GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L12704, doi:10.1029/2008GL033894, 2008

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Southwestern U.S. tree-ring carbon isotope indices as a possible proxy for reconstruction of greenness of vegetation

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Received 6 March 2008; accepted 14 May 2008; published 21 June 2008.

[1] Southwestern U.S. pinyon tree-ring carbon-isotope indices showed promise two decades ago as an indicator of moisture and drought. However, because those isotopic indices were developed on 5-year ring groups rather than annual rings, the full extent of their effectiveness as environmental proxies was not established. Recent re-sampling of the sites and subsequent availability of annual isotopic indices for 1985 through 1999 has allowed us to more definitively characterize environmental relationships across 14 sites in six southwestern states. Principal component (PC) analysis reveals a significant positive relationship ($p \leq 0.02$) between isotope indices and summer-season Normalized Difference Vegetation Index (NDVI), a satellite-derived "greenness index". Correlation and PC analysis also show a negative relationship of isotope indices with cumulative monthly precipitation ($p \leq 0.05$) and confirm a strong positive relationship with Palmer Drought Index (especially spring and summer, $p \leq 0.0002$). Although the drought and NDVI relationships are not as simply interconnected as hypothesized, the NDVI link reveals the potential of the existing multi-century record of isotope indices for long-term assessment of southwestern ecology and carbon cycling. **Citation:** Leavitt, S. W., T. N. Chase, B. Rajagopalan, E. Lee, and P. J. Lawrence (2008), Southwestern U.S. tree-ring carbon isotope indices as a possible proxy for reconstruction of greenness of vegetation, *Geophys. Res. Lett.*, *35*, L12704, doi:10.1029/2008GL033894.

1. Introduction

[2] Tree-ring width analysis has exceptional established merit as a tool for reconstructing climate, including drought [e.g., *Cook et al.*, 1999, 2004; *Meko et al.*, 2007]. Additionally, tree-ring stable-carbon isotope composition ($\delta^{13}C = [{}^{13}C/{}^{12}C_{sample} \div {}^{13}C/{}^{12}C_{PDB\ standard} - 1] \times 1000$) has utility for representing leaf-level environmental moisture conditions, as evidenced by significant correlations with precipitation [e.g., *Saurer et al.*, 1995; *Gagen et al.*, 2004], soil moisture [e.g., *Dupouey et al.*, 1993], drought indices [e.g., *Leavitt*, 1993; *Leavitt et al.*, 2002], relative humidity [e.g., *Saurer and Siegenthaler*, 1989; *Hemming et al.*, 1998], and vapor pressure deficit [*Hemming*, 1998]. According to plant carbon isotope fractionation theory [*Farquhar et al.*, 1982], $\delta^{13}C$ of plants can be influenced by several variables including temperature, moisture and light, all of which can affect the ratio of intercellular to atmospheric CO_2 concentrations (C_i/C_a):

$$\delta^{13}C_{plant} = \delta^{13}C_{air} - a - (b - a) \times C_i/C_a \quad (1)$$

In this model, $\delta^{13}C_{air}$ is the $\delta^{13}C$ of atmospheric CO_2, a is fractionation during CO_2 diffusion through stomata (~4.4‰); b is fractionation by Rubisco (~27‰ including effects of PEP-C). Under low moisture conditions, leaf pores tend to close to conserve water (reducing stomatal conductance), continuing leaf photosynthesis therefore discriminates less against ${}^{13}C$ because of the restricted size of the intercellular CO_2 pool, so the resulting photosynthate (and tree ring) has elevated $\delta^{13}C$ values (higher ${}^{13}C/{}^{12}C$ ratios) [*Francey and Farquhar*, 1982]. In arid and semi-arid regions, such as the U.S. Southwest, the effect of moisture should dominate over temperature and sunlight parameters [*Warren et al.*, 2001], and furthermore in such environments, "drought" itself can be driven by a combination of precipitation and temperature. Under these circumstances, the carbon isotopes are thus a direct leaf-level indicator of moisture status.

[3] Tree-ring $\delta^{13}C$ time series were developed in a 14-site network of pinyon pine (Table 1) in six southwestern states [*Leavitt and Long*, 1988]. These were initially based on 5-year ring groups ending in 1980–84, but re-sampling of the network has brought it up to 1999 [*Leavitt et al.*, 2007]. The initial analysis with the pentad $\delta^{13}C$ values produced good evidence for moisture/drought being a major influence, such that mapping of isotope composition could be used to infer past spatial drought patterns [*Leavitt and Long*, 1989a]. We exploit the recent availability of isotope analyses for each year from 1985–1999 in the network to examine in detail their interannual relationship with environment indicators, which could not be done with the original set of pentad Indices. We hypothesized that given the tight linkage of water to growth in the Southwest, not only might we better resolve drought (and precipitation) influence on $\delta^{13}C$, but the $\delta^{13}C$ could capture NDVI (Normalized Difference Vegetation Index), a measure of plant "greenness" (productivity), which should be driven in major part by moisture.

2. Data and Methodology

[4] The original $\delta^{13}C$ time series from the 14 sites (map in Figure 1) collected in the mid-1980s [*Leavitt and Long*, 1988, 1989b] were developed on the holocellulose compo-

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Table 1. Site Information for the Pinyon Tree-Ring Isotope Network

Site	Elevation (m)	Latitude	Longitude	Landcover[a]	Species
Kane Springs, UT	1965	37.52429N	−109.89557W	open shrublands	P. edulis
Alton, UT	2245	37.44418N	−112.49445W	open shrublands	P. edulis
Dry Canyon, CO	2150	37.58333N	−108.55155W	grasslands	P. edulis
Lower Colonias, NM	2375	35.55558N	−105.55388W	closed shrublands	P. edulis
Aztec, NM	2080	36.99832N	−107.81605W	open shrublands	P. edulis
Cerro Colorado, NM	2500	35.28096N	−107.72012W	open shrublands	P. edulis
Ozena, CA	1370	34.72461N	−119.23648W	evergreen needleleaf forest	P. monophylla
Hawthorne, NV	2330	38.43201N	−118.74830W	open shrublands	P. monophylla
Mimbres, NM	2025	32.99723N	−107.93031W	closed shrublands	P. edulis
Owl Canyon, CO	1860	40.78765N	−105.17778W	evergreen needleleaf forest	P. edulis
NC AZ, AZ	1470	34.82793N	−111.98200W	open shrublands	P. edulis
NE AZ, AZ	2090	34.08128N	−109.34610W	evergreen needleleaf forest	P. edulis
Gate Canyon, UT	2220	39.87712N	−110.23055W	grasslands	P. edulis
Lamoille, NV	2130	40.69124N	−115.46634W	grasslands	P. monophylla

[a]Landcover vegetation categories based on satellite remotely sensed ground cover in 2001 from the 0.05° × 0.05° cell corresponding to each site [after *Lawrence and Chase*, 2007].

nent from tree-ring pentads rather than each ring because of the effort and expense of isotopic analysis at that time. The network contained sites inhabited by either of two pinyon species, *Pinus monophylla* and *Pinus edulis*, at elevations ranging from 1370 to 2500 m (Table 1). The relationships with moisture/drought were established after deriving indices by first smoothing the δ^{13}C series with spline curves to remove low-frequency trends and then calculating in two steps [*Leavitt and Long*, 1989a]:

$$\text{Isotopic Index} = \delta^{13}\text{C}_{\text{measured}}/\delta^{13}\text{C}_{\text{spline}} \tag{2}$$

$$\text{Del Index} = (\text{Isotopic Index} - 1) \times 1000 \tag{3}$$

The Del Indices so computed ranged from −60 to +60 where negative values should indicate moisture 'deficiency' (associated with reduced stomatal density) and positive values moisture 'excess'. The calculation has since been modified [*Leavitt et al.*, 2007] according to the following algorithm:

$$\text{Drought Index} = \text{Del Index} \div 10, \tag{4}$$

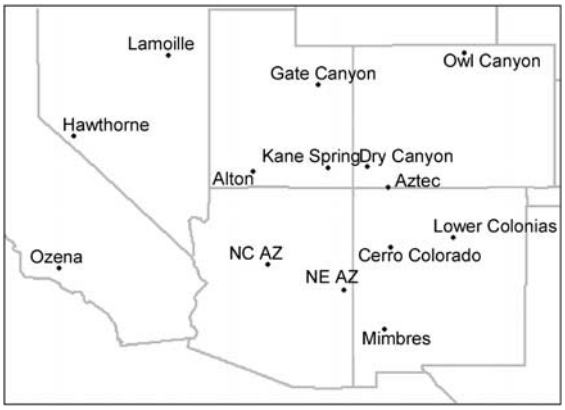
which produces isotope Drought Indices falling between about −6 to +6, similar in range to Palmer Drought Indices, although no linear correspondence has been established. The single-year δ^{13}C values from 1985–1999 (also holocellulose from rings of 4 tree pooled at each site) were simply fit with a straight line to derive indices because of the short interval. The isotope Drought Indices for all pentads and single years are accessible at the NOAA National Climate Data Center website, http://www.ncdc.noaa.gov/paleo/treering/isotope/iso-drought.html, as are maps of the Indices for each pentad and year derived by gridded interpolation (Table S1 in auxiliary material[1] contains the δ^{13}C values and calculated indices for the 15 years). Some have suggested [e.g., *McCarroll and Loader*, 2004] that standardization of isotope series be kept simple, e.g., just correction for changing $\delta^{13}\text{C}_{\text{air}}$, but this is largely an effort to retain low-frequency variability. As we are looking at high-frequency variability, and because the absolute values among sites differ by up to 2–3‰, the detrending and index calculation are a legitimate means of isolating this variability. Furthermore, indices derived from $\delta^{13}\text{C}_{\text{air}}$-corrected tree-ring δ^{13}C values fitted with linear regressions are strongly correlated with the isotope indices derived from "uncorrected" δ^{13}C at r ≥ 0.9999, with mean absolute differences at all sites between 0.07 and 0.17‰, i.e., within error of preparation and analysis.

[5] Although these isotope Drought Indices capture leaf-level isotopic fractionation and all environmental factors that influence it, we sought to explore the relationships of the Drought Indices with specific, well known environmental and ecological measures. Thus for the years 1985–99 we obtained representative monthly Palmer Drought Severity Index (PDSI) and precipitation from the National Climate Data Center for the state climate subdivisions corresponding to each site (http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp). Besides the monthly precipitation values, a fraction of long-term average accumulated precipitation (FAAP) was calculated for each month in each year as

$$\text{FAAP}_m = \frac{\sum_{i=1}^{m} Pi}{\sum_{i=1}^{m} \bar{P}i} \tag{5}$$

where the FAAP of a given month (m) is the sum of actual monthly precipitation (Pi) through that month in a year divided by the sum of the long-term average monthly precipitation through that month. In this study, the calculation is based on a "water year", with the first month being October of the previous growing season through September of the current growing season, and we use the 15-year period 1985–99 for the long-term monthly values in the denominator. Additionally the NDVI for the first 15 days of each month was obtained from the NOAA Pathfinder AVHRR products [*Tucker et al.*, 2005] (see also http://iridl.ldeo.columbia.edu/expert/SOURCES/.UMD/.GLCF/.GIMMS/.NDVIg/.global/ndvi/streamrescale/-999/

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033894.



Lamoille		Gate Canyon		Owl Canyon
Hawthorne	Alton	Kane Spring	Dry Canyon	Aztec
Ozena	NC AZ	NE AZ	Cerro Colorado	Lower Colonias
			Mimbres	

(+)	ns	p<0.10	p<0.05	p<0.01
(–)	ns	p<0.10	p<0.05	p<0.01

Oct					
	0.116		0.722		[illegible]
	0.331	0.864	0.356	0.563	0.549
	0.077	0.425	0.527	0.060	0.322
				0.462	

Nov					
	0.077		0.688		[illegible]
	0.561	0.840	0.324	0.564	0.542
	0.324	0.546	0.559	0.136	0.304
				0.389	

Dec					
	[illegible]		0.636		[illegible]
	0.505	0.766	0.433	0.520	0.459
	0.441	0.621	0.579	0.200	0.387
				0.498	

Jan					
	0.090		0.611		[illegible]
	0.378	0.661	0.525	0.581	0.511
	0.658	0.635	0.603	0.295	0.356
				0.375	

Feb					
	0.013		0.532		[illegible]
	0.361	0.579	0.440	0.553	0.588
	0.682	0.650	0.572	0.339	0.337
				0.303	

Mar					
	0.091		0.443		[illegible]
	0.277	0.569	0.531	0.562	0.546
	0.409	0.567	0.561	0.351	0.307
				0.334	

Apr					
	0.023		0.529		[illegible]
	0.472	0.611	0.578	0.664	0.578
	0.481	0.659	0.590	0.423	0.362
				0.367	

May					
	0.242		0.520		0.053
	0.453	0.555	0.565	0.748	0.607
	0.518	0.670	0.595	0.478	0.169
				0.358	

Jun					
	0.261		0.518		0.124
	0.455	0.550	0.567	0.763	0.532
	0.557	0.673	0.607	0.536	0.145
				0.497	

Jul					
	0.305		0.544		0.210
	0.507	0.635	0.490	0.744	0.484
	0.553	0.437	0.439	0.676	0.267
				0.656	

Aug					
	0.315		0.384		0.159
	0.485	0.644	0.417	0.763	0.584
	0.539	0.447	0.432	0.665	0.223
				0.620	

Sep					
	0.334		0.273		0.145
	0.484	0.586	0.310	0.741	0.241
	0.549	0.492	0.420	0.697	0.272
				0.582	

Figure 1. Correlation (r) results for isotope Drought Index versus monthly PDSI for the state climate subdivisions in which the pinyon sites reside. The results for each month are arrayed like a map, with the relative positions of the sites and results arranged approximately as they appear geographically north to south and west to east.

setmissing_value/dods) for the 0.073° × 0.073° cells containing the pinyon sites.

[6] Relationships at each site were examined by correlation analysis to help identify the parameters and their timing (months) most strongly related to the isotope Drought Indices. Additionally, the first leading principal components (PC1s) of the isotope Drought Indices and the seasonal means of precipitation and NDVI anomalies (deviations from their 1985–99 means) and PDSI data for 1985–99 were derived with the statistical computation package R [*R Development Core Team*, 2008] and compared in order to further establish broad fundamental relationships.

3. Results and Discussion

3.1. Correlations of Drought Indices With Environmental Parameters

3.1.1. Precipitation

[7] Few correlations between Drought Index and monthly precipitation (using state climate division data corresponding

to each site) were significant. Only 8% of the correlations were significant at $p < 0.10$ and 4% at $p < 0.05$, although about 65% were positive as theorized (Table S2 in auxiliary material). This result seems counterintuitive to the expected reliance of carbon isotopes on moisture, but the precipitation ratio described in equation (5) is probably more fundamental in terms of soil moisture and plant response.

[8] *Leavitt* [2007] had found that carbon isotopic composition of conifer ring subdivisions in the Great Lakes areas was much better correlated to the ratio of measured annual precipitation accumulated through a given month in any year to the long-term average annual precipitation normally accumulated through that month ($FAAP_m$ in equation (5)). This is based on an assumption that the trees are growing in "equilibrium" with a particular long-term average precipitation (moisture) accumulation regime, but will show isotopic responses to greater or lesser accumulation more so than to the specific amount of precipitation in a given month. In a year with a relatively low accumulated precipitation total by a given month, $FAAP_m$ would be less than one. If accumulated precipitation is above average through a given month, then $FAAP_m$ is greater than one. Indeed, in the present study this parameter produces positive correlations in 96% of the cases for the water year (October of the previous year through September of the current growing season), 44% of which are significant at $p < 0.10$ (Figure S1 in auxiliary material). The month of June has the greatest number of sites (10) with correlations at $p < 0.10$, and July has the greatest number of sites (7) with correlations at $p < 0.05$.

3.1.2. Palmer Drought Severity Index (PDSI)

[9] Palmer Drought Indices are derived from values of precipitation and temperature, both of which can contribute to available soil moisture and the water stress experienced by plants. PDSI is a long-term drought measure such that current moisture conditions are dependent on antecedent moisture conditions. PDSI values close to zero are considered "normal" moisture conditions for a particular site, with negative values below normal and positive values above normal.

[10] Overall, 95% of the correlations of PDSI with isotopic Drought Index are positive as anticipated (Figure 1). The month of June has the greatest number of sites (11) with correlations at $p < 0.10$, and it also has the greatest number of sites (9) with correlations at $p < 0.05$. Interestingly, the Lamoille (Nevada), Owl Canyon (Colorado), and Lower Colonias (New Mexico) sites show no significant positive correlations for any month, and in fact Owl Canyon (Colorado) has significant negative correlations for October through February. The lowest correlations reported by *Leavitt and Long* [1989a] between pentad isotope Drought Indices and 5-year averaged Palmer Drought Indices were also for Owl Canyon and Lower Colonias, although Lamoille was significantly positively correlated. In the present study, Owl Canyon was, however, significantly correlated to May precipitation ($p < 0.05$) and June $FAAP_m$ ($p < 0.10$), but Lamoille and Lower Colonias were not significantly correlated with either precipitation parameter (except Lamoille for May precipitation at $p < 0.10$). The large spatial climate variability within mountainous terrains may contribute to these observed discrepancies, where climate subdivision averages, usually encompassing the area of several counties, were used as a proxy for climate at these discrete sites.

Table 2. Correlation Matrix (With p Significance) of PC1 of Isotope Drought Indices and PC1 of Seasonal Precipitation Anomalies, Seasonal PDSI, and Seasonal NDVI Anomalies

	DJF	MAM	JJA	SON
Precipitation				
r	0.219	0.526	0.197	0.254
p	0.4335	0.0441	0.4821	0.3601
PDSI				
r	0.786	0.824	0.816	0.605
p	0.0005	0.0002	0.0002	0.0169
NDVI				
r	−0.416	−0.131	0.594	0.389
p	0.1230	0.6417	0.0196	0.1518

3.1.3. NDVI

[11] The Normalized Difference Vegetation Index is based on satellite spectral measurements in the visible and near-infrared to capture absorption by the green leaves of plants in proportion to their abundance. Here we have used NDVI "anomalies" computed from their deviation from the 1985–99 mean to identify periods with greater-than-average leaf abundance or less-than-average leaf abundance in the vicinity of each of the pinyon sites. We would expect isotope Drought Indices to correlate positively with NDVI anomalies, but given the 8° range of latitude among sites in the network, some north-south differences in timing might be expected related to growing season and snow cover.

[12] In fact, 56% of the correlations are positive and the months of July, August and September have the greatest number of sites with positive correlations (Table S3 in auxiliary material). However, only 14% of all correlations are significant at $p < 0.10$ (only 8% significant at $p < 0.05$).

[13] The weakness of relationships may result from NDVI not capturing conditions that are exclusively representative of pinyon growth activity over a growing season. For example, rainfall events may immediately affect shallow-rooted annual plants to produce a "greening" (positive NDVI anomaly), but in the short-term this would not influence the activity of more deeply rooted pinyon trees. This effect is especially well illustrated in El Niño (wetter than average winter/springs) and La Niña (drier than average winter/springs) years in the Southwest (Figure S2 in auxiliary material).

3.2. Principal Component Analysis

[14] To better assess the inherent relationship between isotope Drought Indices and environmental measures over the whole region, principal components analysis was employed. The dominant PC1 of isotope Drought Indices was found to explain ca. 36% of the total variance (18% PC2, 15% PC3, 8% PC4), so its value for each year 1985–99 was compared to the corresponding PC1s of the precipitation anomaly, PDSI and NDVI anomaly data. In this test, the precipitation, PDSI and NDVI data were seasonalized to December through February (DJF), March through May (MAM), June through August (JJA), and September through November (SON). The results (Table 2) confirm the strong relationship of isotope Drought Index in pinyon at these 14 sites with PDSI, showing highly significant

correlations for DJF, MAM and JJA. They also confirm a significant positive relationship of isotope Drought Index with precipitation for MAM, perhaps because widespread spring frontal storms may be key to preconditioning summer moisture conditions in the region.

[15] The most promising finding uncovered by the PC analysis is the significant relationship ($p < 0.02$) of NDVI with Drought Indices for JJA, which is when growth at all sites is active and there is no snow on the ground to confound the NDVI signal. This is encouraging for the prospective use of the isotope Drought Indices for reconstructing past regional "greenness". Furthermore, the PC analysis revealed this significant relationship that dominates the station network, whereas it is much less apparent in station by station regression analysis. Further investigation may help refine and improve these relationships, such as determining the spatial resolution and heterogeneity aspects of remotely sensed NDVI compared to the tree-ring isotope site signal, and comparing and perhaps incorporating ring width relationships with NDVI (and drought) in the model.

4. Conclusions

[16] This analysis more definitively confirms the express influence of drought on isotope Drought Indices (derived from $\delta^{13}C$) in southwestern pinyon tree rings. Significant relationships are very numerous for Drought Indices with monthly PDSI (and to a lesser extent with $FAAP_m$), but infrequent with monthly precipitation and temperature (Table S4 in auxiliary material), suggesting the Palmer Drought Index, as an aggregate and accumulated parameter influenced by precipitation and temperature, more effectively capture the environmental influence on leaf $\delta^{13}C$.

[17] Principal components analysis likewise finds highly significant relationships of PC1 of isotope Drought Indices and seasonalized PDSI, which gives us great confidence that the original pentad isotope Drought Index records going back over 400 years are a robust tool for mapping Southwestern drought [*Leavitt et al.*, 2007]. More importantly, the significant relationship between PC1 of Drought Indices and summer NDVI offer the unprecedented potential for similarly reconstructing vegetation "greenness" back in time. The isotope Drought Indices may thus have utility for regional carbon cycle investigations via the NDVI link.

[18] **Acknowledgments.** We thank the Cooperative Institute for Research in Environmental Sciences, University of Colorado, for fellowship support to S.W.L. We also thank David Noone for helpful discussions as the project progressed and two anonymous reviewers of the manuscript for their thoughtful comments.

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