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Correlation between maximum latewood density of annual tree rings and NDVI based estimates of forest productivity

R. D. D'ARRIGO[1], C. M. MALMSTROM[2], G. C. JACOBY[1], S. O. LOS[3] and D. E. BUNKER[1]

[1]Tree Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA; e-mail: druidrd@ldeo.columbia.edu
[2]Department of Botany and Plant Pathology, Michigan State University, East Lansing, MI 48824, USA; e-mail: carolyn@bsrsi.msu.edu
[3]Science Systems and Applications Inc. code 923, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA; e-mail: sietse@scirocco.gsfc.nasa.gov

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Abstract. In boreal conifers, maximum latewood density (MXD) of annual rings varies in response to warm-season temperatures. Vegetation productivity can be estimated using the Normalized-Difference Vegetation Index (NDVI) calculated from satellite sensor data. Ground measurements related to productivity are required in order to evaluate these estimates. MXD from three boreal sites was compared with estimates of net primary productivity (NPP) for 1982–1990 produced by the CASA (Carnegie-Ames-Stanford-Approach) model from FASIR (Fourier adjustments, solar zenith angle correction, interpolation at high latitudes, and reconstruction of tropical values) NDVI. All three density series correlated significantly with the CASA estimates, suggesting that in boreal conifers MXD may be an appropriate index for productivity or canopy growth in regions where productivity is strongly temperature-related.

1. Introduction

The world's boreal forests have been the subject of recent questions about unusual or changing forest growth patterns in the past few decades, as observed both in tree-ring (Jacoby and D'Arrigo 1995, Briffa *et al.* 1998) and satellite sensor (Myneni *et al.* 1997) data. Intercomparison of these two data types may help deepen our understanding of the response of the boreal forest to recent warming trends.

Tree-ring data provide valuable information about how tree growth responds to climatic and environmental change, in boreal forests and elsewhere (Jacoby and D'Arrigo 1989, Lara and Villalba 1993). Time series of one type of tree-ring measurement, annual ring width, have been used to investigate relationships between NDVI and forest growth patterns (Hunt *et al.* 1991, Malmstrom *et al.* 1997). In boreal conifers, annual ring widths often reflect conditions from previous non-growing-season periods (months or even years) as well as from the current season (Fritts 1976, Jacoby and D'Arrigo 1989, 1995). A second measurement type, annual maximum latewood density (MXD), provides somewhat different information. MXD is the greatest density of latewood measured in an annual ring. Latewood, as the name implies, is formed in the later part of a growing season and is comprised of

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thickly-walled, flatter cells with smaller lumen. Boreal conifer MXD usually correlates positively with monthly temperatures from May through September, making MXD a good proxy for warm season temperature (Fritts 1976, Jacoby *et al.* 1988, Schweingruber 1988, Briffa *et al.* 1992, D'Arrigo *et al.* 1992).

It is relatively straightforward to evaluate interannual variation in NDVI at desert calibration sites or to compare NDVI-based estimates of net primary productivity (NPP) against production data from selected agricultural regions (Justice *et al.* 1985, Malingreau 1986, Los 1997, Malmstrom *et al.* 1997). The task is more difficult in forested and taiga regions, where large-area, multi-year measurements of canopy growth patterns are sparse. One promising source of information is from tree-ring time series (Hunt *et al.* 1991). However, comparisons of NDVI with tree-ring data originally collected for dendroclimatology can be hampered if the tree-ring series are not spatially representative of a large area.

Malmstrom *et al.* (1997) evaluated NDVI-based estimates of net primary production (NPP) produced by the CASA (Carnegie-Ames-Stanford-Approach) model. They suggested that tree-ring data for NDVI comparison should be collected from multiple dominant species and from different age classes of trees over a large region. Information about species areal extent can be useful for extrapolation to the grid-cell scale. Using this approach, Malmstrom *et al.* (1997) found significant correlation ($r = 0.86$) between detrended NDVI-based NPP estimates and area-weighted ring-width indices derived from paper birch and white spruce data collected at Fort Richardson, Alaska (table 1). They showed that paper birch and white spruce may have markedly different responses to climate variability.

It would be of considerable interest to expand the study of tree rings and NDVI within the boreal forest. Ultimately, a sampling program designed to measure forest responses over large areas is needed. In the short-term, we can examine the utility of comparing NDVI with existing tree-ring data developed for standard dendroclimatology.

In this Letter, we compared MXD series from conifers at three boreal sites with NPP estimates produced by the CASA model from FASIR NDVI, a monthly maximum-value composite derived from the 5–8 km GIMMS (Global Inventory Monitoring and Modeling Studies) product, with Fourier adjustments, solar zenith angle correction, interpolation at high latitudes, and reconstruction of tropical values (FASIR). The CASA model and variations have been previously described (Los *et al.* 1994, Sellers *et al.* 1996, Los 1997, Malmstrom *et al.* 1997).

2. Methods

2.1. *Tree-ring data*

Maximum latewood density (MXD) series were derived from white spruce (*Picea glauca*, an evergreen) at two Alaskan sites: at Silvertip in the Wrangell-St. Elias Mountains, and near Fairbanks in Central Alaska and from larch (*Larix gmelinii*, a deciduous conifer) at a northern treeline site on the Taymir Peninsula, Siberia (table 1). X-ray densitometry was used to measure the density values. Standard techniques were used in chronology development (Fritts 1976, Cook and Kairiukstis 1990). MXD series were developed from ten or more trees at each sampling location.

2.2. *NDVI-based estimates of NPP*

The Normalized Difference Vegetation Index (NDVI), derived from red and infrared relative radiance data, is a useful tool for assessing extent and condition of vegetation

Table 1. Correlation between tree-ring data and CASA model NPP estimates.

Tree-ring series	Percentage cover (%)	Ring width	Maximum latewood density
Taymir, Siberia:	~ 10		
72 30°N, 105 09°E			
Standard run			0.79*
Variable run			0.79*
Silvertip, Alaska, USA:	~ 46		
62 33°N, 142 20°W			
Standard run			0.65†
Variable run			0.76*
Twelve-Mile Summit, Alaska, USA:	~ 28		
65 24°N, 145 57°W			
Standard run			0.59†
			− 0.16[a]
Variable run			0.74*
			− 0.19[a]
Fort Richardson, AK, USA[b]	~ 63		
61 18°N, 149 43°W			
Spruce		0.16[c]	
Birch		0.80[c]**	
Weighted (1:1.2) spruce birch average		0.83[c]**	

Statistical significance: $^{**}P \leqslant 0.01$; $^{*}P \leqslant 0.05$; $^{\dagger}P \leqslant 0.10$.

[a]Detrended density versus detrended CASA estimates. [b]From Malmström *et al.* 1997, values for variable FASIR run. [c]Compared with detrended CASA estimates ($+4.7\%\ \mathrm{yr}^{-1}$ trend removed).

(Kumar and Monteith 1982, Sellers *et al.* 1996). It is calculated as (NIR − R)/(NIR + R), where NIR is relative radiance in near infrared wavelengths and R is relative radiance in red wavelengths. Satellite-sensor-borne instruments, such as the Advanced Very High Resolution Radiometer (AVHRR), yield global-scale NDVI time series for estimating interannual changes in vegetation activity (Justice *et al.* 1985, Malingreau 1986, Goward *et al.* 1994, Myneni *et al.* 1997). However, changes in instrumentation and other factors introduce extraneous variability (Holben 1986, Los *et al.* 1994, Fung 1997, Malmstrom *et al.* 1997). Models, as noted above, must be used to make estimates which then should be compared with independent ground-based data.

Estimates of annual net primary production for 1982–1990 were produced by the CASA model (Potter *et al.* 1993, Field *et al.* 1995, Malmstrom *et al.* 1997) driven by FASIR NDVI (Sellers *et al.* 1996, Los 1997). In the Standard FASIR run, CASA was driven by variable meteorological data and variable NDVI. In the Variable FASIR run, the climate data were replaced with nine-year means.

2.3. *Comparisons*

To evaluate how well the tree-ring data might represent the 1° × 1° NDVI grid cells, the area covered by different vegetation types within each grid cell from which tree-ring data had been collected was quantified (table 1). For Siberia, GIS and vegetation maps were employed. For Alaska, we used the final version of a 1 km^2 Alaskan statewide vegetation map based on Landsat Thematic Mapper (TM) data (Fleming, USGS/EROS, Anchorage, AK, personal communication).

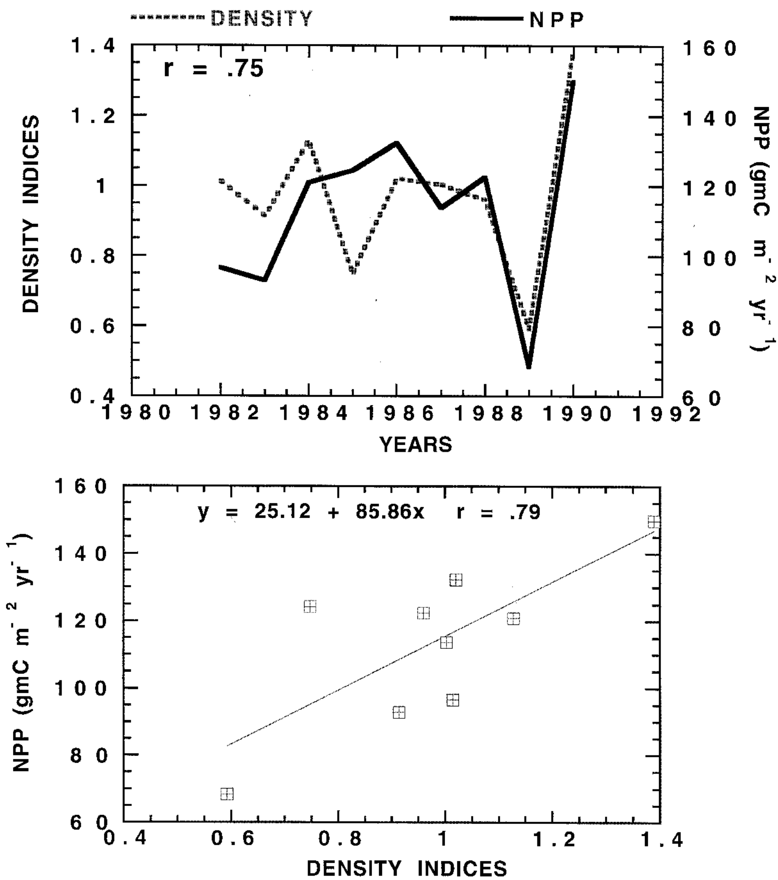

Figure 1. Density and NPP estimates from CASA model with standard FASIR NDVI for Taymir, Siberia. Top graph, line plot and bottom graph, scatterplot.

NDVI-based assessments suggest that large production increases may have occurred in some regions during the 1980s (Malmstrom *et al.* 1997, Myneni *et al.* 1997). An unresolved question is to what degree the trends seen in the NDVI represent real production increases and to what degree they represent artifacts or other factors in the data. Along with NDVI, tree-ring data must also be considered with care, in part because growth measured at an individual site may not represent growth patterns of an entire region. The tree-ring data were detrended by standard methods (Cook and Kairiukstis 1990), but some trend remained in the density data for central Alaska; both detrended as well as original estimates and data were compared for this site. Parallel trends support the idea of both time series being valid and should not be totally ignored.

3. Results

Taymir Peninsula, Siberia: The maximum latewood density data (MXD) from deciduous larch agrees well with NPP estimates from both CASA runs. Note the extreme low value in 1989 (figure 1 and table 1), captured by the tree-ring values and the CASA model estimates and attributable to below-average summer temperatures.

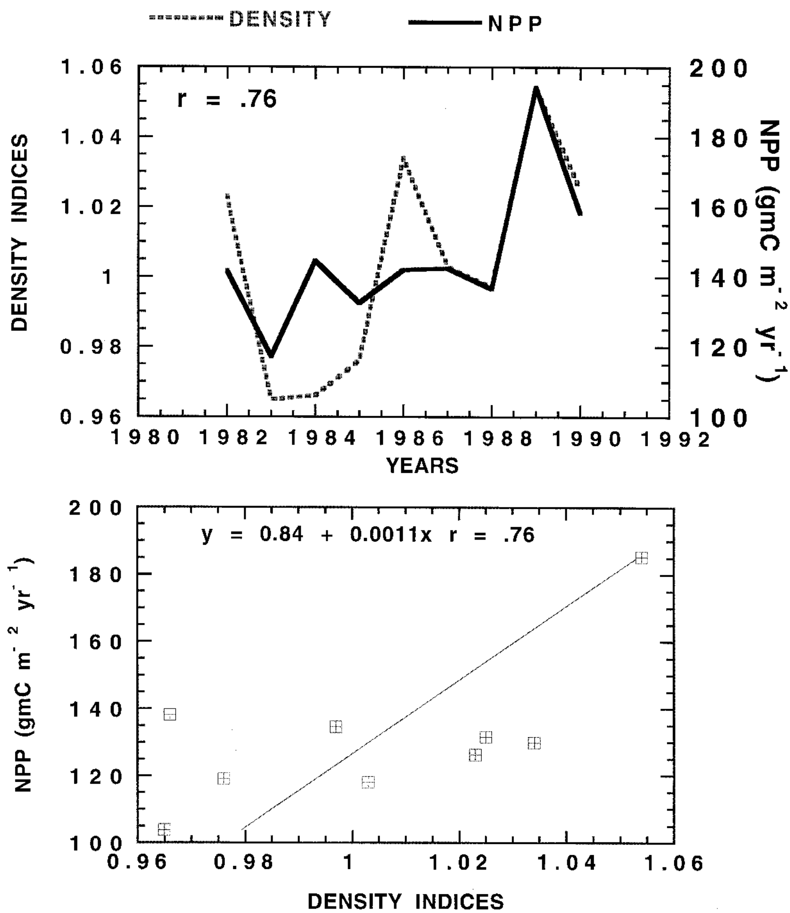

Figure 2. Density and NPP estimates produced by CASA model with variable FASIR NDVI for Silvertip, Alaska. As in figure 1.

Silvertip, Alaska: At this site there was a weak +3.4% per year trend (*P* 0.072) in the FASIR-based estimates, but detrending did not dramatically effect the correlations. Since the trend is weak, correlations were presented with un-detrended FASIR-based estimates (figure 2 and table 1). As at Taymir, white spruce density is correlated with both CASA estimates.

Central Alaska-Fairbanks: There was a +5.4% to +5.5% per year trend (*P* 0.001, *P* 0.01) in the FASIR-based estimates and a residual trend of +1.5% per year (*P* 0.011) in the density data, both of which may reflect increasing temperatures (figure 3 and table 1). The growing seasons for 1988–1990 were particularly warm. Correlations between the white spruce density series with the residual trend and the original FASIR-based estimates were high, although when the trends were removed from both, there was no significant correlation.

4. Discussion and conclusions

Our results show significant positive correlations between maximum latewood density data and NDVI-based NPP estimates, at sites where temperature is the primary factor limiting growth. Malmstrom *et al.* (1997) had previously shown the

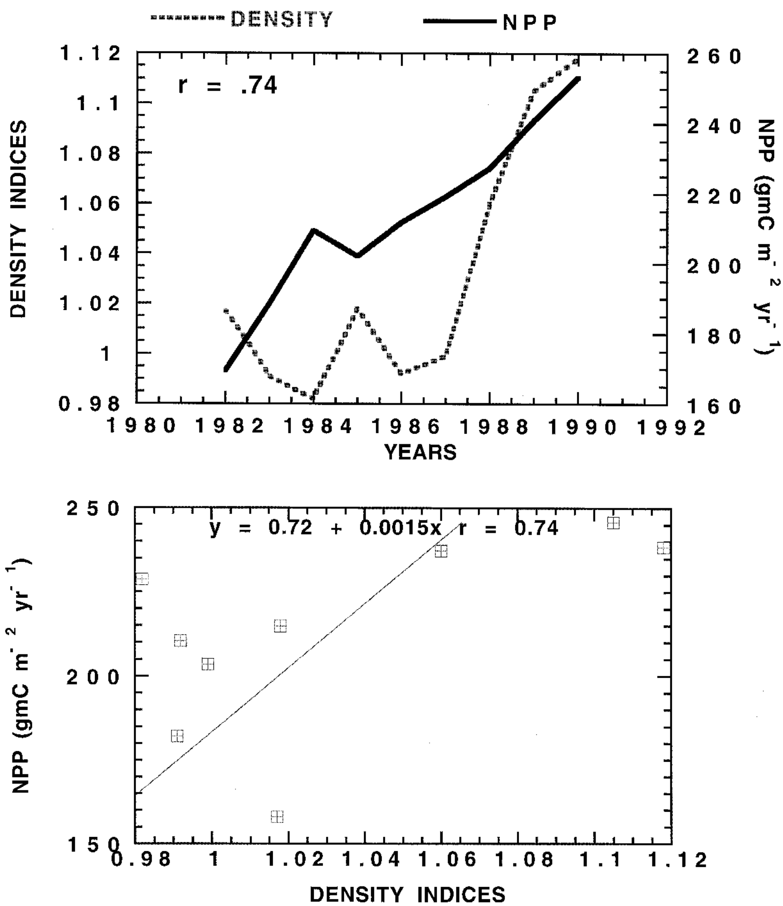

Figure 3. Density and NPP estimates produced by CASA model with variable FASIR NDVI for Fairbanks, Alaska. As in figure 1.

potential of using the tree-ring width parameter for comparison with NDVI-based NPP estimates, using a birch/spruce mix that represented a relatively large fraction of grid cell area (table 1). The correlations we found with MXD occurred even at sites where the species sampled represented a relatively small fraction of the regional vegetation.

These results suggest that, in the absence of multi-species or spatially extensive data, a tree-ring parameter from a single tree species may be an approximate index to regional production if both the tree-ring parameter and regional production are limited by the same environmental factor. Thus, MXD in boreal conifers may be an approximate index for production or canopy growth in regions where production is strongly temperature-limited. At Taymir, for example, location of the northernmost limit of trees on earth (72° 30′N), all vegetation growth is likely to be quite responsive to temperature. As a result, even though larch covers only 10% of the grid cell area, the larch MXD series may be well synchronized with growth patterns of other species in the region. This hypothesis should be tested by studies in other regions with a single dominant limiting vegetation growth factor, e.g. semi-arid lower forest borders. In regions where limiting factors may differ among species, the relationship between

MXD and NDVI-based estimates could be explained several ways. At the Central Fairbanks site, for example, the correlation could arise if spruce MXD (reflecting summer temperature) parallels growth variation in a codominant species, such as paper birch, with a strong contribution to canopy variability.

This study demonstrates both the potential value and some limitations of using tree-ring data to evaluate NDVI. To do so, we must have confidence that the data adequately capture large-area growth responses (e.g. tree-ring width data in Malmstrom *et al.* 1997) or that the series is a valid proxy for the regional limiting factor to growth (herein). Sampling strategies need to evaluate a range of tree-ring parameters, including MXD, and to consider the mix of species types, age classes, regional limiting factors, and landscape heterogeneity.

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