

The effect of growing season and summer greenness on northern forests

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[1] We investigate the physiological effects of the elongation of the growing season and the increase in summer greenness on northern hemisphere forests by examining the relationship between NDVI and tree rings. These variables are correlated during June and July only. These results suggest that NDVI proxies the physiological status of trees and that the summer status of the canopy has a larger effect on tree vigor than the duration of the canopy. **INDEX TERMS:** 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); 1640 Global Change: Remote sensing; 1851 Hydrology: Plant ecology. **Citation:** Kaufmann, R. K., R. D. D'Arrigo, C. Laskowski, R. B. Myneni, L. Zhou, and N. K. Davi (2004), The effect of growing season and summer greenness on northern forests, *Geophys. Res. Lett.*, 31, L09205, doi:10.1029/2004GL019608.

1. Introduction

[2] Over the last two decades, satellite measures of surface greenness such as the normalized difference vegetation index (NDVI) have detected two large-scale changes in northern hemisphere forests: an elongation of the growing season and an increase in summer greenness [Myneni *et al.*, 1997; Zhou *et al.*, 2001]. These changes raise the question, what is their physiological significance? Here, we investigate this question using statistical techniques to examine the relationship between NDVI and a widely accepted measure for the physiological status of trees, tree rings [Fritts, 1976; Cook and Kairiukstis, 1990]. The results indicate that interannual variations in NDVI and tree-ring data from selected sites share a common signal that may reflect a fundamental aspect of tree physiology. The timing of this shared signal indicates that the increase in summer greenness may be a more important physiological change than the elongation of the growing season for the sites analyzed here.

[3] We assemble time series of NDVI and tree rings for forty-eight middle to high latitude sites in North America

and Eurasia (Figure 1). The tree-ring series are annual chronologies comprised of dimensionless indices that result from standardization of raw ring width and density measurements [Cook and Kairiukstis, 1990]. Locations are where growth is limited primarily by either precipitation or temperature. Interannual changes in these limiting factors impart a signal to the tree-ring series that may be captured by the Advanced Very High Resolution Radiometer (AVHRR) measurements of NDVI. For each site, we average cores (usually at least two per tree) from about twenty or more trees per site that cover an area which varies, but generally is one to a few square kilometers. These spatial averages are analogous to the AVHRR measures of NDVI, which have an 8-km resolution (square pixels). The latitude and longitude (nearest second) of the tree ring sites are used to locate the corresponding pixel from the GIMMS NDVI data set [Zhou *et al.*, 2001]. Because the tree-ring site is not always in the center of the pixel, the fifteen day composites of NDVI, solar zenith angle, and aerosol optical depth for this pixel are averaged with those of the eight "surrounding" pixels to generate monthly values from July 1981 through December 1999. Many of the tree-ring sites were sampled before 1999; therefore, the number of observations varies among sites. This is known as an unbalanced panel.

[4] To test whether the interannual changes in NDVI reflect changes in the physiological status of trees as reflected by the tree-ring data, we estimate equation (1):

$$\text{NDVI}_{ijt} = \alpha + \beta \text{TRI}_{it} + \gamma \text{SZA}_{ijt} + \varphi \text{AOD}_{ijt} + \mu_{it} \quad (1)$$

in which NDVI is NDVI for month j in year t at site i , in year t TRI is the standardized tree-ring index, SZA is solar zenith angle, AOD is aerosol optical depth [Sato *et al.*, 1993], α , β , γ , φ are regression coefficients, and μ is a regression residual. Equation (1) includes SZA and AOD to reduce their possible effect on AVHRR measurements of NDVI [Gutman, 1999; Vermote and Kaufman, 1995].

[5] Differences in the species present and other unobserved variables may cause the intercept (α) to vary among sites. To test the null hypothesis that the intercept is equal across sites, we use a test statistic [Hsiao, 1986] that can be evaluated against an F distribution under the assumption that the error term is stationary (Panel cointegration tests indicate that μ_{it} is stationary). If the test statistic exceeds the critical value ($p < .05$), we estimate equation (1) using the fixed effects estimator. The fixed effects estimator allows the intercept to vary among sites.

[6] To evaluate the timing of the relationship between NDVI and tree rings, equation (1) is estimated eight times, once with an average value for NDVI (and SZA and AOD) over the growing season, April through October, and once

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Table 2. Analysis of Causal Order (Equations (2)–(5))

	TRI “Granger Causes” NDVI (Equation (2))				NDVI “Granger causes” TRI (Equation (3))			
	β_1	S_{2a}	S_{3a}	F(47,662) ^a	β_1	S_{2a}	S_{3a}	F(47,662) ^a
June	-1.73E-05	-1.20	-0.59	10.36 ^c	-47.16	0.60	1.00	5.49 ^e
July	-2.76E-06	1.50	1.56	10.82 ^c	215.3	-0.82	-1.27	5.60 ^e

^aTests the null hypothesis that the intercepts are the same across the forty-eight sites.

Coefficients are statistically significantly different from zero at the:

^b5% level.

^c1% level.

^d10% level.

in which T_{it} is the observed value for NDVI or tree-ring index for site i at time t , \hat{T}_{itU} is the out-of-sample forecast for NDVI or TRI generated by the unrestricted version of equation (2) or (3), and \hat{T}_{itR} is the out-of-sample forecast generated by the restricted version of equation (2) or (3). The values of d are used to generate the S_{2a} and S_{3a} statistic [Diebold and Mariano, 1995] as follows:

$$S_{2a} = \frac{\sum_{t=1}^N I_+(d_t) - 0.5N}{\sqrt{0.25N}}$$

$$S_{3a} = \frac{\sum_{t=1}^N I_+(d_t) \text{rank}(|d_t|) - \frac{N(N+1)}{4}}{\sqrt{\frac{N(N+1)(2N+1)}{24}}}$$

$$I_+(d_t) = 1 \quad \text{if } d_t > 0$$

$$= 0 \quad \text{otherwise}$$
(5)

in which N is the number of observations (714).

[13] The S_{2a} and S_{3a} statistics test the null hypothesis that the accuracy of the out-of-sample forecasts is equal. These test statistics can be evaluated against a student's t distribution with 713 degrees of freedom ($N - 1$). If the test statistic rejects the null hypothesis, the more accurate model is identified by the sign on the test statistic. The test statistic will be negative if the out-of-sample forecast errors simulated by the unrestricted model are smaller (absolute values). This result would indicate that eliminating NDVI from equation (2) or eliminating TRI from equation (3) reduces the accuracy of the out-of-sample forecast and that TRI “Granger causes” NDVI (equation (2)) or that NDVI “Granger causes” TRI (equation (3)).

[14] The results indicate that the regression coefficient associated with the potentially causal variable is not statistically different from zero (Table 2). Consistent with this result, we cannot reject the null hypothesis that the accuracy of the out-of-sample forecast generated by the restricted model (that omits the potentially causal variable) is as accurate as the out-of-sample forecast generated by the unrestricted model.

[15] Together, these results indicate that there is no causal relationship between the NDVI and tree ring data. The lack of causal order in either direction (coupled with the relationship given by equation (1)) implies that NDVI and tree rings share a common signal that is imparted contemporaneously by some common causal variable which may represent a fundamental element of tree physiology, perhaps net primary productivity [Hunt et al., 1991; D'Arrigo et al., 2000]. Net primary productivity represents the amount of

energy available to a tree that it can use to produce leaves, which is proxied by NDVI, and to increase biomass, which is proxied by tree rings.

[16] The lack of causal order is surprising given the differences in what NDVI and tree rings measure. NDVI measures the amount of photosynthetically active pigment. Therefore, NDVI measures above-ground conditions, such as leaf area index, during the growing season. Tree rings are a more integrative measure. Physiological studies indicate that each tree-ring value reflects the overall status of the tree during the current growing season and to varying degrees, those of the recent past [e.g., Schweingruber, 1988]. Tree rings, particularly ring width, also may integrate conditions during non-growing season months [Jacoby and D'Arrigo, 1989]. These differences imply that tree rings could induce changes in NDVI.

[17] The increase in the maximum value of NDVI at the sites studied and those reported by Myneni et al. [1997] and Zhou et al. [2001] occurs in June and July. These are the only months in which NDVI is related to the tree ring index. This correlation implies that the summer peak in NDVI measures an important physiological change. Conversely, the lack of an overall relationship between tree rings and NDVI for months at the start or end of the growing season may indicate that the advance in spring and the delay in fall are less important to the physiological status of the trees.

[18] The lack of a correlation between NDVI and tree rings in April and May implies that the spring-time status of the canopy is relatively unimportant. For the sites analyzed here, April and May values of NDVI are weakly correlated with June and July values of NDVI (adjusted R squares vary between 0.003 and 0.14). This implies that early greening does not lead to a larger summer canopy, which could be used to increase NPP. This finding is consistent with results by White and Nemani [2003] but contradicts results by Keyser et al. [2000].

[19] The correlation between tree rings and NDVI in June and July imply that summer changes may have important implications for northern forests. A one degree increase in summer temperature has a greater effect on summer NDVI than a similar increase in spring temperature [Zhou et al., 2003]. Similarly, summer temperatures are correlated with uptake by the unknown carbon sink -there is no correlation with spring, fall, or winter temperatures [Kaufmann and Stock, 2003]. Together, these results imply that spring time changes may be easier to detect, but that summer changes may have a bigger effect on the terrestrial carbon cycle.

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