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Variability of seasonal $\delta^{13}C$ patterns in Apache Pine from Southern Arizona, USA

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ABSTRACT

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Seasonal $\delta^{13}C$ changes observed in tree rings offer the potential of reconstructing environmental conditions at finer than annual resolution. In the American Southwest, an opportunity to better expose environmental influences on tree-ring $\delta^{13}C$ at seasonal scales is fortuitously afforded by the presence of a time marker within rings. The strong winter-summer bimodal precipitation distribution is conducive to formation of a false-latewood band in the middle of the growing season, approximately June, after which normal growth usually resumes to the end of the growing season. The variability in seasonal $\delta^{13}C$ patterns in the 1991-1993 growth rings of two Apache pine (*Pinus engelmannii*) containing these false rings was investigated by descriptive comparison (1) between radii in a tree, (2) between different vertical heights in the trunks of both trees, and (3) between trees. The patterns of seasonal $\delta^{13}C$ change in tree-ring cellulose were broadly similar between radii, but with differences in amplitude and differences in absolute values of up to nearly 2‰. Between trees, the isotopic patterns were quite similar: concave downward for 1991 and 1993, and continuously increasing in 1992. There were differences of *ca.* 0·5‰ among patterns at different heights within a tree, but there was no common gradient in the isotopic change with height. Comparison of the seasonal patterns with environmental variations suggests that they are more tightly linked to moisture conditions than to temperature or changes in atmospheric $\delta^{13}C$.

Key-words—Tree rings, Carbon isotopes, Drought, *Pinus engelmannii*, False rings, Latewood.

अमरीका के दक्षिणी एरीज़ोना प्रान्त से प्राप्त अपाचे चीड़ में मौसमी $\delta^{13}C$ विन्यास का वैविध्य

स्टीवन डब्ल्यू. लीविट एवं क्रिस्टोफ़र एच. बाइसन

सारांश

वृक्ष वलयों में देखे गए मौसमी $\delta^{13}C$ परिवर्तन वार्षिक वियोजन की अपेक्षा अधिक उत्कृष्ट पर्यावरण स्थितियों के पुनर्सृजन हेतु आधार प्रदान करते हैं। दक्षिण-पश्चिमी अमरीका में वलयों के भीतर समय सूचक चिह्नकों की उपस्थिति से मौसमी पैमाने पर $\delta^{13}C$ वृक्ष वलयों में बेहतर पर्यावरणीय प्रभाव जानने हेतु एक उत्कृष्ट अवसर प्राप्त हुआ है। मजबूत शीत-ग्रीष्म द्विबहुलकीय (बाइमोडल) वर्षण वितरण वृद्धि के मौसम के मध्य में सम्भवतः जून माह में कूट पश्चदारु पट्टिका (बैण्ड) के निर्माण हेतु अनुकूल है, जिसके पश्चात वृद्धि के मौसम के अन्त में सामान्य वृद्धि सामान्यतः आरम्भ होती है। इन कूट वलयों से युक्त दो अपाचे चीड़ (*पाइनस इन्जेलमैनाइ*) के सन् 1991-93 ई. के वृक्ष वलयों में मौसमी $\delta^{13}C$ विन्यास में वैविध्य (1) एक वृक्ष के त्रिज्याओं के मध्य, (2) दो वृक्षों के स्तम्भों में भिन्न-भिन्न ऊर्ध्वाधर ऊँचाइयों के मध्य, तथा (3) वृक्षों के मध्य विस्तृत तुलना द्वारा खोजा गया है। वृक्ष वलय सेलुलोज़ में मौसमी $\delta^{13}C$ परिवर्तन के विन्यास प्रायः त्रिज्याओं

के मध्य एक समान हैं, परन्तु वृक्षों के मध्य आयाम में परिवर्तन एवं लगभग 2‰ तक एकल मान में परिवर्तनों के साथ हैं। समस्थानिक विन्यास पूर्णतः एक समान अर्थात वर्ष 1991 हेतु अवतल अधोमुखी तथा वर्ष 1992 में वृद्धिगामी हैं। वृक्ष के भीतर विभिन्न ऊँचाइयों में विन्यासों के मध्य सी.ए. 0·5‰ की भिन्नताएँ हैं, परन्तु ऊँचाई के साथ समस्थानिक परिवर्तन में कोई उभयनिष्ठ प्रवणता (ग्रेडिएन्ट) नहीं है। पर्यावरणीय विविधता के साथ मौसमी विन्यासों की तुलना से प्रस्तावित होता है कि ये तापमान अथवा वातावरणीय $\delta^{13}C$ तापमान में परिवर्तन की अपेक्षा आर्द्र स्थितियों से अधिक सघनतः सम्बद्ध हैं।

संकेत शब्द—वृक्ष वलय, कार्बन समस्थानिक, अनावृष्टि, *पाइनस एन्जिलमैनाइ,* कूट वलय, अग्र दारु.

INTRODUCTION

MEASUREMENTS of stable-carbon isotopic composition ($\delta^{13}C$) of successive growth increments in leaves (Leavitt & Long, 1982; Lowden & Dyck, 1974; Smedley *et al.*, 1991; Tieszen & Boutton, 1989) and tree rings (Leavitt & Long, 1982, 1985, 1991; Leavitt, 1993; Loader *et al.*, 1995; Ogle & McCormac, 1994; Walcroft *et al.*, 1997; Wilson & Grinsted, 1977) exhibit seasonal changes, perhaps containing a climate signal. For example, empirical results of seasonal intra-ring $\delta^{13}C$ patterns from several field studies (Leavitt, 1993; Leavitt & Long, 1991; Livingston & Spittlehouse, 1996) suggest that soil water conditions, presumably influencing stomatal conductance, are frequently the primary driving mechanism for the seasonal $\delta^{13}C$ observed in tree rings. This is consistent with carbon isotope fractionation models (Farquhar *et al.*, 1982; Francey & Farquhar, 1982) that indicate in addition to $\delta^{13}C_{air}$ of atmospheric CO_2, plant $\delta^{13}C$ is influenced by rates of stomatal conductance and photosynthetic assimilation, both of which can be affected by environmental factors.

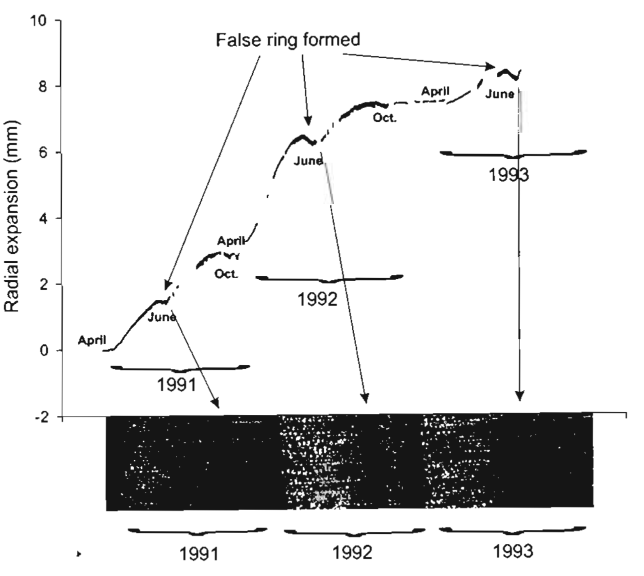

Fig. 1—The 1991-93 daily stem size progression of a nearby *Pinus englemannii* tree monitored by dendrometer, along with photomicrograph of corresponding cell-size patterns. Growth hiatus and stem shrinkage in the second half of June occurs as the false ring (arrows) is formed. Missing data was interpolated.

The southwestern U.S. experiences precipitation from winter frontal storms and summer monsoon airmasses. The late spring-early summer interval between these bimodal precipitation peaks is hot and arid, contributing to the frequent formation of a false latewood band ("false ring") prior to mid-summer re-initiation of cambial growth (Fig. 1). This false latewood provides a time marker (representing approximately the very end of June and beginning of July) with which to more precisely explore timing of correlation between isotopic composition and climate.

The presence of the time marker also offers the potential to help resolve remaining uncertainties about seasonal isotopic patterns in tree rings, including the period they represent and the fidelity of their signal at different locations in a tree. This study expands previous baseline isotopic work on seasonal $\delta^{13}C$ variation in ponderosa pine species in the Southwest, USA (Leavitt *et al.*, 1998, 1999), by exploring seasonal variation of $\delta^{13}C$ in tree rings from different radii, in different years and at various heights in which the false-latewood band is in different locations within the ring or not present at all.

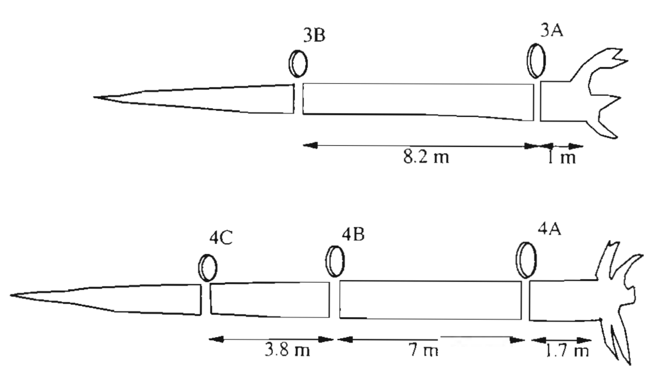

Fig. 2—Location of cross-sections sampled from two trees deposited in flood debris at the lower Rhyolite Canyon Site.

METHODS

The Lower Rhyolite Canyon Site in Chiricahua National Monument (elevation *ca.* 1620 m; location ca. 32·00°N, 109·35°W), southeastern Arizona, was visited on 1 December 1994 to sample Apache pine (*Pinus engelmannii*) trunks of dead trees that had been deposited with debris in and near the streambed by major flooding that occurred the last few days of August 1993. These tree trunks had the disadvantage that we did not know their exact provenience, but it was probably in the lower reaches of the canyon just upstream from the site. It had the advantage that we were free to sample as much material as needed. We sampled cross-sections from different heights of two mature trees (Fig. 2).

The cross-sections were surfaced to enhance growth ring recognition, and the outer rings were cross-dated. Two opposite radii were sampled from each cross-section to minimize effects of circumferential isotope variability (Leavitt & Long, 1984, 1986). The 1991, 1992 and 1993 rings from each radius were sampled by subdividing each ring into 4 equal parts with a razor knife under magnification. The subdivisions from the 2 radii from section 4C were processed separately to determine the extent of circumferential variability. Additionally, the subdivisions from each radial pair (including replicate radial samples from 4C) were pooled to a single series of samples from each cross-section. The holocellulose component of each segment was isolated from ground wood (20-mesh) by removing extractives with toluene-ethanol, treating with hot water, and delignifying in an acetic acid-acidified sodium chlorite solution (Leavitt & Danzer, 1993). Holocellulose was combusted to CO_2 in the presence of excess oxygen in a recirculating microcombustion system. The CO_2 was measured mass-spectrometrically and results are expressed as $\delta^{13}C$ ($=[((^{13}C/^{12}C)_{sample}$, $(^{13}C/^{12}C)_{standard}) - 1] \times 1000$) in permil (‰) with respect to the international PDB standard (Craig, 1957). Repeated combustion and analysis of a holocellulose laboratory standard during the study gave a standard deviation of 0.27‰. This value is larger than the long-term reproducibility for analysis of the laboratory standard (*ca.* 0.2‰), but it is still quite satisfactory to distinguish and compare the isotopic patterns in this study.

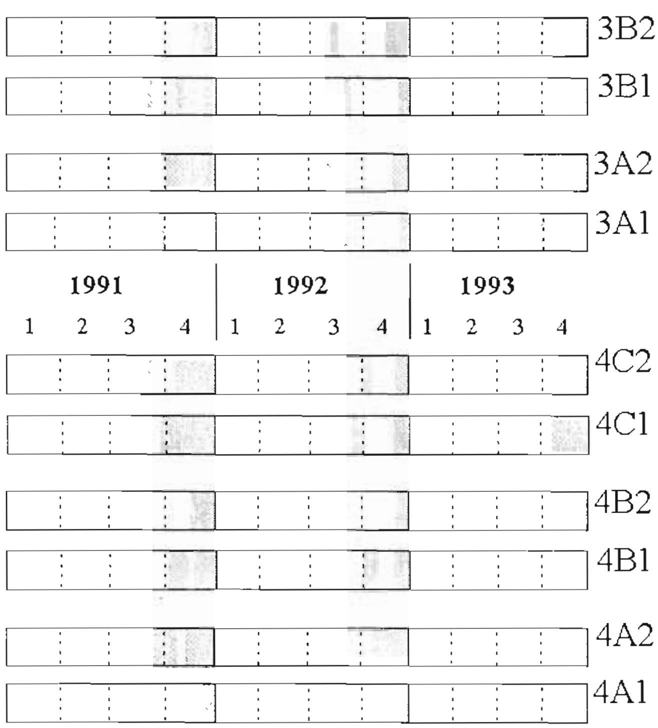

Fig. 3—Position of latewood bands (indicated by shading) in each of the tree rings, with growth proceeding from left to right. The rings were not actually the same width but the 4 subdivisions in each ring (dotted lines) were approximately equal width.

RESULTS AND DISCUSSION

The position of false latewood and latewood bands within each of the radial samples is depicted in Fig. 3. A false-latewood band appears in the majority of the rings, but it was not clearly identifiable in about 25% of the rings. The presence of false rings and at least partial latewood in most of the 1993 rings indicates that this year's xylem growth had nearly been completed by the time of the catastrophic flood. When present, the false-latewood band was always situated in either subdivision 3 or 4. In cross-sections 4A and 4B, false rings in all 3 years were obvious in only one of the two radii. The abundance of false rings in the cross-sections from higher in the trunk is consistent with observations by Fritts (1976) showing a trend of increasing occurrence of false rings with height in a ponderosa pine tree from Flagstaff, Arizona, USA.

The potential value of sampling more than one radius is underscored in the seasonal $\delta^{13}C$ results from the two opposite radii of cross-section 4C (Fig. 4). For the 1992 ring, the patterns are very similar and the absolute differences are small (<1‰). For the 1993 ring, however, the seasonal isotopic shifts are larger in radius 2, and the absolute differences between radii are 1-2‰ for most subdivisions. Many studies have found circumferential variability in the range of 0·5-1·0‰ (Francey, 1981; Leavitt & Long, 1984, 1986; Ramesh *et al.*, 1986) or 1-1·5‰ (Sheu *et al.*, 1996; Stuiver *et al.*, 1984), with variability up to 5‰ reported in the extreme (Tans & Mook, 1980). The mean of the radii at 1·7 m for 1993, however, appears to be fairly representative as suggested by its similarity to the 1993 patterns from the other 2 cross-sections of tree no. 4 and those of tree no. 3 (Figs 5 & 6).

The seasonal $\delta^{13}C$ patterns at most heights are quite similar, with some differences in absolute values (Figs 5 & 6). In tree no. 3, there is the suggestion that higher levels in the tree (8·2 m) are generally less negative than at 1m. In tree no.

4, however, only the 1992 ring shows increasing $\delta^{13}C$ from 1·7 m to 8·7 m to 12·5 m; for the 2 other years the 1·7 m height is most negative, but the 8.7 m height is least negative. Under some circumstances, more negative isotopic values have been found in the foliage of lower branches (Broadmeadow & Griffiths, 1993; Heaton & Crossley, 1995; Medina & Minchin, 1980; Medina *et al.*, 1991; Schleser & Jayasekera, 1985; Sternberg *et al.*, 1989) as a consequence of low light level reducing rates of photosynthesis and the contribution of isotopically light respired CO_2 mixing with the air below the canopy. Within tree rings, vertical $\delta^{13}C$ variability has been typically found in the range of 0·5-1·5% (Heaton, 1999; Leavitt & Long, 1986; Robertson *et al.*, 1995; Schleser, 1992), usually with ambiguous gradient with height. Integrated photosynthetic products dominantly from the upper crown would supply most of the ring development in the trunk, so that gradients are less likely than for leaves, unless there are some lower branches with leaves contributing a significant amount of carbon to part of the associated trunk.

The isotopic patterns for each year are not only consistent among heights in a tree, but they are also consistent between trees, although the $\delta^{13}C$ values of tree no. 3 are generally more negative than tree no. 4. The 1991 and 1993 rings are characterized by a seasonal pattern of increasing $\delta^{13}C$, generally to a maximum in subdivision 3 and then a sharp decline to subdivision 4. Because the false-latewood band is located in subdivision 4 or late in subdivision 3 of these years, the increasing $\delta^{13}C$ of subdivisions 1-3 would be consistent with increased moisture stress through spring and early summer prior to the monsoon onset. The drought relief following monsoon initiation would then be associated with the decline in $\delta^{13}C$. The 1992 ring of both trees shows increasing $\delta^{13}C$ generally sustained over all four subdivisions. This suggests that even after the onset of monsoon-related precipitation, moisture stress persisted. In a related study, living pine trees cored at breast height in 1996 from the lower Rhyolite Canyon in the Chiricahua Mts. (Leavitt *et al.*, 1999) showed similar patterns: $\delta^{13}C$ initially increasing to false-latewood and then decreasing for 1991 and 1993, and increasing throughout the growing season for 1992. The decline at the end of 1993 tended to be larger than in this study, again suggesting that the 1993 ring is not quite complete. In the other study, however, 3 unequal subdivisions were sampled including one after the false-latewood band that contained true latewood and the large-tracheid xylem immediately after the false ring, one containing the false ring, and the third prior to the false ring.

The average monthly climate conditions of the 3 study years (Fig. 7) provide insight into the prevailing environmental conditions at this site. Although the 1991-92 winter seems to have been somewhat cooler than the following winter, minimum and maximum temperatures during the 3 growing seasons do not exhibit distinctive differences. Palmer Drought Severity Index (PDSI) is an integrated climate index representing water status, with values of zero indicative of normal moisture conditions. Numbers above zero are progressively wetter and below zero progressively drier, with –4 being an "extreme" drought condition. The moisture status in 1991 and 1992 is driven largely by winter conditions, with PDSI decreasing from spring to late fall. In 1993, the declining PDSI is interrupted by a major abrupt increase in August. At the Chiricahua National Monument visitor center (near sampling site), it rained *ca.* 25 cm in August distributed over 23 of the 31 days, including 13.1 cm over the last 7 days (with 4.3 cm on the last day). A rainguage in the upper watershed recorded >17 mm on the last 2 days of August alone. The high and sustained August rainfall probably contributed to the strong upturn of PDSI from *ca.* –1 to +1.5.

Many of the features of these isotopic patterns are remarkably consistent with this climatology. The 1991 seasonal tree-ring $\delta^{13}C$ pattern records the monsoon onset with

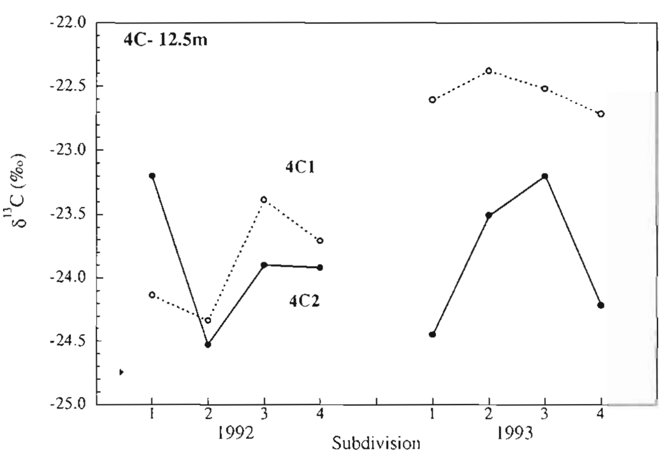

Fig. 4—Isotopic composition of the 1992 and 1993 rings along two opposite radii of the cross-section at 12·5 m above the root crown in Fig. 2.

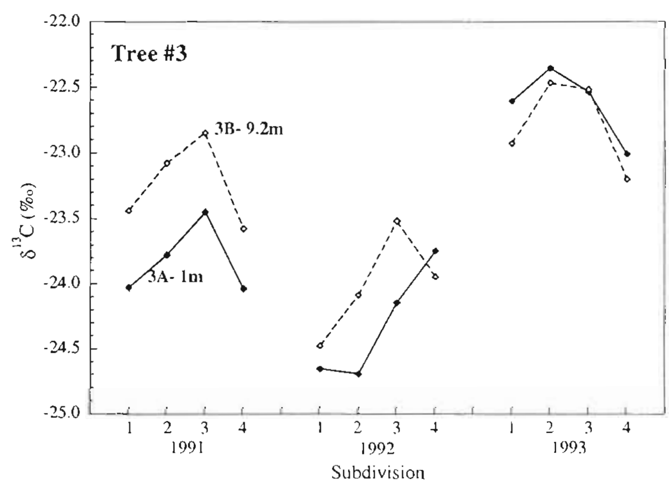

Fig. 5—Seasonal $\delta^{13}C$ patterns in growth rings of tree no. 3 at 1 m and 9·2 m heights in trunk.

declining $\delta^{13}C$ in subdivision 4, even though the monsoon moisture is not sufficiently above normal to increase PDSI. In 1992, the onset of declining spring PDSI was delayed until June, perhaps displayed in the 1992 first subdivision being much more negative than that in 1991 or 1993. Additionally, PDSI declines to lower values at the end of 1992 than either 1991 or 1993, consistent with the continued increase in $\delta^{13}C$ in subdivision 4. Depending on when the trees were killed by flooding, the $\delta^{13}C$ decline in subdivision 4 of the 1993 ring could represent the influence of the sustained August precipitation. Had the trees survived, subdivision 4 may likely have become much more negative than exhibited in our chronology. Also, the first subdivision in 1993 begins at a much less negative value than either 1991 or 1992, consistent with the relatively low spring PDSI values that were already starting to decline after February.

Because $\delta^{13}C_{air}$ can also influence $\delta^{13}C$ of the tree rings, the $\delta^{13}C_{air}$ values (Trolier *et al.*, 1996) at the closest air monitoring site (Niwot Ridge, Colorado, 40.05°N, 105.63°W) were also examined. For 1991-1993, the seasonal $\delta^{13}C_{air}$ fluctuated from *ca.*

−7.65‰ to −8.10‰, representing a range generally lower than the 0.5-1.0 ‰ seasonal variation seen in Figs 5 and 6. The most negative values are in March-April and the least negative values are in August-September. Furthermore, the other tree rings from living trees in Chiricahua National Monument (Leavitt *et al.*, 1999) show an amplitude of seasonal variation from 0.5-1.2‰ for 1991-1993, and 0.5-1.5‰ for 1985-1995. The $\delta^{13}C_{air}$ of local CO_2 undoubtedly contributes to $\delta^{13}C$ of tree rings at lower Rhyolite Canyon, but if Niwot Ridge is representative of the air in southeastern Arizona then it is probably not a first-order effect in the seasonal patterns.

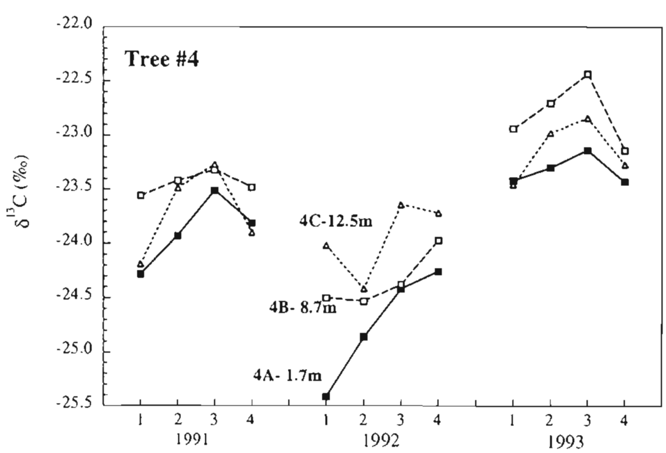

Fig. 6—Seasonal $\delta^{13}C$ patterns in growth rings of tree no. 4 at 1·7 m, 8·7 m and 12·5 m heights in trunk.

CONCLUSIONS

Seasonal tree-ring $\delta^{13}C$ patterns generally have the same shape at different heights, although there are differences in the absolute value and amplitude. This supports sampling all trees at a similar height for a seasonal isotope study.

Uncertainties remain about the exact provenance of both trees. However, the trees show both coherent patterns and similar variations in absolute values over the 3-years period.

The changing absolute values of $\delta^{13}C$ in successive years and the seasonal patterns within each of the 3 years seem best explained by records of drought index and rainfall when supplemented by knowledge of the location of the false ring within each series of subdivisions.

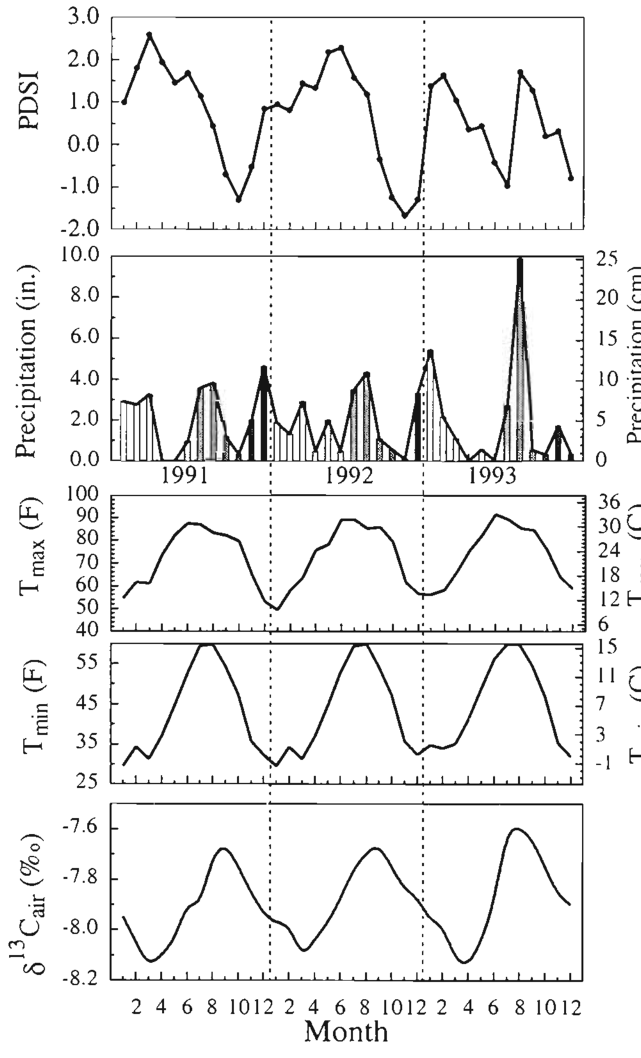

Fig. 7—The $\delta^{13}C_{air}$ of atmospheric CO_2 collected at Niwot Ridge, Colorado (after Trolier *et al.*, 1996), and Chiricahua National Monument climate station monthly mean minimum and maximum temperatures, monthly total precipitation, and Palmer Drought Severity Index (PDSI) for 1991 through 1993.

The $\delta^{13}C_{air}$ of local CO_2 should contribute to the tree-ring isotopic composition but the record available from Niwot Ridge, Colorado, exhibits seasonal variability of *ca.* 0.4‰ that is about one-half of the average seasonal tree-ring isotope variability and the shift may not be synchronous.

The seasonal trends contain environmental information, and given time constraints such as provided by false rings, the environmental information may be more fully exploited. An additional contributing factor, yet to be resolved, is the timing of xylem tracheid expansion versus construction of the cell wall, i.e., although the initial false-latewood cell formation may be timed in response to pre-monsoon hyper-arid conditions, the bulk of cell-wall thickening could occur in subsequent days/weeks. A large lag in these two events would necessitate development of empirical models based on environmental data specific to the period of the bulk of cell-wall formation rather than for the period at which the cells are initially expanded.

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