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DROUGHT INDICATED IN CARBON-13/CARBON-12 RATIOS OF SOUTHWESTERN TREE RINGS[1]

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ABSTRACT: Stomatal closure during periods of moisture deficiency should theoretically lead to elevated $^{13}C/^{12}C$ ratios as reduction of available CO_2 leads to diminished photosynthetic discrimination against ^{13}C in favor of ^{12}C. Stable-carbon isotope ratio chronologies developed from 5-yr tree-ring groups at 17 sites in six southwestern states were tested for a drought relationship by first fitting a spline curve to each chronology to remove the long-term trend and calculating indices as the ratio of actual to spline curve value. The time series of "Del Indices" so developed are significantly correlated with 5-yr mean Palmer Hydrological Drought Indices (post-1930 period) and reconstructed July Palmer Drought Severity Indices from respective areas. Overall, in the period since 1790, the driest pentads were 1900-04 and 1960-64, whereas the wettest were 1980-84 and 1915-19. Maps of drought represented for two pentads seem to be reasonable representations, although spatial correlations of Del Indices with PHDI were generally not significant. These Del Index drought reconstructions may provide a useful measure of past physiological response to drought (stomatal closure), although the present cost of analysis would prevent this from being a routine method.
(KEY TERMS: stable-carbon isotopes; C-13/C-12; pinyon pine; Pinus edulis; drought; Palmer Drought Indices; Southwest.)

INTRODUCTION

One of the primary methods of reconstructing precipitation and drought in the western U.S. has been through tree-ring width measurements and analysis (e.g., Stockton and Meko, 1975; Meko, et al., 1980; Michaelsen, et al., 1987). Narrow rings are consistent with one or more of a number of physiological responses to stress associated with low precipitation and/or high temperatures (Fritts, 1976). One of these physiological responses during the growing season is increased daytime stomatal closure, and it is this response of decreased stomatal conductance in particular that relates to changes in the $^{13}C/^{12}C$ ratio of carbon fixed by plants (Francey and Farquhar, 1982).

In principle, when abundant CO_2 is available, plants tend to discriminate against $^{13}CO_2$ relative to $^{12}CO_2$ during photosynthesis. When stomatal closure cuts off CO_2 supply, continued carbon fixation is then necessarily less discriminating in order to sustain operation under reduced CO_2 availability. We have found evidence that those tree rings (actually 5-yr ring groups) with high $^{13}C/^{12}C$ ratios are also narrow rings (drought conditions) (Leavitt and Long, 1985a; 1986; 1987). Elevated $^{13}C/^{12}C$ ratios would also be favored by high CO_2 fixation rates depleting CO_2 (Francey and Farquhar, 1982). Thus, the narrow rings associated with high ratios (Leavitt and Long, 1986) could also result from relatively high fixation rates (high gross photosynthesis) with accompanying increased respiration, producing reduced net photosynthesis in (hot) drought periods (Fritts, 1976). This link between stomatal closure and $^{13}C/^{12}C$ ratios in tree rings forms the basis for a new potential method of climate reconstruction that merits exploration.

In this paper we derive isotopic drought indices from long $\delta^{13}C$ ("del C-13") chronologies determined from sites in six southwestern states, compare them to other climate measures (direct and proxy), and construct maps based on these indices. The value of $\delta^{13}C$ is obtained by:

$$\delta^{13}C\ (‰\ \text{units}) = \left[\frac{^{13}C/^{12}C(\text{sample})}{^{13}C/^{12}C(\text{standard})} - 1\right] \times 1000 \quad (1)$$

where del C-13 in permil (‰) units is expressed as the $^{13}C/^{12}C$ ratio of the sample with respect to the same ratio of the PDB carbonate standard (Craig, 1957).

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METHODS

The sites for which we have isotopic time series are depicted in Fig. 1, and the site specifics are detailed in Table 1. Most of the $\delta^{13}C$ isotopic chronologies used in this paper have been previously derived during various stages of research to reconstruct atmospheric $\delta^{13}C$ from tree-ring isotopic measurements (Leavitt and Long, 1985b; 1986; 1988). The chronologies represent isotopic measurements on the cellulose component of wood, and the analyses were performed on dendrochronologically-dated rings grouped into pentads in the sequence 1800-04, 1805-09, 1810-14.... Most of the isotopic chronologies represent four orthogonal cores pooled from four separate trees at the same site producing curves that are representative of the whole site (Leavitt and Long, 1984). For comparison, tree-ring width index chronologies used in climate reconstructions normally consist of at least 8 to 12 trees. The exceptions include the Ozena and Figueroa Mt. sites where two opposite cores were pooled from each of four trees, and Mt. Laguna site where two cores were pooled from each of two trees. Additionally, the NCAZ and NEAZ (see Table 1 for site abbreviations) were produced by merging four isotopic chronologies derived from single trees at four separate sites. All the original $\delta^{13}C$ chronologies were treated like ring-width chronologies by fitting a curve to them (high-pass filter) and calculating indices as the ratio of each measured $\delta^{13}C$ value to the corresponding value from the spline curve. Ideally, this removes the long-term trend that we believe is more related to changes in atmospheric CO_2 (Leavitt and Long, 1986; 1988) and leaves the short-term fluctuations that are drought related. With southwestern trees, the trend of ring widths is commonly best fit with a negative exponential growth curve (Fritts, 1976), but for $\delta^{13}C$ we chose more generally to fit a spline curve to the data rather than assuming that any specific type of curve would best fit the data. The program ARSTAN (Cook and Holmes, 1985) of the Laboratory of Tree-Ring Research at the University of Arizona was used to fit cubic smoothing splines to the isotopic time series and calculate the indices. Because our longest chronologies are nearly 500 years in length (100 pentads) and the trends were generally smooth (Leavitt and Long, 1986; 1988), we chose a stiffness of 50 (pentads) for the spline curves. We used a stiffness of 50 even for shorter time series of 15-20 pentads to provide greater uniformity for comparison of indices among sites. A test in which splines with a stiffness of 25 were fit to each time series indicated very limited absolute numerical differences and no alteration of the conclusions from the stiffness=50 curves as reported in this paper.

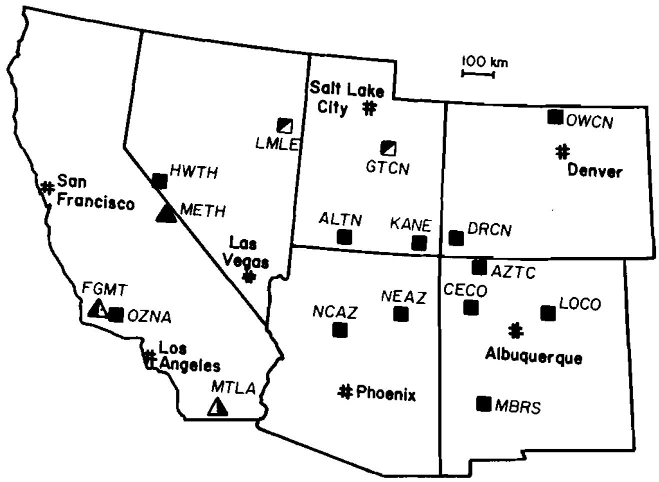

Figure 1. Sites with $\delta^{13}C$ Time Series Used to Develop the Del Index Chronologies in This Paper. Published $\delta^{13}C$ chronologies of pinyon pine [■], bristlecone pine [▲], ponderosa pine [◭] and Jeffrey pine [Δ]; unpublished pinyon pine [◩]. Table 1 contains details.

The average of indices from each $\delta^{13}C$ chronology derived in this fashion is 1.00, with the values less than 1.00 corresponding to pentads interpreted as having moisture deficiency and those greater than 1.00 a moisture excess. These isotopic index values are decimal fractions and they were subsequently transformed into "Del Indices," which are integers, according to the algorithm;

$$\text{Del Index} = [\text{isotopic index} - 1] \times 1000 \qquad (2)$$

The Del Indices have no units. The more negative the value of the Del Index, the greater the moisture deficiency, whereas the more positive the greater moisture excess as interpreted in this paper.

RESULTS

Correlation with Other Time Series

The validity of these Del Index chronologies as a proxy indicator of drought was addressed by comparison with measured climate parameters in the form of Palmer Hydrological Drought Indices (PHDI), which have been calculated and compiled monthly for each state's "homogeneous" climatic divisions by Karl, et al. (1983) for the period 1931 to 1982. Five-yr (60-month) means of PHDI were calculated from these monthly tabulations for the same pentads as the Del Indices.

TABLE 1. Information on $\delta^{13}C$ Isotopic Time Series.

Site (Abbrev.)	Species	Elev.	Length of Time Series	Source of $\delta^{13}C$ Time Series	
Kane Spring (KANE)	*Pinus edulis* (pinyon pine)	1965m	1490-1983	Leavitt and Long	(1986)
Alton (ALTN)	"	2245	1520-1983	"	
Dry Canyon (DRCN)	"	2150	1625-1983	"	
Lower Colonias (LOCO)	"	2375	1655-1983	"	
Aztec (AZTC)	"	2080	1710-1983	"	
Cerro Colorado (CECO)	"	2500	1650-1983	Leavitt and Long	(1988)
Ozena (OZNA)	*P. monophylla* (pinyon pine)	1370	1750-1983	"	
Hawthorne (HWTH)	"	2330	1620-1983	"	
Mimbres (MBRS)	*P. edulis*	2025	1790-1983	"	
Owl Canyon (0WCN)	"	1860	1600-1984	"	
Northcentral Arizona (NCAZ)*	"	1470	1725-1981	Leavitt and Long	(1985)
Northeast Arizona (NEAZ)*	"	2090	1700-1981	"	
Gate Canyon (GTCN)	"	2220	1580-1986	Unpublished	
Lamoille (LMLE)	"	2130	1620-1986	"	
Pigueroa Mt. (FGMT)	*P. ponderosa* (ponderosa pine)	1280	1860-1983	Leavitt and Long	(1988)
Mt. Laguna (MTLA)	*P. jeffreyi* (Jeffrey pine)	1780	1800-1983	"	
Methuselah Walk (METH)	*P. longaeva* (bristlecone pine)	2880	1420-1983	Long, *et al.*	(1987)

*Each of these isotope chronologies represents the means of 4 sites where isotope chronologies had been derived from single trees at each.

Additionally, 5-yr averages of a second drought parameter, Palmer Drought Severity Index (PDSI developed by Palmer (1965)) as reconstructed in other studies are used for comparison with the Del Indices.

Table 2 displays correlation coefficients of Del Indices with the 60-month PHDI averages. The left section of Table 2 indicates how well the Del Indices correlate with PHDI spatially over the pinyon pine network (for uniformity of comparison the non-pinyon pine species were not included in this analysis) when each time interval is calculated separately. In this mode, strongest correlations are the 1930-34 and 1950-54 pentads. The right-hand section of Table 2 contains temporal correlations for each pinyon pine site of Del Indices with respective PHDI. Eight of these 14 correlations are significant at $P \leq 0.05$ and ten are significant at $P \leq 0.1$. The Owl Canyon site, which represents the most northeasterly pinyon pine stand in North America, shows very poor correlation of $\delta^{13}C$ with PHDI. The temporal Del Index-PHDI correlation coefficients for the non-pinyon pine sites are also low: MTLA=0.19; FGMT=0.36; METH=0.10. Additional calculations (not shown) for the pinyon pine sites indicate stronger correlations of Del Indices with PHDI than with PDSI (a test using 5-yr mean July Palmer Indices).

Proxy measures of drought, such as 5-yr means of reconstructed July PDSI and Upper Colorado River flow as measured at Lee's Ferry, Arizona, were also correlated with corresponding Del Index chronologies (Table 3). Technically, these proxy climate time series derive from ring-width indices so it should not be too surprising that we find them related to our Del Indices. However, it should be noted that these proxy climate parameters (1) had been reconstructed with ring-width chronologies from a large number of sites generally not including any of ours, and (2) represent the "average" of fairly large areas from the size of state climatic divisions to that of the Upper Colorado River drainage basin. Five-yr means of reconstructed July Southern California PDSI were significantly correlated with Del Indices from all the California sites with the exception of Mt. Laguna in the very southernmost part of the state. Five-yr means of July PDSI reconstructed for the Northern Rio Grande (NRG), Northwest Plateau (NWP), and Southwestern Mountains (SWM), New Mexico, and Southwest Colorado (SWC) were all significantly correlated with the respective Del Index chronologies that are located in those regions. Correlations of five-yr means of reconstructed annual Upper Colorado River flow with Del Indices of sites in or near the upper basin were also significant, with the exception of the Aztec, New Mexico, site in the southeastern section of the basin.

TABLE 2. Correlation Coefficients of Del Indices vs. 60-Month Averages of PHDI of State Climatic Divisions Corresponding to Each Pinyon Site.

For Each Time Interval (n=14)		For Each Site (n=11)	
Pentad	r	Site	r
1930-34[1]	0.74**	KANE	0.78**
1935-39	0.46+	ALTN	0.67*
1940-44	0	DRCN	0.47
1945-49	0.41	LOCO	0.39
1950-54	0.57*	AZTC	0.86**
1955-59	0.40	CECO	0.71*
1960-64	0.14	OZNA	0.58+
1965-69	0.46+	HWTH	0.61*
1970-74	0.24	MBRS	0.56+
1975-79	0. 26	OWCN	0.29
1980-84[2]	0	NCAZ	0.47
		NEAZ	0.83**
		GTCN	0.67*
		LMLE	0.76**

[1] for PHDI this was 1931-34.
[2] for PHDI this was 1980-82, and most Del Index chronologies ended in 1980-83.
Statistical significance: +P≤0.1, *P≤0.05, **P≤0.01

Drought Maps

The chronologies of Del Indices for these widely separated sites (available from S.W.L.) have an obvious application of representing spatial distribution of drought. For comparison, the pinyon Del Indices for the period 1950-54 have been plotted and contoured in Fig. 2 along with a plot and contour map of 5-yr (60-month) mean PHDI for all climate divisions in these states. PHDI show greatest drought (≤–2) throughout most of New Mexico with smaller areas in northeastern Colorado and northwestern Arizona/southwestern Utah. The Del Indices show the greatest drought (≤–20) likewise over most of New Mexico. A second comparison may be made with 5-yr mean July PDSI reconstructed from ring widths for the western U.S. as computed by Stockton and Meko (1975; and personal communication). The bottom map in Fig. 2 shows this PDSI, and although the number of reconstructed locations is more widely spaced than for the PHDI, the pattern of greatest drought (PDSI≤–1.0) stretches over New Mexico and Arizona. Thus, a fairly good correspondence with all of these drought measures emerges from the data. Neither the Del Indices nor the reconstructed PDSI perfectly match the actual PHDI, but they are reasonable approximations. The Del Indices for the non-pinyon pine sites were held out of the contour plotting to see if they independently conform to the pinyon plot. Because Del Indices are –6 for METH, +14 for MTLA, and –6 for FGMT, only the MTLA value clearly does not conform to the contour map.

TABLE 3. Correlation Coefficients of Del Indices with Various Proxy Climate Measures.

Reconstructed 5-yr Mean July PDSI		
a. Southern California 1700-1963 (Meko, et al., 1980)		
Correlation with	*r*	*n*
OZNA	0.59**	43
METH	0.55**	53
FGMT	0.63**	21
MTLA	0.17	33
b. New Mexico and Colorado Climate Divisions[1] 1500-1969 (Rose, et al., 1982)		
Correlation	*r*	*n*
NRG with COCO	0.55**	63
NWP with AZTC	0.36**	52
SWM with CECO	0.52**	64
SWC with DRCN	0.56**	69
Reconstructed Colorado River Flow 1512-1961 (Stockton, 1976)		
Correlation with	*r*	*n*
KANE	0.50**	91
ALTN	0.57**	89
NCAZ	0.61**	48
NEAZ	0.41**	53
GTCN	0.40**	77
DRCN	0.53**	68
AZTC	0.26	51

[1]Climate division abbreviations in text.
Statistical significance: **P≤0.01.

Figure 3 contains a contour map of Del Indices and 5-yr mean reconstructed July PDSI (Stockton and Meko, 1975; personal communication) for the pentad 1900-04. The Del Indices indicate a zone of heavy drought between the –20 contours in Nevada/California and Colorado/New Mexico. The values of –50 in Utah are among the lowest Del Indices calculated in this study. The area between the –1 PDSI contours is the greatest area of reconstructed drought and is consonant with the Del Index results. The Del Indices for the non-pinyon pine METH, FGMT, and MTLA sites are –14, –4, and –1, respectively, and thus only the METH index fits the pinyon pine map well. The bristlecone pine METH site along with the pinyon pine sites could probably be characterized as relatively more xeric, whereas the Ponderosa pine FGMT and Jeffrey pine MTLA are relatively more mesic.

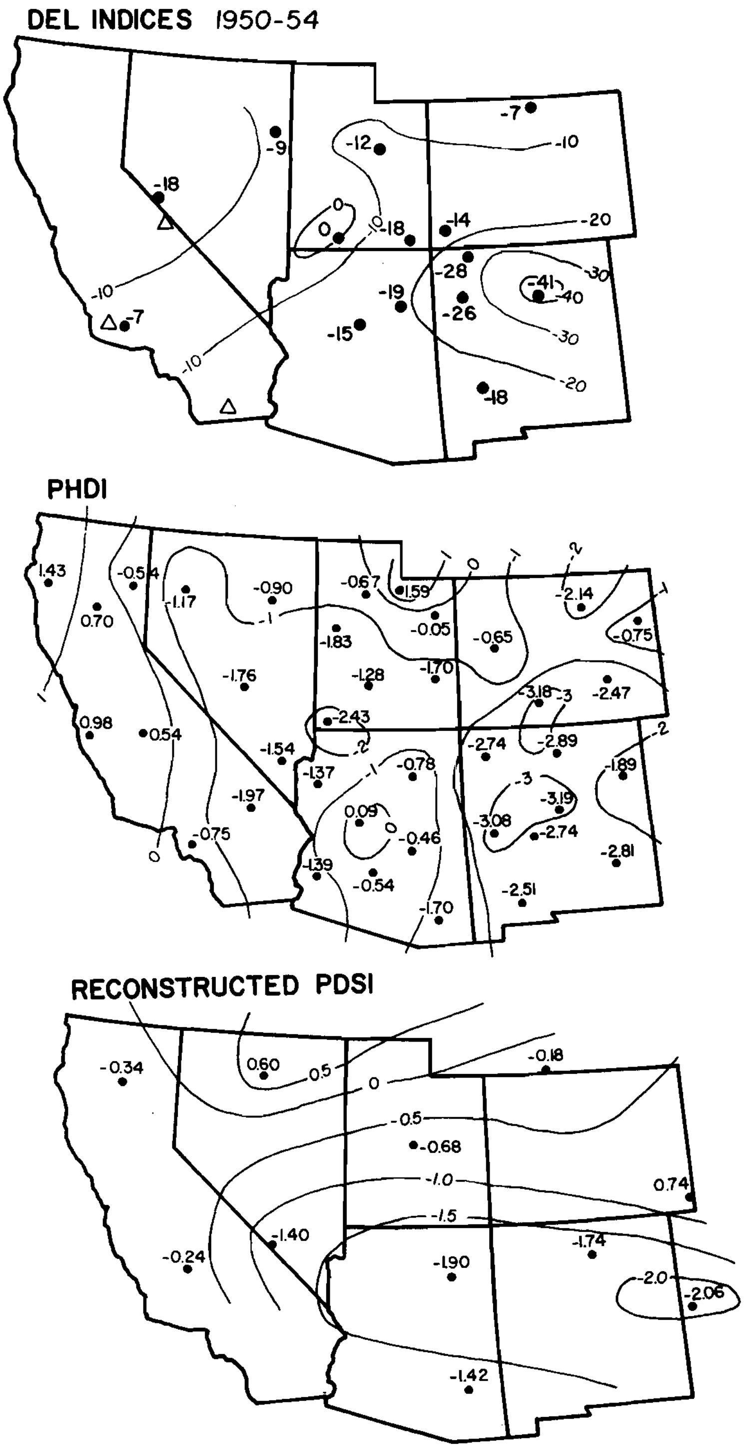

Figure 2. Contour Maps of Del Indices (This Study), 5-Yr (60-Month) Mean PHDI (Karl, et al., 1983), and 5-Yr Mean July PDSI (Stockton and Meko, 1975) for the Period 1950-54.

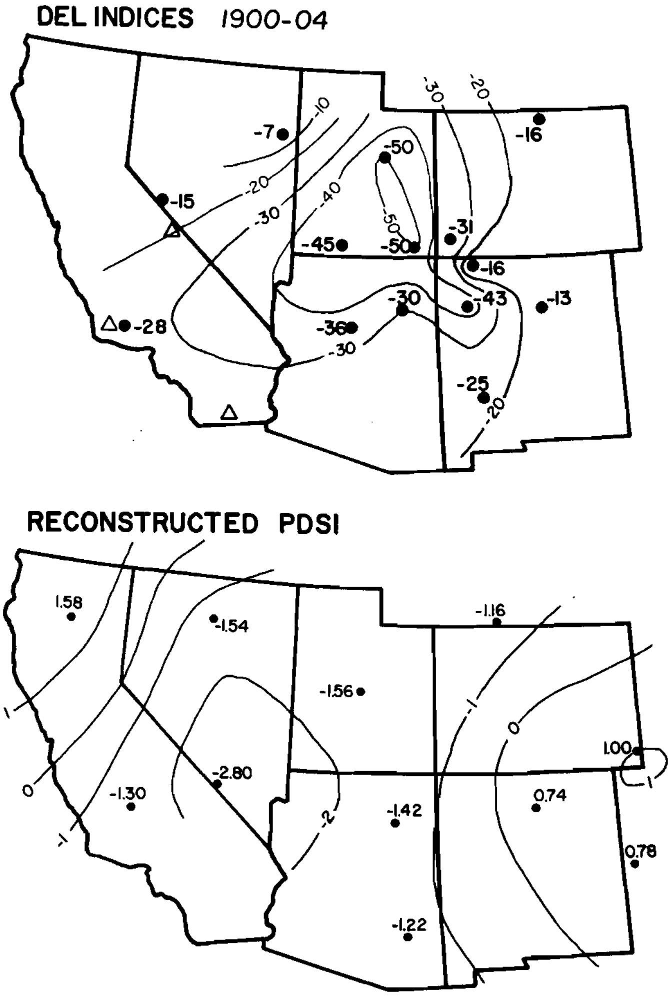

Figure 3. Contour Maps of Del Indices (This Study) and 5-Yr Mean July PDSI (Stockton and Meko, 1975) for the Period 1900-04.

DISCUSSION

The results seem to support the validity of Del Indices as a proxy indicator for drought. They also act as a degree of independent confirmation of reconstructions obtained from tree-ring width studies. However, their value, at least as far as reconstructing mean 60-month PHDI, or 5-yr July means of PDSI and 5-yr means for Upper Colorado River flow, are far from perfect. In most cases, temporal correlations are statistically significant, but if we look at the r^2, which is the percent of variation explained by these correlations, they are usually less than 50% and frequently they are only between 20 and 35%. Perhaps this should not be too surprising considering that the PHDI's, for instance, are determined from weather data from a number of stations scattered throughout each state climate division (hundreds of square kilometers with lowland areas represented by more stations than high-elevation areas), whereas the pinyon pine sites represent only a single small locality (a few hectares) within those divisions. Mountainous western states are characterized by a diversity of climate associated with elevational effects, so a single locality may not be expected to be fully representative of the climate division. Furthermore, the 5-yr mean PHDI values used in these correlations were calculated for the full 12-month year, whereas the Del Indices may be more appropriately related to moisture during the growing season months only.

Additionally, we are dealing with simple 5-yr averages of climate parameters compared to Del Indices derived from the $\delta^{13}C$ of 5-yr ring groups. Within the isotopically-analyzed 5-yr group, each ring actually has a different $\delta^{13}C$ value presumably related to moisture availability in that year. The $\delta^{13}C$ value of the pentad, however, is not the simple average of the $\delta^{13}C$ of each ring, but is weighted according to the mass contribution of each ring (in turn dependent on ring widths, ring densities, and cellulose composition). This may also contribute to some of the variance not accounted for in the correlations, but to remedy this with single-year isotopic analysis might make such studies prohibitively expensive. Commercial costs of isotopic analyses are about $40 per sample so a set of 10 sites each 200 years in length (40 pentads), would cost $16,000 for isotopic analysis of pentads but $80,000 for single-year chronologies (and these are exclusive of costs of sampling and dating).

Another problem is that the correlations of Del Indices with PHDI (Table 2) are much better when calculated temporally for each site than when calculated spatially for each time interval. This may be somehow related to the relatively small number of cases, but the implication is that these Del Indices may be better for time-series reconstructions than for mapping, at least with regard to PHDI. For the examples shown (Figs. 2, 3), however, the Del Index maps certainly seem reasonable representations of the drought situation over the 5-yr periods.

Perhaps at this point, we may also consider that the Palmer Indices represent drought in a meteorological or hydrological sense, whereas the Del Index chronologies may more accurately represent drought in a physiological sense. If this Del Index is distinguishable from meteorological and hydrological drought indices, perhaps it is a new, useful parameter in its own right. For example, Del Index may be a good overall measure of relative stomatal opening, including that induced primarily from moisture stress (related to drought indices), as well as stomatal regulation influenced by light and carbon dioxide (Fritts, 1976). However, the Del Index may go beyond stomatal condition, because models of carbon isotope fractionation in plants suggest a number of factors (CO_2, $\delta^{13}C$ of CO_2, light, nutrition and others) may contribute to the ultimate $\delta^{13}C$ of the tree rings.

If these Del Indices are good drought indicators as we have evidenced, we may consider which of the 5-yr time periods in our sample grid were the wettest and driest. Over the period since 1790-94 for which we have Del Indices for all pinyon pine sites, the sum of the Del Indices was used as a measure of moisture abundance. The wettest and driest pentads on this basis are given in Table 4. For this array the 1900-04 period was the driest and the 1980-84 period the wettest. Additional earlier pentads which were dry, but for which we did not have Del Indices from all 14 chronologies, include 1735-39, 1755-59 and 1775-79. Some of these moist and dry periods contain 3-yr periods which Stockton and Meko (1975) reconstructed to be among the driest and wettest periods over the whole area west of the Mississippi River.

TABLE 4. Wettest and Driest Periods from 1790-94 to 1980-84 based on the Sum of Del Indices from All Sites.

Moist		Dry	
Sum Del Indices	Pentad	Sum Del Indices	Pentad
312	1980-84[1]	-405	1900-04
244	1915-19	-279	1960-64
241	1940-44	-273	1895-99
224	1790-94	-247	1820-24
201	1865-69	-232	1950-54

[1]For 10 of the 14 chronologies this was actually 1980-83, for 2 it was 1980-81, and for 2 it was 1980-84.

SUMMARY AND CONCLUSIONS

In this paper, Del Indices were derived from $\delta^{13}C$ time series previously developed for the purpose of reconstructing atmospheric chemistry, in order to test a theoretically predictable link with drought related to stomatal closure and CO_2 fixation during photosynthesis. Comparisons with other measures of drought (PHDI, PSDI) support such a relationship, although temporal correlations appear stronger than spatial correlations. Examples of Del Index drought maps seem to conform well with other drought measures and reconstructions in the six southwestern states.

The cost of these isotope analyses may prohibit this from becoming a routine method, and there is reason to believe the method would be more accurate with single rings rather than the 5-yr ring groups used in this study, making the method even more expensive. As a result, standard reconstructions with ring widths may be preferred for most studies, but if tree-ring isotope chronologies are being developed for some other purpose, or if Del Indices are truly a direct measure of stomatal opening (a direct physiological response to drought), perhaps there would be instances where the application of this method may be justified. Additional study is warranted to prove the method, perhaps beginning with development of a Del Index Chronology at a site with long records from which site-specific PHDI can be calculated for comparison. By making this a single-year chronology, some of the uncertainties of interpreting pentad results can be avoided and clear relationships may be obtained.

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