# The effect of growing season and summer greenness on northern forests

R. K. Kaufmann,[1,2] R. D. D'Arrigo,[3] C. Laskowski,[4] R. B. Myneni,[1] L. Zhou,[5] and N. K. Davi[3]

[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):

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

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], $\alpha$, $\beta$, $\gamma$, $\varphi$ are regression coefficients, and $\mu$ 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 ($\alpha$) 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 $\mu_t$ 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

[1] Department of Geography, Boston University, Boston, Massachusetts, USA.

[2] Also at Center for Energy and Environmental Studies, Boston University, Boston, Massachusetts, USA.

[3] Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA.

[4] Center for Energy and Environmental Studies, Boston University, Boston, Massachusetts, USA.

[5] School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.
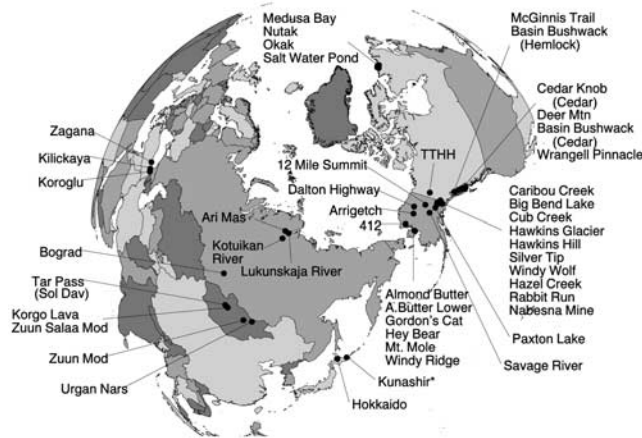
**Figure 1.** Location of tree ring sites (detailed information available on request). Most are coniferous sites—sites with deciduous species are indicated by (*).

with the NDVI series for each of the seven monthly time series (e.g., tree rings and June NDVI). The relationship between NDVI and tree rings is evaluated by testing the null hypothesis $\beta = 0$. This null is evaluated with a test statistic (commonly called a t statistic) that can be evaluated against a t distribution. Values that reject the null hypothesis indicate that there is a statistically meaningful relationship between NDVI and tree rings.

[7] Using the fixed effects estimator (the F tests strongly reject the null), we reject the null hypothesis, $\beta = 0$, for the growing season average and the monthly values for June and July (Table 1). The statistical significance of $\beta$ in equation (1) indicates that the relationship between tree rings and NDVI goes beyond any effect of solar zenith angle and/or aerosol optical depth on NDVI. This result confirms a theoretical and empirical analysis which indicates that NDVI is relatively unaffected by the solar zenith angle in land covers with a high leaf area [*Kaufmann et al.*, 2000].

[8] The correlation between tree rings and NDVI for the growing season, June, and July implies that the relation between ring width and growing season NDVI is generated by its inclusion of values for June and July. As such, information about the relation between NDVI and tree rings can be gleaned more precisely from monthly values, rather than the growing season average. The timing of the relationship between NDVI and tree rings generally is consistent with the timing of the growing season at the tree-ring sites. The largest values for NDVI tend to occur in June and July. Conditions during these months often are an important determinant of tree growth at northern latitudes, although the phasing can vary considerably with site, species, and parameter [e.g., *Fritts*, 1976].

[9] Next, we examine the nature of the relationship between NDVI and the tree-ring data for June and July. Four relations are possible: (1) changes in surface greenness induce changes in tree rings; (2) changes in tree rings induce changes in surface greenness: (3) the variables induce changes in each other simultaneously, or (4) some other variable induces changes in both surface greenness and tree rings. We chose among these possibilities using the statistical concept of Granger causality [*Granger*, 1969]. Granger

causality is used to investigate physical systems [*Kaufmann et al.*, 2003] and is based on the notion of predictability. The detection of Granger causality does not necessarily imply a physically causal mechanism between the two variables. Furthermore, the detection of Granger causality depends on the other variables in the equation.

[10] To test for a causal relationship between NDVI and tree rings for months in which these variables are correlated, we estimate the following equations:

$$NDVI_{ijt} = \alpha + \beta_1\ TRI_{it-1} + \beta_2\ NDVI_{ijt-1} + \gamma SZA_{ijt-1} + \varphi AOD_{ijt-1} + \mu_{it} \quad (2)$$

$$TRI_{it} = \alpha + \beta_1 NDVI_{ijt-1} + \beta_2\ TRI_{it-1} + \gamma SZA_{ijt-1} + \varphi AOD_{ijt-1} + \mu_{it} \quad (3)$$

These equations are derived from a vector autoregression in which NDVI and tree rings are endogenous. The technique used to estimate equations (2)–(3) (OLS vs. fixed effects) is chosen using the test statistic described previously. Granger causality is indicated by the statistical significance of $\beta_1$. Rejecting the null hypothesis $\beta_1 = 0$ in equation (2) indicates the tree ring index "Granger causes" NDVI. To determine whether NDVI "Granger causes" tree rings, $\beta_1 = 0$ is tested in equation (3).

[11] We extend the analysis of Granger causality by testing whether equation (2) or (3) (unrestricted model) generates a more accurate out-of-sample forecast than a restricted model, in which the lagged value of TRI (equation (2)) or NDVI (equation (3)) is eliminated by imposing $\beta_1 = 0$ [*Granger and Huang*, 1997]. To compute the out-of-sample forecast, we eliminate one site from the sample and use observations from the remaining sites to estimate the unrestricted and restricted versions of equations (2) and (3). These regression results are used to generate an out-of-sample forecast of NDVI and TRI for the site excluded from the sample. This process is repeated for each site so that we have an out-of-sample forecast for all years for all sites.

[12] We compare the accuracy of the two out-of-sample forecasts with tests for predictive accuracy that use the following loss function:

$$d_t = \left[T_{it} - \hat{T}_{itU}\right]^2 - \left[T_{it} - \hat{T}_{itR}\right]^2 \quad (4)$$

**Table 1.** The Relation Between Tree Rings and NDVI (Equation (1))

|  | TRI ($\beta$) | SZA ($\gamma$) | AOD ($\varphi$) | $F_{(47, 711)}$[a] | $R^2$ |
|---|---|---|---|---|---|
| Grow Sea. | 1.19E-05[b] | 1.06E-03 | −0.197 | 125.7[c] | 0.91 |
| April | −7.26E-06 | 1.42E-04 | 3.52E-02 | 83.4[c] | 0.86 |
| May | −5.39E-06 | −1.31E-03[b] | −1.24E-01[b] | 58.9[c] | 0.84 |
| June | 4.38E-05[c] | −8.65E-04[d] | −1.34E-01[b] | 38.8[c] | 0.75 |
| July | 3.47E-05[c] | −8.28E-04[b] | −1.10E-01[b] | 33.9[c] | 0.68 |
| August | 8.08E-06 | −2.01E-03[c] | −2.18E-01[c] | 39.4[c] | 0.72 |
| September | −4.12E-06 | −1.05E-03[b] | −3.63E-01[c] | 54.0[c] | 0.80 |
| October | −6.04E-06 | −2.17E-03[c] | −1.60E-01[b] | 52.6[c] | 0.85 |

[a]Tests the null hypothesis that the intercepts are the same across the forty-eight sites.
Coefficients are statistically significantly different from zero at the:
[b]5% level.
[c]1% level.
[d]10% level.

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

| | TRI "Granger Causes" NDVI (Equation (2)) | | | | NDVI "Granger causes" TRI (Equation (3)) | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | $\beta_1$ | $S_{2a}$ | $S_{3a}$ | $F(47,662)^a$ | $\beta_1$ | $S_{2a}$ | $S_{3a}$ | $F(47,662)^a$ |
| June | −1.73E-05 | −1.20 | −0.59 | 10.36[c] | −47.16 | 0.60 | 1.00 | 5.49[c] |
| July | −2.76E-06 | 1.50 | 1.56 | 10.82[c] | 215.3 | −0.82 | −1.27 | 5.60[c] |

[a]Tests the null hypothesis that the intercepts are the same across the forty-eight sites.
Coefficients are statistically significantly different from zero at the:
[b]5% level.
[c] 1% level.
[d] 10% 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:

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

$$S_{3a} = \frac{\sum_{t=1}^{N} I_+(d_t)rank(|d_t|) - \frac{N(N+1)}{4}}{\sqrt{\frac{N(N+1)(2N+1)}{24}}} \quad (5)$$

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

$$= 0 \ otherwise$$

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 that 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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R. D. D'Arrigo and N. K. Davi, Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA.

R. K. Kaufmann and R. B. Myneni, Department of Geography, Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA. (kaufmann@bu.edu)

C. Laskowski, Center for Energy and Environmental Studies, Boston University, Boston, MA 02215, USA.

L. Zhou, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332, USA.