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Identifying Climatic Controls on Ring Width: The Timing of Correlations between Tree Rings and NDVI

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ABSTRACT: The authors examine the effects of latitude and life history on the timing of relationships between satellite measures of normalized difference vegetation index (NDVI) and ground-based measures of tree-ring width in forests at mid- and high latitudes in the Northern Hemisphere. Results indicate a correlation between NDVI and tree rings over the entire growing season for all areas analyzed. For sites south of 40°N, a correlation appears in early spring and late fall while a correlation appears during summer months north of 40°N. For conifers, the correlation appears in summer while deciduous trees show the

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relationship during early spring and late fall. Of these two correlations, the effect of life history seems to dominate the effect of latitude. The timing of these correlations may help clarify the relationship between climate and tree rings and the effect of canopy duration on carbon uptake by trees.

KEYWORDS: Tree rings; NDVI; Climate control

1. Introduction

An extensive amount of literature attempts to reconstruct climate using tree rings (e.g., Fritts 1976; Schweingruber 1988; Cook and Kairiukstis 1990; http://web.utk.edu/~grissino/references.htm). These efforts are based in part on studies that identify the month(s) in which temperature and/or precipitation correlates most closely with density or ring width. Studies indicate that the ability to isolate the months and climate variables (e.g., temperature, soil moisture) that control tree rings is limited. Rings are correlated with several monthly values of temperature and precipitation during the year of growth, and in some cases, previous years (e.g., Briffa et al. 2002).

Efforts to identify the timing and type of climate variables that most strongly influence tree rings may be furthered by studying the relationship between tree rings and the normalized difference vegetation index (NDVI), which measures chlorophyll and is correlated with the fraction of photosynthetically active radiation absorbed by plant canopies (Myneni et al. 1995), leaf area index (Myneni et al. 1997a; Myneni et al. 1997b), potential photosynthesis (Nemani et al. 2003), biomass (Myneni et al. 2001), and the physiological status of trees (Kaufmann et al. 2004). Kaufmann et al. (Kaufmann et al. 2004) find that the relationship between tree rings and NDVI varies over the growing season. Tree rings are correlated with NDVI during June and July—there is no correlation in April–May or August–October. The correlation between NDVI and tree rings in June and July suggests that summertime climate, as measured by its effect on NDVI, may be the most important control on ring width.

This preliminary interpretation is limited by the geographic location of sites analyzed and types of trees studied. Kaufmann et al. (Kaufmann et al. 2004) analyze high-latitude sites mainly in Alaska and Asia where conifer trees dominate. Because the start of the growing season is correlated with latitude (Figure 1), the phenological stage that is associated with a relationship between tree rings and NDVI during June and July probably varies among sites. That is, June may be the start of the growing season at high latitudes—at lower latitudes June probably corresponds to later phases. Similarly, extrapolating results found for conifers to deciduous trees is tenuous at best, given the multitude of factors that influence tree growth.

Here, we test the hypotheses that the timing of the relationship between tree rings and NDVI varies over space and between tree types (deciduous versus conifer) and these variations can help identify climatic controls on tree rings. This effort is described in five sections. The next section, section 2, describes how we expand the dataset and alter the statistical methodology to detect variations in the relationship between tree rings and NDVI by latitude and tree type and how these

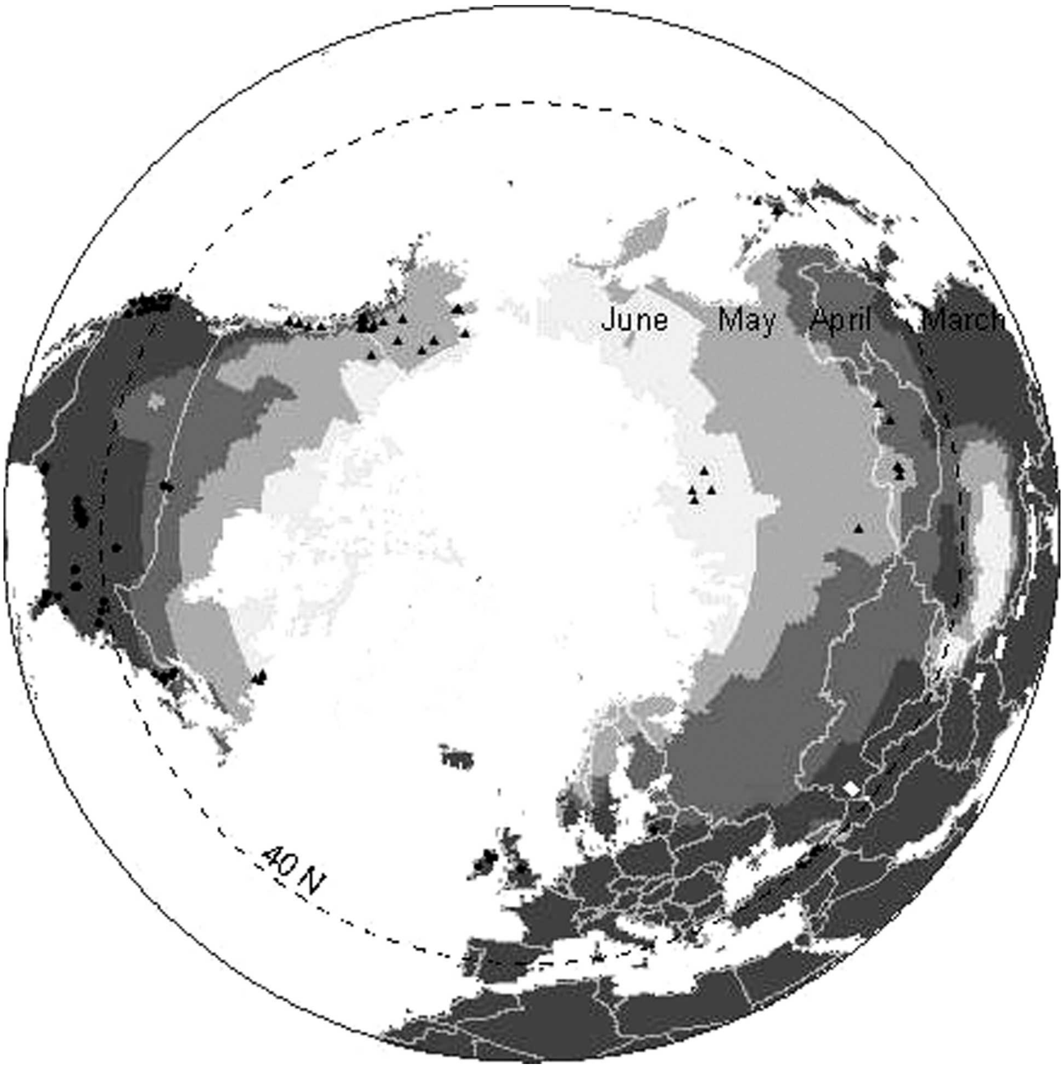

Figure 1. The location of sites analyzed (circles indicate deciduous trees; triangles indicate conifers). Shading identifies the first month in which the average temperature is greater than 0°C.

variations can be used to identify climatic controls. Section 3 describes results that indicate the relationship between tree rings and NDVI varies north and south of 40°N and between conifer and deciduous trees, and that climate controls on these relationships cleave consistently by latitude. Section 4 discusses differences in the persistence of the relationship between tree rings and NDVI relative to the relationship between tree rings and temperature, and whether the timing of climate controls is consistent with the relationship between tree rings and NDVI. Section 5 concludes with a brief outline for additional research that may allow scientists to use the relationship between tree rings and NDVI to refine the use of tree rings to reconstruct climate.

2. Data and methodology

2.1. Data

To evaluate the effect of location and tree type on the relationship between tree rings and NDVI, we add information from 53 sites to the 48 sites analyzed by Kaufmann et al. (Kaufmann et al. 2004). Because the data analyzed by Kaufmann et al. (Kaufmann et al. 2004) include mainly conifer trees located in Alaska and Asia, additional sites are located in the lower 48 states of the United States and western Europe and are dominated by deciduous trees. Together, the new dataset includes 101 sites from large forests at mid- and high latitude (29.17°–72.5°N) in the Northern Hemisphere and includes 52 sites that represent deciduous trees and 49 sites that represent conifer trees (Figure 1). Sites are located at altitudes that vary between 5 and 2321 m above sea level.

Kaufmann et al. (Kaufmann et al. 2004) analyze annual chronologies of dimensionless indices that result from the standardization of raw ring width and density measurements (Cook and Kairiukstis 1990). We recognize that ring width and density parameters often differ in their response to climate, with density data typically responding positively to temperature at northern sites over an extended warm season (e.g., Schweingruber 1988). In general, cores sampled for dendrochronology include at least two per tree, from about 20 or more trees per site. The samples and trees typically cover an area that varies, but generally is one to a few square kilometers. Tree-ring data for the additional 53 sites are obtained from the International Tree-Ring Data Bank (ITRDB; http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering).

Latitude and longitude (to the nearest second) of the tree-ring sites are used to locate the corresponding pixel from the Global Inventory Modelling and Mapping Services (GIMMS) NDVI dataset (Zhou et al. 2001), which has an 8-km resolution (square pixels). 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 2003. We analyze the average for these nine pixels (as opposed to the center pixel only) because the GIMMS NDVI dataset has an accuracy of plus or minus one pixel (Tucker et al. 2005). Furthermore, tree-ring sites are not necessarily in the center of a pixel, and so trees may be located in two or more adjacent pixels. Analyzing only the center pixel changes the results only slightly—contrary to the results reported in below, there is no relationship between NDVI and tree rings at any site during May.

Many tree-ring sites were sampled before 1999; therefore, the number of observations varies among sites. This creates what is known as an unbalanced panel. Regression techniques used to estimate the relationship between tree rings and NDVI from unbalanced panels account for the unequal number of observations across sites with a weighting scheme derived from the variance–covariance matrix that is efficient if we assume that the observations are missing randomly. This assumption seems reasonable because the sites were chosen and visited by an array of analysts, none of whom knew of this experimental design a priori.

2.2. The relationship between tree rings and NDVI

We use this unbalanced panel to validate the relationship between tree rings and NDVI reported by Kaufmann et al. (Kaufmann et al. 2004) by estimating Equation (1):

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

in which NDVI is NDVI at site i for month j in year t; TRI is the standardized tree-ring index; SZA is solar zenith angle; AOD is aerosol optical depth; α, β, γ, and ϕ are regression coefficients; and μ is the regression error. Time series for solar zenith angle also are available from the GIMSS NDVI dataset (Zhou et al. 2001). A monthly time series for aerosol optical depth by latitudinal bands (about 8°) are available from Sato et al. (Sato et al. 1993).

To account for the possible effect of solar zenith angle and aerosol optical depth on satellite measures of NDVI (Gutman 1999; Privette et al. 1995), Equation (1) specifies NDVI as the dependent variable and specifies the tree-ring index, solar zenith angle, and aerosol optical depth as right-hand-side variables. This specification allows γ and ϕ to account for the effects of solar zenith angle and aerosol optical depth on NDVI that might contaminate the relationship between NDVI and tree-ring index, which is given by β. Contaminating effects may not be removed if Equation (1) specifies the tree-ring index on the left-hand side and NDVI on the right-hand side—a contaminating effect of solar zenith angle and/or aerosol optical depth on NDVI would appear as colinearity among the right-hand-side variables. According to standard statistical theory, colinearity inflates the size of the standard errors for the regression coefficients. Such an increase would make it less likely to reject $\beta = 0$, which would obfuscate a relationship between the tree-ring index and NDVI. A nonzero value for β in Equation (1) indicates that the tree-ring index has information about NDVI beyond any effects of solar zenith angle and aerosol optical depth.

Differences in latitude, species, and/or 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 [univariate Augmented Dickey Fuller (ADF) tests developed by Levin et al. (Levin et al. 2002) indicate that the time series for NDVI (-23.75, $p < 0.001$) and TRI (-13.66, $p < 0.001$) are stationary]. If the test statistic exceeds the critical value ($p < 0.05$), we estimate Equation (1) using a fixed or random effects estimator. We chose between these two estimators based on a test developed by Hausman (Hausman 1978). Results of this test indicate that the fixed effects estimator should be used to obtain all of the results described below.

The fixed effects estimator allows the intercept to vary among sites. Following standard statistical procedures, the mean value of the left- and right-hand-side variables for each site is subtracted from that site's annual observations to create a set of transformed variables. These transformed variables, which are anomalies relative to a site's mean value, are used to estimate Equation (2):

$$\widetilde{\mathrm{NDVI}}_{ijt} = \beta \widetilde{\mathrm{TRI}}_{it} + \gamma \widetilde{\mathrm{SZA}}_{ijt} + \phi \widetilde{\mathrm{AOD}}_{ijt} + \mu_{ijt}, \quad (2)$$

in which the tilde indicates the transformed value of a particular variable. Equation (2) does not have an intercept because the mean value for each site's transformed variables is zero, which causes the regression line to pass through the origin.

To validate the relationship between the tree-ring index and NDVI estimated from Equation (2), we also estimate Equation (3):

$$\widetilde{\mathrm{TRI}}_{it} = \beta\widetilde{\mathrm{NDVI}}_{ijt} + \gamma\widetilde{\mathrm{SZA}}_{ijt} + \phi\widetilde{\mathrm{AOD}}_{ijt} + \mu_{ijt}, \tag{3}$$

in which the tree-ring index and NDVI are reversed (i.e., the tree-ring index is the left-hand-side variable). This specification allows us to examine the rate at which the tree-ring index adjusts to changes in NDVI. To do so, we estimate a partial adjustment model as follows:

$$\widetilde{\mathrm{TRI}}_{it} = \beta\widetilde{\mathrm{NDVI}}_{it} + \gamma\widetilde{\mathrm{SZA}}_{it} + \phi\widetilde{\mathrm{AOD}}_{it} + \Psi\widetilde{\mathrm{TRI}}_{it-1} + \mu_{it}, \tag{4}$$

in which NDVI, SZA, and AOD are average values for growing season in year t (April to October) and $(1 - \Psi)$ represents the rate at which the tree-ring index adjusts to NDVI.[1] A value of 1 for $(1 - \Psi)$ would indicate instantaneous adjustment, a value of zero would indicate no adjustment, and a value of 0.5 would indicate that 50% of the change in the tree-ring index that is associated with a change in NDVI appears during that growing season.

To identify the timing of the relationship between the tree-ring index and NDVI, Equations (2) and (3) are each estimated eight times, once with an average value for NDVI (and SZA and AOD) over the growing season, April through October, and once with each of the seven monthly time series (e.g., the tree-ring index and June values of NDVI, SZA, and AOD). The relationship between the tree-ring index and NDVI is evaluated by testing the null hypothesis $\beta = 0$. This null is evaluated with a test statistic (commonly called a t statistic) that is evaluated against a t distribution. Values that exceed a critical threshold ($p < 0.05$) reject the null hypothesis that there is no relationship between tree rings and NDVI.

2.3. Variations in the relationship between tree rings and NDVI

To determine whether the timing of the relationship between tree rings and NDVI varies by latitude and tree type, we estimate Equation (5):

$$\widetilde{\mathrm{NDVI}}_{ijt} = \beta_1\widetilde{\mathrm{TRI}}_{it} + \mathrm{Dum}_1\beta_2\widetilde{\mathrm{TRI}}_{it} + \mathrm{Dum}_2\beta_3\widetilde{\mathrm{TRI}}_{it} + \gamma\widetilde{\mathrm{SZA}}_{ijt} + \phi\widetilde{\mathrm{AOD}}_{ijt} + \mu_{ijt}, \tag{5}$$

in which Dum_1 and Dum_2 are binary variables that have a value of either zero or one depending on the conditional statement used to define it. To test whether the relationship between tree rings and NDVI varies by latitude, Dum_1 is assigned a value of one if a site is north of 40°N and zero if it is south of 40°N (preliminary results indicate that defining Dum_1 by a site's location relative to 40°N generates the clearest conclusions about latitudinal variations in the relationship between the

[1] The partial adjustment model is derived from the following equation (to simplify the discussion, we eliminate SZA and AOD variables and the panel subscripts): $\mathrm{TRI}_t^* = \alpha + \beta\mathrm{NDVI}_t + \mu_t$, in which TRI_t^* is the value for the tree-ring index that would appear after the tree adjusts completely to the value of NDVI at time t. But the tree-ring index does not adjust completely within one period. The rate of adjustment δ is given by the following equation: $\mathrm{TRI}_t - \mathrm{TRI}_{t-1} = \delta(\mathrm{TRI}_t^* - \mathrm{TRI}_{t-1})$. If the value for TRI_t^* is replaced by the right-hand side of the first equation in this footnote, we derive $\mathrm{TRI}_t = \delta\alpha + \delta\beta\mathrm{NDVI}_t + (1-\delta)\mathrm{TRI}_{t-1} + \delta\mu_t$. This model is essentially the same as Equation (4) except that the intercept and coefficient associated with NDVI in Equation (4) are products that include the rate of adjustment.

tree-ring index and NDVI). To test whether the relationship between the tree-ring index and NDVI depends on tree type, Dum_2 is assigned a value of one if the trees at a site are deciduous and a value of zero if they are conifers. It is possible to break the 101 sites into subsamples (e.g., conifer sites north of 40°N, deciduous sites south of 40°N) and estimate Equation (5) for each sample separately. But this procedure reduces the degrees of freedom and so is less reliable than the methodology and interpretation described below.

Estimating Equation (5) from our panel quantifies the relationship between the tree-ring index and NDVI for three types of sites: 1) sites north of 40°N with conifer trees, 2) sites north of 40°N with deciduous trees, and 3) sites south of 40°N with deciduous trees (the sample does not include sites with conifer trees south of 40°N). For each site, the relationship between the tree-ring index and NDVI is given by a combination of β_1, β_2, and/or β_3. For example, if Dum_1 is set to one for sites north of 40°N and Dum_2 is set to one for confer sites, the relationship between the tree-ring index and NDVI for deciduous sites south of 40°N is given by β_1. For conifer sites north of 40°N, the relationship between tree rings and NDVI is given by $\beta_1 + \beta_2 + \beta_3$.

We test the statistical significance of a relationship between the tree-ring index and NDVI by imposing a restriction that makes the sum of β_1, β_2, and/or β_3 zero. Continuing with the previous example, to test whether there is a relationship between the tree-ring index and NDVI for conifer sites north of 40°N, we impose the restriction $\beta_1 + \beta_2 + \beta_3 = 0$. Rejecting this restriction would indicate a relationship between tree rings and NDVI for conifer trees north of 40°N. The sign of this relationship (negative or positive) is given by the sum of β_1, β_2, and/or β. To ensure that the values of zero and one used to define Dum_1 and Dum_2 do not affect the results, we estimate Equation (5) with all possible definitions for the dummy variables (four combinations are possible).

2.4. Climatic controls on the relationship between tree rings and NDVI

Geographic variations of the role of light, temperature, and water as climatic controls may affect the timing of a correlation between tree rings and NDVI. We investigate this possibility by analyzing the relationship between the timing of correlations between tree rings and NDVI [as represented by Equation (5)] and climatic controls on NDVI. Climate controls are represented with the growing season index assembled by Jolly et al. (Jolly et al. 2005). For each month, Jolly et al. (Jolly et al. 2005) calculate an index that indicates the degree to which light (L_{ij}), temperature (T_{ij}), and water supply (VPD_{ij}), as measured by vapor pressure deficit, affect seasonal phenology in month j at site i. The index for each climatic control varies between zero and one—a value of one indicates that a particular factor does not limit the vegetation index [for all 101 sites (L_{ij}) has a value of one for months during the growing season, and so this variable is eliminated from further consideration]. The product of monthly indices for light, temperature, and vapor pressure deficit generates a vegetation index that is closely correlated with NDVI (Jolly et al. 2005).

To identify the climatic control for a given site, we create 14 binary variables ($\sum_{j=4}^{10}\text{Min}T_{ij}$, $\sum_{j=4}^{10}\text{MinVPD}_{ij}$), one for each of the two factors (temperature Min$T$

and vapor pressure deficit MinVPD) and one for each of the seven months in the growing season, April ($j = 4$) through October ($j = 10$). For any given site i, 13 of these binary variables have a value of zero and one has a value of one. The binary variable with a value of one is the factor and month that corresponds to the lowest value of the growing season index during the growing season. To illustrate, suppose that the smallest value of the growing season index for site i is associated with temperature during April. Under these conditions, the value of $\mathrm{Min}T_{i4}$ is one and all other variables have a value of zero. Conversely, MinVPD_{i7} has a value of one if the value for the growing season index associated with July VPD is smallest for site i. As such, the dummy variable with a value of one identifies the most limiting climatic control for site i during the growing season, as indicated by an average of values between 1982 and 1999. This average is chosen to be consistent with the observations for NDVI.

To quantify the effect of local climatic controls on the timing of the relationship between tree rings and NDVI, we estimate Equation (6):

$$\mathrm{Month}_{ij} = \alpha + \lambda \mathrm{Alt}_i + \sum_{j=4}^{10} \theta_i \mathrm{Min}T_{iyj} + \sum_{j=4}^{10} \xi_i \mathrm{MinVPD}_{ij} + \varepsilon_{ij}, \tag{6}$$

in which Month is a binary variable that has a value of one if there is a correlation between the tree-ring index and NDVI at site i during month j (zero otherwise) as determined by the estimate for Equation (5); Alt is the altitude of site i; α, λ, θ_i, and ξ_i are regression coefficients; and ε is the regression error. Equation (6) is estimated 7 times, once for each category of latitude and tree type for which Equation (5) indicates that there is relationship between the tree-ring index and NDVI. For each estimate of Equation (6), we start with the full set of 16 right-hand-side variables. Variables that are not statistically significant are eliminated and Equation (6) is reestimated. This process is repeated until we identify the greatest number of right-hand-side variables for which we can estimate a statistically meaningful relationship.

Month is a binary variable; therefore, Equation (6) is estimated as a logit model. As such, the coefficients quantify the effect of a given variable on the probability that there is a relationship between tree rings and NDVI for that month. For example, a statistically significant positive value of θ_4 for the version of Equation (6) in which the dependent variable is an August relationship between tree rings and NDVI would indicate that sites where April temperatures are limiting are more likely to show a correlation between the tree-ring index and NDVI during August.

3. Results

Regression results generated by Equation (2) indicate that there is a statistically measurable relationship between the tree-ring index and NDVI for the growing season and monthly NDVI values for April–July and October (Table 1). This relationship is indicated by estimates for β that reject the null hypothesis $\beta = 0$ at $p < 0.05$. This result is confirmed by regression results for Equation (3), which indicate that NDVI is correlated with the tree-ring index when tree rings are the left-hand-side variable (Table 1). Together, these results confirm the conclusion that solar zenith angle has relatively little effect on interannual variations in NDVI

Table 1. The relationship between tree rings and NDVI as indicated by regression results for Equations (2)–(4).

	β from Equation (2)	β from Equation (3)	Ψ from Equation (4)
Growing season	9.71E-04[a]	7.61[a]	0.19[a]
April	1.28E-03[a]	4.44[a]	0.22[a]
May	1.04E-03[a]	2.17[a]	0.23[a]
June	1.96E-03[a]	2.72[a]	0.19[a]
July	2.94E-03[a]	5.53[a]	0.19[a]
August	4.37E-04	0.92	0.19[a]
September	−3.54E-04	−1.22	0.19[a]
October	−1.04E-04[a]	−6.37[a]	0.19[a]

Coefficients are statistically significantly different from zero at the [a]1%, [b]5%, and [c]10% level. No observations are significant at only the 5% or 10% level.

(Kaufmann et al. 2000) and that satellite measures of NDVI can be used to measure interannual changes in terrestrial vegetation (Kaufmann et al. 2004)

As expected, most correlations between ring width and NDVI are positive—October is a sole exception. An autumnal reduction in net primary production may account for a negative relationship between tree rings and NDVI for deciduous sites south of 40°N. Positive October NDVI anomalies indicate a later than average leaf shed. Retaining leaves increases autotrophic respiration. Higher rates of autotrophic respiration may reduce net carbon uptake during October because other factors may not support a concomitant increase in photosynthesis. The reduction in net carbon uptake may reduce ring width.

Regression results for Equation (5) indicate that Equation (1) hides important variations in the relationship between the tree-ring index and NDVI (Table 2). Regression coefficients for Dum_1 and Dum_2 indicate that the relationship between tree rings and NDVI varies by latitude and/or between deciduous and conifer trees. For deciduous trees, the timing of the relationship between the tree-ring index and NDVI varies by latitude. There is a relationship between the tree-ring index and NDVI for deciduous trees south of 40°N during April, May, October and the growing season. Conversely, there is a relationship between the tree-ring index and NDVI for deciduous trees north of 40°N during August.

Deciduous and conifer trees show little overlap in the timing of the correlation between the tree-ring index and NDVI. For deciduous trees, there is a correlation between the tree-ring index and NDVI in April, May, August, and October—conifer trees show a relationship between tree rings and NDVI during May, June, and July. These results are not sensitive to the values of zero and one that are used to define Dum_1 and Dum_2.

Month-to-month changes in the relationship between tree rings and NDVI do not imply that tree rings adjust immediately to changes in NDVI. Regression results for the partial adjustment model [Equation (4)] indicate that the tree-ring index adjusts fairly quickly to changes in NDVI. Values for the regression coefficient (Ψ) in Equation (4) vary between 0.17 and 0.22 (Table 1), which implies that the value of δ varies between 0.78 and 0.82 and indicates that about 80% of the difference between the previous year's ring index and the value that is associated with this year's growing season NDVI is reflected in the current year's value of the tree-ring index. The lack of complete adjustment suggests that another

Table 2. The relationship between NDVI and tree rings as indicated by the four specifications for Dum_1 and Dum_2 in Equation (5). The symbol + indicates a positive correlation between tree rings and NDVI (p < 0.05); − indicates a negative correlation between tree rings and NDVI (p < 0.05). Upper left: Dum_1 = 1 for sites north of 40°N and Dum_2 = 1 for conifer trees. Upper right: Dum_1 = 1 for sites north of 40°N and Dum_2 = 1 for deciduous trees. Lower left: Dum_1 = 1 for sites south of 40°N and Dum_2 = 1 for deciduous trees. Lower right: Dum_1 = 1 for sites south of 40°N and Dum_2 = 1 for conifer trees.

	Deciduous trees south of 40°		Deciduous trees north of 40°		Conifers north of 40°	
Growing season	+	+				
	+	+				
April	+	+				
	+	+				
May	+	+			−	−
	+	+			−	−
June					+	+
					+	+
July					+	+
					+	+
August			+	+		
			+	+		
September						
October	−	−				
	−	−				

20% of the interannual variation in NDVI remains to be represented in future values of the tree-ring index. This is consistent with studies that indicate tree rings are correlated with climate variables from previous growing seasons (e.g., Briffa et al. 2002; D'Arrigo et al. 2004).

Regression results for Equation (6) indicate that differences in the relationship between NDVI and tree rings are associated with three limiting conditions: April temperature, the vapor pressure deficit in July, and the vapor pressure deficit in August (Table 3). The importance of these climate controls cleaves consistently by latitude. For the sites south of 40°N with deciduous trees analyzed here, climatic controls associated with vapor pressure deficit during July and August help explain the timing of the correlation between the tree-ring index and NDVI. For sites north

Table 3. Climatic controls on the relationship between tree rings and NDVI (Equation (6)).

Month (j)	Tree type	Latitude	$T\min_4$	MinVPD_7	MinVPD_8	Pseudo-R^2	$T\min_j$	MinVPD_j
April	Deciduous	South of 40°N		3.15[a]	2.52[a]	0.39	−1.41	−33.82
May	Deciduous	South of 40°N		3.15[a]	2.52[a]	0.39	35.74	−1.17
May	Conifer	North of 40°N	10.98[a]			0.87	−35.40	2.07[b]
June	Conifer	North of 40°N	10.98[a]			0.87	−34.31	0.66
July	Conifer	North of 40°N	10.98[a]			0.87	−32.20	2.47[a]
August	Deciduous	North of 40°N	1.95[a]			0.29	−33.82	0.24
October	Deciduous	South of 40°N		3.15[a]	2.52[a]	0.39	3.28[a]	−1.09

Coefficients are statistically significantly different from zero at the [a]1%, [b]5%, and [c]10% level. No observations are significant at only the 10% level.

of 40°N with either tree type, climatic controls associated with April temperatures help explain the timing of the correlation between the tree-ring index and NDVI.

4. Discussion

4.1. Tree rings: Correlations with NDVI versus correlations with temperature

To evaluate whether the relationship between tree rings and NDVI can be used to refine the relationship tree rings and climate, we compare the persistence of correlations between the tree-ring index and monthly values of NDVI with correlations between the tree-ring index and monthly values of temperature. [To evaluate the relationship between tree rings and temperature, we obtain monthly temperature data for the 101 tree-ring sites for the same period of the tree-ring and NDVI analysis, 1982–2000. Reanalysis data are provided by the National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/ Earth System Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD), Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/.] Unlike the results indicated in Table 2, correlations between tree rings and temperature are highly persistent. For example, there is a relationship between tree rings and temperature for April, May, June, July, and October for sites with conifer trees north of 40°N [this result is generated by estimating Equation (5) in which monthly temperature anomalies replace monthly NDVI anomalies].

The transient nature of the correlation between the tree-ring index and NDVI relative to the persistent correlations between the tree-ring index and temperature may be caused by a rapid decay in positive or negative anomalies for NDVI relative to a slower decay for temperature anomalies (Table 4). Regression coefficients for consecutive monthly observations of NDVI vary between 0.16 and 0.53, but drop well below 0.1 for months separated by one or more months. For example, NDVI anomalies during April and May have little or no relationship to

Table 4. Autocorrelation of NDVI and temperature anomalies. Top number is the value of β in the regression $\mathrm{NDVI}_t = \beta \mathrm{NDVI}_{t-i} + \mu_t$; bottom number is the value of β in the regression $\mathrm{Temperature}_t = \beta \mathrm{Temperature}_{t-i} + \mu_t$.

Independent variable	Dependent variable					
	May	June	July	August	September	October
April	0.521[a]	0.062[c]	−0.059[c]	−0.013	0.029	0.028
	0.261[a]	0.093[a]	0.035[b]	0.082[a]	0.052[a]	0.054[b]
May		0.496[a]	−0.005	−0.039[c]	−0.037[c]	0.007
		0.251[a]	0.161[a]	0.118[a]	0.190[a]	0.109
June			0.264[a]	−0.052[a]	−0.062[a]	−0.001
			0.320[a]	0.195[a]	0.283[a]	0.022
July				0.161[a]	0.087	0.011
				0.403[a]	0.311[a]	0.074
August					0.267[a]	0.077[a]
					0.340[a]	0.031
September						0.300[a]
						0.165[a]

Coefficients are statistically significantly different from zero at the [a]1%, [b]5%, and [c]10% level.

NDVI anomalies during July or August, which have little or no relationship to NDVI anomalies for September and October. Regression coefficients for consecutive monthly temperature anomalies vary between 0.26 and 0.40, which is slightly smaller than those for the NDVI anomalies (Table 4). But correlation coefficients for months separated by one or more months generally are greater than 0.1 (and are statistically different from zero) compared to the corresponding correlation coefficients for NDVI anomalies, which are not measurably different from zero. In other words, temperature anomalies in a given month have more information about temperature anomalies in other months of the same growing season than NDVI anomalies in a given month have about NDVI anomalies in other months of the same growing season. Under these conditions, the timing of correlations between tree rings and NDVI may identify more precisely months in which climatic variables have the greatest effect on ring width.

4.2. Climatic controls on the relationship between tree rings and NDVI

To test whether the timing of the relationship between tree rings and NDVI can be used to identify more precisely the months in which climate has the greatest effect on ring width, Equation (6) examines the relationship between climatic controls and the timing of correlations between ring width and NDVI. Results in Table 3 indicate that the correlation between the tree-ring index and NDVI is correlated with climatic controls. That these climate controls are associated with latitude, rather than tree type, may not be surprising—trees north of 40°N face similar climatic conditions, regardless of whether they are conifer or deciduous trees.

More surprising is the mismatch between month(s) during which there is a correlation between the tree-ring index and NDVI and the month in which climate conditions are most limiting. The correlation between the tree-ring index and NDVI for deciduous trees south of 40°N occurs in April, May, and October (Table 2), but these spring and fall correlations are more likely at sites where vapor pressure deficits in July and August limit growth (Table 3). Conversely, trees north of 40°N show a relationship between tree rings and NDVI from May to August (Table 2), but these summertime correlations are more likely at sites where April temperatures limit growth (Table 3). This mismatch is not associated with the procedure that is used to reduce the number of independent variables in Equation (6). If we specify Equation (6) with the binary variables for temperature and vapor pressure deficit for the month that corresponds to the month of the correlation between the tree-ring index and NDVI, there is no instance in which any of the binary variables for climatic controls are a statistically significant predictor of the correlation between the tree-ring index and NDVI for that month.

This mismatch between the timing of climate controls and the timing of the correlation between tree rings and NDVI may be caused by differences in the effect of temperature and moisture. To investigate this possibility, we identify two limiting factors—the month in which the temperature index is most limiting and the month in which the vapor pressure deficit index is most limiting. Following this procedure, 2 of the 14 binary variables ($\sum_{i=4}^{10}\mathrm{Min}T_{ij}$, $\sum_{i=4}^{10}\mathrm{MinVPD}_{ij}$) have a nonzero value. This set of variables is used to reestimate Equation (6).

For three of seven cases in which there is a correlation between tree rings and NDVI, this new set of variables identifies a contemporaneous relationship between the timing of this correlation and one of the limiting factors. Sites where October temperatures are the most limiting temperature have an increased likelihood of an October relationship between tree rings and NDVI for deciduous trees south of 40°N. Sites where vapor pressure deficit in July is the most limiting moisture level have an increased likelihood of a July correlation between tree rings and NDVI for conifer trees north of 40°N. Finally, sites where vapor pressure deficit in May is the most limiting moisture level have an increased likelihood of a May correlation between tree rings and NDVI for conifer trees north of 40°N. These results suggest the possibility that the timing of the correlation between tree rings and NDVI identifies months in which climate controls have the greatest effect on ring width.

5. Conclusions

Results obtained here suggest that climate controls on vegetation may affect the timing of the correlations between tree rings and NDVI. If borne out by additional research, such understanding could help refine efforts to reconstruct climate using tree rings. Specifically, scientists may be able to interpret tree rings as representing temperature or water conditions during specific months of the growing season. By choosing sites that are constrained by a range of narrowly defined climate controls, analysts may be able refine the resolution of their climatic reconstructions.

To explore this possibility, future efforts will use monthly climate observations of temperature and vapor pressure deficit to calculate values for the growing season index that vary by year. The ability of these values to account for ring width and the timing of the correlations between tree rings and NDVI will be compared to the explanatory power of the monthly measurements. Hopefully, these comparisons will help determine whether correlations between tree rings and NDVI can be used to identify the month(s) and climate conditions that are the largest determinants of ring width.

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