMS NDVI3g and 8-day MODIS NDVI data records. Secondly, we estimate the peak of season maximum NDVI value (POSvalue) by fitting Equation (1) on raw time series [14].

In order to assess the impacts of vegetation density and cover type on the relationship between spring and summer vegetation activity, we separately analysed the statistical strength of the observed relationships per fractional tree cover classes. The fractional tree cover data is categorized into classes ranging from 0.0 to 0.7 at 0.1 interval. In order to assess the impact of average plant available soil water on the relationship between spring and summer vegetation activity, we separately analysed the statistical strength of the observed relationships per long-term average soil moisture classes. For this particular purpose, the plant available soil water was estimated from the average value of the entire GLEAM root-zone soil moisture data records and categorized into six classes ranging from 0.15 to 0.4 m³/m³ at 0.05 m³/m³ interval and classifying those above 0.4 m³/m³ as 0.4 m³/m³ and those below 0.15 m³/m³ as 0.15 m³/m³.

The spatial relationship analyses between datasets with different spatial resolutions are conducted by reprojecting the finer data onto the spatial grid of coarser data using bilinear aggregation. For this purpose, all pixels with NDVI < 0.1 for GIMMS NDVI3g and NDVI < 0.15 for MODIS NDVI and EVI are given value of zero before spatial aggregation. Linear slopes are estimated using the robust Theil–Sen slope estimator and correlations are estimated using the Kendall’s tau estimator. The Mann–Kendall test was used to assess the statistical significance of both the linear slope and correlation.

3. Results and Discussion

We begin by comparing the relationships between spring and summer greenness from MODIS NDVI and EVI for 2000–2017 per land cover class. Spring greenness from MODIS NDVI and EVI are significantly negatively related ($p < 0.05$) with summer greenness for all land cover classes (Figure 3). There was no significant difference in relationships between spring and summer greenness among the land cover classes. To strengthen the results presented in Figure 3, we further analysed the inter-annual relationships between spring and summer greenness from MODIS NDVI and EVI for 2000–2017 relative to long-term mean soil moisture and tree cover classes. The results show that spring greenness from MODIS NDVI and EVI are significantly negatively related ($p < 0.05$) with summer greenness for all soil moisture (Figure 4a) and tree cover classes (Figure 4c). Although there was no consistent difference in the relationships along the soil moisture classes, MODIS NDVI and EVI the strengthening negative relationship between spring and summer greenness with decreasing tree cover (Figure 4c). The strengthening negative relationship with decreasing tree cover is expected as trees have deeper and more extensive root systems that facilitate larger access to available moisture than herbaceous vegetation. However, strengthening negative relationship with decreasing tree cover is not observed

in the GIMMS NDVI3g data. MODIS NDVI, EVI and tree cover data have the same spatial resolutions while GIMMS is approximately 16 times coarser that may explain the discrepancy.

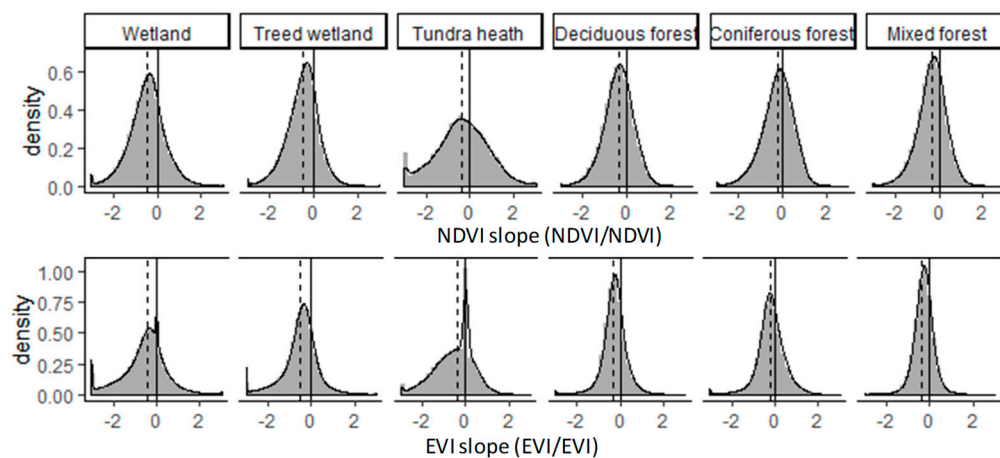


Figure 3. Density plot of linear slopes between the spring and summer greenness from MODIS normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) for 2000–2017 per land cover classes. The dashed vertical lines indicate the mean value of slope while the solid vertical lines indicate the slope value of zero, the latter added for visual clarity. Mean of linear slope is significantly different from zero in all cases ($p < 0.05$, two-tailed one-sample t -test).

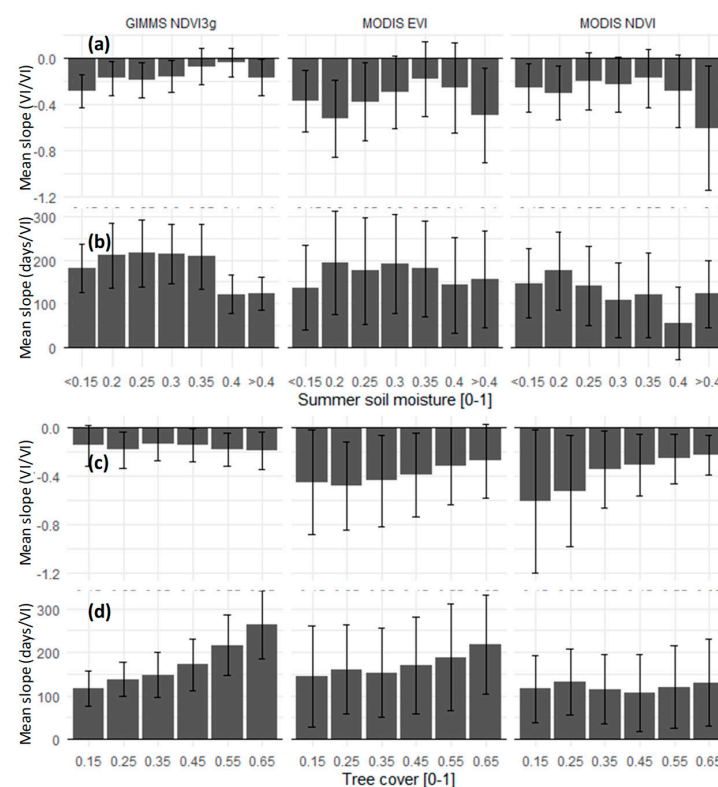


Figure 4. Linear slopes of summer greenness with spring greenness (a) and start of growing season (SOS) (b) along soil moisture (m^3/m^3) classes. Linear slopes of summer greenness with spring greenness (c) and SOS (d) along tree cover classes. VI is vegetation index (i.e., NDVI or EVI). Error bars represent one standard deviation of spatial slopes in each soil moisture or tree cover class. The linear slopes are computed at native spatial resolutions of Global Inventory Modeling and Mapping Studies third-generation (GIMMS) and MODIS data. Mean of linear slope is significantly different from zero in all cases ($p < 0.05$, two-tailed one-sample t -test).

We further analysed the inter-annual relationships of SOS with summer NDVI and EVI. The results indicate that the later onset of growing season is significantly ($p < 0.05$) related to increased summer greenness for all soil moisture (Figure 4b) and tree cover classes (Figure 4d). Moreover, earlier onset of SOS is consistently related to lower peak of season greenness values as estimated from two methods throughout soil moisture and tree cover classes (Figure 5). Earlier arrival of spring leads to decreased summer greenness and reduced maximum greenness consistently from both GIMMS and MODIS data.

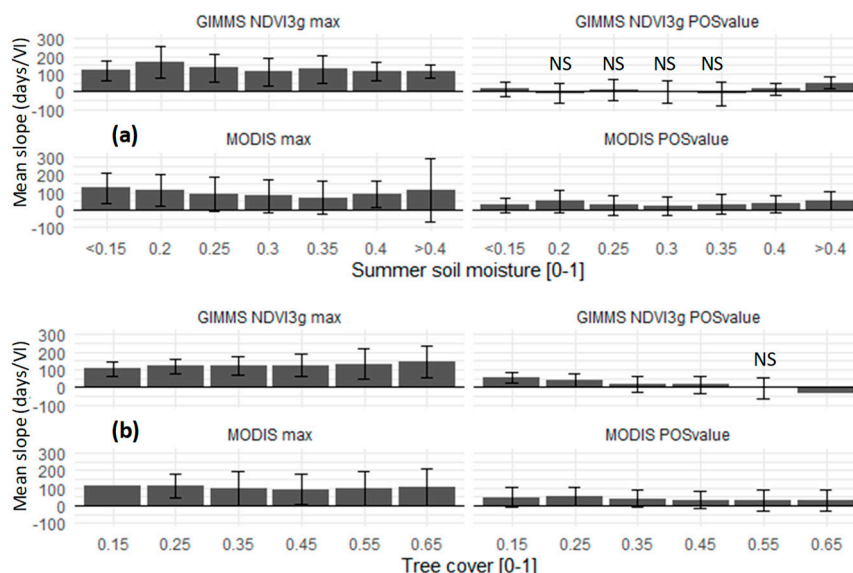


Figure 5. Linear slopes of start of season (SOS) with maximum productivity obtained from GIMMS NDVI3g and MODIS NDVI plotted along the long-term mean summer soil moisture (m^3/m^3) (a) and tree cover (b) classes. VI is vegetation index (i.e., NDVI or EVI). Error bars represent one standard deviation of spatial slopes in each soil moisture or tree cover class. The linear slopes are computed at native spatial resolutions of GIMMS and MODIS data. Maximum productivity values are obtained from peak of season day (i.e., POSvalue) using the curve-fitting algorithm and directly from maximum annual value of the raw data (i.e., max). Mean of linear slope is significantly different from zero in all cases ($p < 0.05$, two-tailed one-sample t -test) except indicated as NS (not significant) otherwise.

Figure 6 further shows that spring NDVI values are negatively correlated with summer soil moisture for the southern part of the study area with low average soil moisture while correlations were positive for the northern part of the study area. This pattern clearly indicates that the effect of spring vegetation growth on summer soil moisture content is highest in areas with relatively low soil moisture content. This result implies that the timing and amount of spring greenness directly affect the summer soil moisture and greenness, consistent with recent findings [36–41,54].

We have also analysed the spring and summer greenness relationships by substrate type, i.e., mineral soil and wetland pixels, and found no consistent discrepancy (Figures S1–S3). The lack of discrepancy between mineral soil and wetland results in this study could arise from our resampling of the 30 m land cover map (Figure 1) into coarser grids, which may not capture the actual heterogeneity of the landscape in the analysis of soil moisture spatial distribution associated with vegetation activities. Previous studies have hypothesized an emerging soil moisture constraint on the summer plant growth rate of high latitude ecosystems [19,41,55–62]. This is consistent with our findings that increased spring greening is depleting summer soil moisture. Therefore, our results support that the weakening summer plant growth sensitivity to temperature reported in several studies [30–33] may be related to summer soil moisture stress partly caused by increased plant growth in spring and earlier onset of growing season.

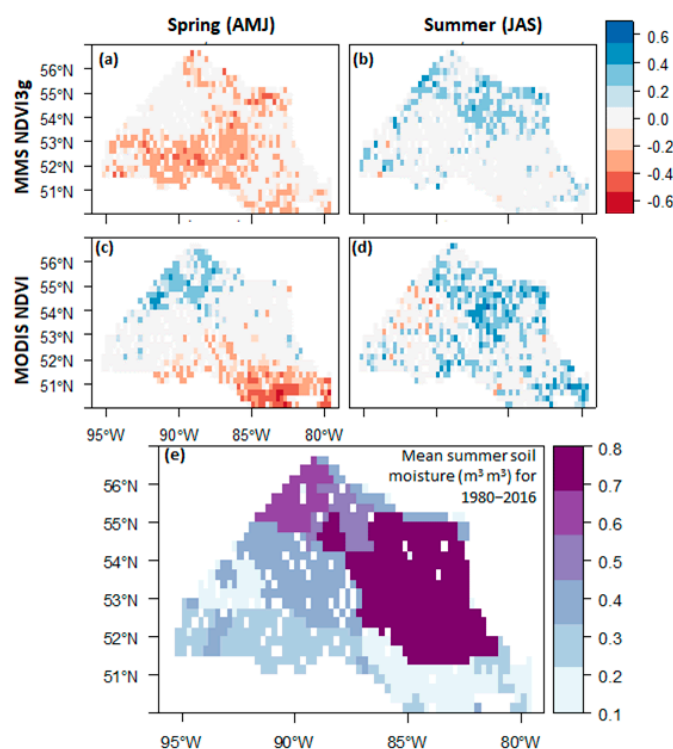


Figure 6. Spatial distributions of the summer soil moisture correlation against the spring GIMMS (a), summer GIMMS (b), spring MODIS (c) and summer MODIS (d) NDVI. All coloured pixels for (a–d) are significantly correlated at 90% confidence level (one-tailed). The relationships of spatial trends were computed after projecting all datasets into $0.25^\circ \times 0.25^\circ$ Latitude-Longitude grids. Long-term (1980–2016) mean summer soil moisture is shown in (e).

4. Conclusions

We used several satellite datasets (MODIS NDVI, EVI and tree cover, GIMMS NDVI3g, and GLEAM root-zone soil moisture) to study the influence of spring plant growth on summer soil moisture content and plant growth on heterogeneous landscapes typical of the tundra-taiga interface, consisting of unmanaged boreal forest, wetlands, and the most southerly part of the tundra. Our results indicate that higher vegetation growth in spring leads to decreased summer soil moisture and greenness. We also found that earlier start of growing season leads to decreased summer and maximum greenness. In conclusion, earlier and increased spring plant growth leads to reduced summer soil moisture and plant growth. Our analysis supports that the weakening summer plant growth sensitivity to temperature reported in several studies may be related to summer soil moisture stress partly caused by increased plant growth in spring that depletes soil moisture. Our analysis, in a study area representative of the northern high latitude terrestrial ecosystems, contributes to a better understanding of the changing coupling between vegetation and Earth's climatic dynamics.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2072-4292/11/17/1989/s1>, Figure S1: The spatial distribution of regression slopes between spring and summer greenness, Figure S2: Regression slopes of start of season (SOS) with summer NDVI and EVI, Figure S3: Regression slopes of start of season (SOS) with maximum productivity.

Author Contributions: A.G. designed the study. A.G., M.T.T.-M., J.M.C. and J.C. wrote the paper.

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greatly contributed to the current work. The GIMMS (Global Inventory Modelling and Mapping) Normalized Difference Vegetation Index (NDVI3g) data is available at <https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/>. The MODIS EVI and NDVI, collection 6 (V006) is available at Earthdata search (<https://search.earthdata.nasa.gov/>). The GLEAM root-zone soil moisture data is available at www.gleam.eu. The CCI soil moisture data is available at <https://www.esa-soilmoisture-cci.org/node/145>. We thank two anonymous reviewers for their valuable time and comments that improved the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nemani, R.R.; Keeling, C.D.; Hashimoto, H.; Jolly, W.M.; Piper, S.C.; Tucker, C.J.; Myneni, R.B.; Running, S.W. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* **2003**, *300*, 1560–1563. [[CrossRef](#)] [[PubMed](#)]
2. Myneni, R.B.; Keeling, C.D.; Tucker, C.J.; Asrar, G.; Nemani, R.R. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **1997**, *386*, 698–702. [[CrossRef](#)]
3. Gonsamo, A.; Chen, J.M.; Shindell, D.T.; Asner, G.P. Coherence among the Northern Hemisphere land, cryosphere, and ocean responses to natural variability and anthropogenic forcing during the satellite era. *Earth Syst. Dyn.* **2016**, *7*, 717–734. [[CrossRef](#)]
4. De Jong, R.; De Bruin, S.; De Wit, A.; Schaepman, M.E.; Dent, D.L. Analysis of monotonic greening and browning trends from global NDVI time-series. *Remote Sens. Environ.* **2011**, *115*, 692–702. [[CrossRef](#)]
5. Gonsamo, A.; Chen, J.M.; Lombardozzi, D. Global vegetation productivity response to climatic oscillations during the satellite era. *Glob. Chang. Biol.* **2016**, *22*, 3414–3426. [[CrossRef](#)] [[PubMed](#)]
6. Zhang, Y.; Song, C.; Band, L.E.; Sun, G.; Li, J. Reanalysis of global terrestrial vegetation trends from MODIS products: Browning or greening? *Remote Sens. Environ.* **2017**, *191*, 145–155. [[CrossRef](#)]
7. Tian, F.; Fensholt, R.; Verbesselt, J.; Grogan, K.; Horion, S.; Wang, Y. Evaluating temporal consistency of long-term global NDVI datasets for trend analysis. *Remote Sens. Environ.* **2015**, *163*, 326–340. [[CrossRef](#)]
8. Graven, H.D.; Keeling, R.F.; Piper, S.C.; Patra, P.K.; Stephens, B.B.; Wofsy, S.C.; Welp, L.R.; Sweeney, C.; Tans, P.P.; Kelley, J.J.; et al. Enhanced Seasonal Exchange of CO₂ by Northern Ecosystems Since 1960. *Science* **2013**, *341*, 1085–1089. [[CrossRef](#)]
9. Forkel, M.; Carvalhais, N.; Rödenbeck, C.; Keeling, R.; Heimann, M.; Thonicke, K.; Zaehle, S.; Reichstein, M. Enhanced seasonal CO₂ exchange caused by amplified plant productivity in northern ecosystems. *Science* **2016**, *351*, 696–699. [[CrossRef](#)]
10. Keeling, C.D.; Chin, J.F.S.; Whorf, T.P. Increased activity of northern vegetation inferred from atmospheric CO₂ measurements. *Nature* **1996**, *382*, 146–149. [[CrossRef](#)]
11. Cleland, E.E.; Chuine, I.; Menzel, A.; Mooney, H.A.; Schwartz, M.D. Shifting plant phenology in response to global change. *Trends Ecol. Evol.* **2007**, *22*, 357–365. [[CrossRef](#)] [[PubMed](#)]
12. Menzel, A.; Sparks, T.H.; Estrella, N.; Koch, E.; Aasa, A.; Ahas, R.; Alm-Kubler, K.; Bissolli, P.; Braslavská, O.; Briede, A.; et al. European phenological response to climate change matches the warming pattern. *Glob. Chang. Biol.* **2006**, *12*, 1969–1976. [[CrossRef](#)]
13. Walther, G.-R.; Post, E.; Convey, P.; Menzel, A.; Parmesan, C.; Beebee, T.J.C.; Fromentin, J.-M.; Hoegh-Guldberg, O.; Bairlein, F. Ecological responses to recent climate change. *Nature* **2002**, *416*, 389–395. [[CrossRef](#)] [[PubMed](#)]
14. Gonsamo, A.; Chen, J.M.; Ooi, Y.W. Peak season plant activity shift towards spring is reflected by increasing carbon uptake by extratropical ecosystems. *Glob. Chang. Biol.* **2018**, *24*, 2117–2128. [[CrossRef](#)] [[PubMed](#)]
15. Xu, C.; Liu, H.; Williams, A.P.; Yin, Y.; Wu, X. Trends toward an earlier peak of the growing season in Northern Hemisphere mid-latitudes. *Glob. Chang. Biol.* **2016**, *22*, 2852–2860. [[CrossRef](#)] [[PubMed](#)]
16. Bhatt, U.S.; Walker, D.A.; Raynolds, M.K.; Bieniek, P.A.; Epstein, H.E.; Comiso, J.C.; Pinzon, J.E.; Tucker, C.J.; Steele, M.; Ermold, W.; et al. Changing seasonality of panarctic tundra vegetation in relationship to climatic variables. *Environ. Res. Lett.* **2017**, *12*, 055003. [[CrossRef](#)]
17. Keenan, T.F.; Gray, J.; Friedl, M.A.; Toomey, M.; Bohrer, G.; Hollinger, D.Y.; Munger, J.W.; O’Keefe, J.; Schmid, H.P.; Wing, I.S.; et al. Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nat. Clim. Chang.* **2014**, *4*, 598–604. [[CrossRef](#)]

18. Keeling, C.D.; Piper, S.C.; Bacastow, R.B.; Wahlen, M.; Whorf, T.P.; Heimann, M.; Meijer, H.A. Atmospheric CO₂ and ¹³CO₂ exchange with the terrestrial biosphere and oceans from 1978 to 2000: Observations and carbon cycle implications. In *A History of Atmospheric CO₂ and its Effects on Plants, Animals, and Ecosystems*; Ehleringer, J.R., Cerling, T.E., Dearing, M.D., Eds.; Springer: New York, NY, USA, 2005; pp. 83–113.
19. Gonsamo, A.; D'Odorico, P.; Chen, J.M.; Wu, C.; Buchmann, N. Changes in vegetation phenology are not reflected in atmospheric CO₂ and ¹³C/¹²C seasonality. *Glob. Chang. Boil.* **2017**, *23*, 4029–4044. [[CrossRef](#)]
20. Guay, K.C.; Beck, P.S.A.; Berner, L.T.; Goetz, S.J.; Baccini, A.; Buermann, W. Vegetation productivity patterns at high northern latitudes: A multi-sensor satellite data assessment. *Glob. Chang. Boil.* **2014**, *20*, 3147–3158. [[CrossRef](#)]
21. Berner, L.T.; Beck, P.S.A.; Bunn, A.G.; Lloyd, A.H.; Goetz, S.J. High-latitude tree growth and satellite vegetation indices: Correlations and trends in Russia and Canada (1982–2008). *J. Geophys. Res. Space Phys.* **2011**, *116*. [[CrossRef](#)]
22. Beck, P.S.A.; Goetz, S.J. Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: Ecological variability and regional differences. *Environ. Res. Lett.* **2011**, *6*, 045501. [[CrossRef](#)]
23. Bunn, A.G.; Goetz, S.J. Trends in Satellite-Observed Circumpolar Photosynthetic Activity from 1982 to 2003: The Influence of Seasonality, Cover Type, and Vegetation Density. *Earth Interact.* **2006**, *10*, 1–19. [[CrossRef](#)]
24. Verbyla, D. The greening and browning of Alaska based on 1982–2003 satellite data. *Glob. Ecol. Biogeogr.* **2008**, *17*, 547–555. [[CrossRef](#)]
25. Ju, J.; Masek, J.G. The vegetation greenness trend in Canada and US Alaska from 1984–2012 Landsat data. *Remote Sens. Environ.* **2016**, *176*, 1–16. [[CrossRef](#)]
26. Pan, N.; Feng, X.; Fu, B.; Wang, S.; Ji, F.; Pan, S. Increasing global vegetation browning hidden in overall vegetation greening: Insights from time-varying trends. *Remote Sens. Environ.* **2018**, *214*, 59–72. [[CrossRef](#)]
27. Phoenix, G.K.; Bjerke, J.W. Arctic browning: Extreme events and trends reversing arctic greening. *Glob. Chang. Biol.* **2016**, *22*, 2960–2962. [[CrossRef](#)]
28. Fu, Y.H.; Zhao, H.; Piao, S.; Peaucelle, M.; Peng, S.; Zhou, G.; Ciais, P.; Huang, M.; Menzel, A.; Peñuelas, J.; et al. Declining global warming effects on the phenology of spring leaf unfolding. *Nature* **2015**, *526*, 104–107. [[CrossRef](#)]
29. Rutishauser, T.; Luterbacher, J.; Defila, C.; Frank, D.; Wanner, H. Swiss spring plant phenology 2007: Extremes, a multi-century perspective, and changes in temperature sensitivity. *Geophys. Res. Lett.* **2008**, *35*. [[CrossRef](#)]
30. Piao, S.; Nan, H.; Huntingford, C.; Ciais, P.; Friedlingstein, P.; Sitch, S.; Peng, S.; Ahlström, A.; Canadell, J.G.; Cong, N.; et al. Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity. *Nat. Commun.* **2014**, *5*, 5018. [[CrossRef](#)]
31. Briffa, K.R.; Schweingruber, F.H.; Jones, P.D.; Osborn, T.J.; Shiyatov, S.G.; Vaganov, E.A.; Osborn, T. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* **1998**, *391*, 678–682. [[CrossRef](#)]
32. Piao, S.; Liu, Z.; Wang, T.; Peng, S.; Ciais, P.; Huang, M.; Ahlstrom, A.; Burkhardt, J.F.; Chevallier, F.; Janssens, I.A.; et al. Weakening temperature control on the interannual variations of spring carbon uptake across northern lands. *Nat. Clim. Chang.* **2017**, *7*, 359–363. [[CrossRef](#)]
33. Trahan, M.W.; Schubert, B.A. Temperature-induced water stress in high-latitude forests in response to natural and anthropogenic warming. *Glob. Chang. Boil.* **2016**, *22*, 782–791. [[CrossRef](#)] [[PubMed](#)]
34. Ding, J.; Yang, T.; Zhao, Y.; Liu, D.; Wang, X.; Yao, Y.; Peng, S.; Wang, T.; Piao, S. Increasingly important role of atmospheric aridity on Tibetan alpine grasslands. *Geophys. Res. Lett.* **2018**, *45*, 2852–2859. [[CrossRef](#)]
35. D'Orangeville, L.; Maxwell, J.; Kneeshaw, D.; Pederson, N.; Duchesne, L.; Logan, T.; Houle, D.; Arseneault, D.; Beier, C.M.; Bishop, D.A.; et al. Drought timing and local climate determine the sensitivity of eastern temperate forests to drought. *Glob. Chang. Boil.* **2018**, *24*, 2339–2351. [[CrossRef](#)] [[PubMed](#)]
36. Yu, Z.; Lu, C.; Cao, P.; Tian, H.; Hessel, A.; Pederson, N. Earlier leaf-flushing suppressed ecosystem productivity by draining soil water in the Mongolian Plateau. *Agric. For. Meteorol.* **2018**, *250*, 1–8. [[CrossRef](#)]
37. Hu, J.; Moore, D.J.P.; Burns, S.P.; Monson, R.K. Longer growing seasons lead to less carbon sequestration by a subalpine forest. *Glob. Chang. Boil.* **2010**, *16*, 771–783. [[CrossRef](#)]
38. Angert, A.; Biraud, S.; Bonfils, C.; Henning, C.C.; Buermann, W.; Pinzon, J.; Tucker, C.J.; Fung, I. Drier summers cancel out the CO₂ uptake enhancement induced by warmer springs. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 10823–10827. [[CrossRef](#)]

39. Buermann, W.; Bikash, P.R.; Jung, M.; Burn, D.H.; Reichstein, M. Earlier springs decrease peak summer productivity in North American boreal forests. *Environ. Res. Lett.* **2013**, *8*, 024027. [\[CrossRef\]](#)
40. Parmentier, F.-J.; Van Der Molen, M.K.; Van Huissteden, J.; Karsanaev, S.A.; Kononov, A.; Suzdalov, D.A.; Maximov, T.C.; Dolman, A.J. Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra. *J. Geophys. Res. Space Phys.* **2011**, *116*. [\[CrossRef\]](#)
41. Parida, B.R.; Buermann, W. Increasing summer drying in North American ecosystems in response to longer nonfrozen periods. *Geophys. Res. Lett.* **2014**, *41*, 5476–5483. [\[CrossRef\]](#)
42. The Far North Science Advisory Panel. *Science for a Changing Far North*; Ontario Ministry of Natural Resources: Nipigon, ON, USA, 2010.
43. Gonsamo, A.; Chen, J.M.; Colombo, S.J.; Ter-Mikaelian, M.T.; Chen, J.; Ter-Mikaelian, M.T. Global change induced biomass growth offsets carbon released via increased forest fire and respiration of the central Canadian boreal forest. *J. Geophys. Res. Biogeosci.* **2017**, *122*, 1275–1293. [\[CrossRef\]](#)
44. Packalen, M.S.; Finkelstein, S.A.; McLaughlin, J.W. Carbon storage and potential methane production in the Hudson Bay Lowlands since mid-Holocene peat initiation. *Nat. Commun.* **2014**, *5*, 4078. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Hugelius, G.; Strauss, J.; Zubrzycki, S.; Harden, J.W.; Schuur, E.A.G.; Ping, C.-L.; Schirmer, L.; Grosse, G.; Michaelson, G.J.; Koven, C.D.; et al. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences* **2014**, *11*, 6573–6593. [\[CrossRef\]](#)
46. Gonsamo, A.; Chen, J.M.; Price, D.T.; Kurz, W.A.; Liu, J.; Boisvenue, C.; Hember, R.A.; Wu, C.; Chang, K.-H. Improved assessment of gross and net primary productivity of Canada's landmass. *J. Geophys. Res. Biogeosci.* **2013**, *118*, 1546–1560. [\[CrossRef\]](#)
47. Huete, A.; Didan, K.; Miura, T.; Rodriguez, E.; Gao, X.; Ferreira, L. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.* **2002**, *83*, 195–213. [\[CrossRef\]](#)
48. Vermote, E.F.; Vermeulen, A. *Atmospheric Correction Algorithm: Spectral Reflectance (MOD09)*; University of Maryland, Department of Geography: College Park MD, USA, 1999.
49. Pinzon, J.; Tucker, C. A Non-Stationary 1981–2012 AVHRR NDVI3g Time Series. *Remote Sens.* **2014**, *6*, 6929–6960. [\[CrossRef\]](#)
50. Martens, B.; Miralles, D.G.; Lievens, H.; Van Der Schalie, R.; De Jeu, R.A.M.; Fernández-Prieto, D.; Beck, H.E.; Dorigo, W.A.; Verhoest, N.E.C. GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. *Geosci. Model Dev.* **2017**, *10*, 1903–1925. [\[CrossRef\]](#)
51. Dorigo, W.; Wagner, W.; Albergel, C.; Albrecht, F.; Balsamo, G.; Brocca, L.; Chung, D.; Ertl, M.; Forkel, M.; Gruber, A.; et al. ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. *Remote Sens. Environ.* **2017**, *203*, 185–215. [\[CrossRef\]](#)
52. Gonsamo, A.; Chen, J.M. Circumpolar vegetation dynamics product for global change study. *Remote Sens. Environ.* **2016**, *182*, 13–26. [\[CrossRef\]](#)
53. Gonsamo, A.; Chen, J.M. Spectral Response Function Comparability among 21 Satellite Sensors for Vegetation Monitoring. *IEEE Trans. Geosci. Remote Sens.* **2012**, *1*–17. [\[CrossRef\]](#)
54. Buermann, W.; Forkel, M.; O'Sullivan, M.; Sitch, S.; Friedlingstein, P.; Haverd, V.; Jain, A.K.; Kato, E.; Kautz, M.; Lienert, S.; et al. Widespread seasonal compensation effects of spring warming on northern plant productivity. *Nature* **2018**, *562*, 110–114. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Girardin, M.P.; Bouriaud, O.; Hogg, E.H.; Kurz, W.; Zimmermann, N.E.; Metsaranta, J.M.; de Jong, R.; Frank, D.C.; Esper, J.; Büntgen, U.; et al. No growth stimulation of Canada's boreal forest under half-century of combined warming and CO₂ fertilization. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, E8406–E8414. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Verbyla, D. Remote sensing of interannual boreal forest NDVI in relation to climatic conditions in interior Alaska. *Environ. Res. Lett.* **2015**, *10*, 125016. [\[CrossRef\]](#)
57. May, J.L.; Parker, T.; Unger, S.; Oberbauer, S.F. Short term changes in moisture content drive strong changes in Normalized Difference Vegetation Index and gross primary productivity in four Arctic moss communities. *Remote Sens. Environ.* **2018**, *212*, 114–120. [\[CrossRef\]](#)
58. Barber, V.A.; Juday, G.P.; Finney, B.P. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* **2000**, *405*, 668–673. [\[CrossRef\]](#) [\[PubMed\]](#)

59. Peng, C.; Ma, Z.; Lei, X.; Zhu, Q.; Chen, H.; Wang, W.; Liu, S.; Li, W.; Fang, X.; Zhou, X. A drought-induced pervasive increase in tree mortality across Canada's boreal forests. *Nat. Clim. Chang.* **2011**, *1*, 467–471. [[CrossRef](#)]
60. Sherriff, R.L.; Miller, A.E.; Muth, K.; Schriver, M.; Batzel, R. Spruce growth responses to warming vary by ecoregion and ecosystem type near the forest-tundra boundary in south-west Alaska. *J. Biogeogr.* **2017**, *6*, 1457–1468. [[CrossRef](#)]
61. Barichivich, J.; Briffa, K.R.; Myneni, R.; Van Der Schrier, G.; Dorigo, W.; Tucker, C.J.; Osborn, T.J.; Melvin, T.M.; Schrier, G. Temperature and Snow-Mediated Moisture Controls of Summer Photosynthetic Activity in Northern Terrestrial Ecosystems between 1982 and 2011. *Remote Sens.* **2014**, *6*, 1390–1431. [[CrossRef](#)]
62. Buermann, W.; Parida, B.R.; Jung, M.; Macdonald, G.M.; Tucker, C.J.; Reichstein, M. Recent shift in Eurasian boreal forest greening response may be associated with warmer and drier summers. *Geophys. Res. Lett.* **2014**, *41*, 1995–2002. [[CrossRef](#)]



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