Summer precipitation influences the stable oxygen and carbon isotopic composition of tree-ring cellulose in *Pinus ponderosa*

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Summary The carbon and oxygen isotopic composition of tree-ring cellulose was examined in ponderosa pine (*Pinus ponderosa* Dougl.) trees in the western USA to study seasonal patterns of precipitation inputs. Two sites (California and Oregon) had minimal summer rainfall inputs, whereas a third site (Arizona) received as much as 70% of its annual precipitation during the summer months (North American monsoon). For the Arizona site, both the $\delta^{18}O$ and $\delta^{13}C$ values of latewood cellulose increased as the fraction of annual precipitation occurring in the summer (July through September) increased. There were no trends in latewood cellulose $\delta^{18}O$ with the absolute amount of summer rain at any site. The $\delta^{13}C$ composition of latewood cellulose declined with increasing total water year precipitation for all sites. Years with below-average total precipitation tended to have a higher proportion of their annual water inputs during the summer months. Relative humidity was negatively correlated with latewood cellulose $\delta^{13}C$ at all sites. Trees at the Arizona site produced latewood cellulose that was significantly more enriched in ^{18}O compared with trees at the Oregon or California site, implying a greater reliance on an ^{18}O-enriched water source. Thus, tree-ring records of cellulose $\delta^{18}O$ and $\delta^{13}C$ may provide useful proxy information about seasonal precipitation inputs and the variability and intensity of the North American monsoon.

Keywords: drought, humidity, isotopes, latewood, monsoon, pine, seasonal rainfall, wood.

Introduction

The oxygen isotopic composition of cellulose is primarily a function of the $\delta^{18}O$ of water taken up by plants (Anderson et al. 1998, Wright et al. 1998, Robertson et al. 2001). However, other environmental factors such as the $\delta^{18}O$ of atmospheric water vapor and factors that modify leaf water evaporative enrichment such as vapor pressure deficit also play an important role (Edwards et al. 1986, Lipp et al. 1996, Roden and Ehleringer 1999*b*). In addition, the $\delta^{18}O$ of cellulose is influenced by exchange with medium water at the site of synthesis (Sternberg et al. 1986, Yakir and DeNiro 1990, Roden and et al. 2000). Meteoric water $\delta^{18}O$ is a function of the environmental conditions at the point of initial evaporation of the moisture source (Wright et al. 2001), condensation temperature (Dansgaard 1964, Welker 2000) and Rayleigh distillation processes that occur as clouds advance across the landscape (Dansgaard 1964). Trees take up water from many sources including recent precipitation inputs, former precipitation inputs from deeper soil layers (winter recharge; Tang and Feng 2001), ground water derived from multiple year inputs and, in special cases, sea water and fog water (Ehleringer and Dawson 1992, Lin and Sternberg 1993, Dawson 1998, Dawson and Ehleringer 1998). Because the $\delta^{18}O$ of these water sources can vary widely, the $\delta^{18}O$ of tree ring cellulose may provide a unique opportunity to probe annual variation in plant water use and associated climate variation.

In certain regions, such as the southwestern USA, both summer and winter precipitation provide substantial portions of annual water inputs (Adams and Comrie 1997, Sheppard et al. 2002). In other regions (e.g., California and the Pacific Northwest), summer storm events are rare. These differences relate to the position of a dominant high-pressure system in the North Pacific during summer months (Barron et al. 2003), which influences convective storm formation with moisture originating from the eastern Pacific (the North American monsoon; Wright et al. 2001). Monsoonal precipitation in Arizona and New Mexico results from a shift in prevailing wind directions associated with a thermal low-pressure area located in the desert Southwest and a subtropical high-pressure located in the Azores (Adams and Comrie 1997, Sheppard et al. 2002).

There are indications that shifts in the interannual variation of summer precipitation inputs in the desert southwest have occurred over recent (Kim 2002) to millennial scales (Feng and Epstein 1994). Shifts in sea surface temperature associated with El Niño/La Niña Southern Oscillations (ENSO; Wright et al. 1998, Pendall 2000) and Pacific Decadal Oscillations (PDO; Sheppard et al. 2002) appear to modify the precipitation patterns of this region, with consequences across the North American continent. For example, because of a shift in flow patterns, heavy winter rains in the desert southwest often

coincide with unusually dry periods in the Pacific Northwest (i.e., Oregon; Sheppard et al. 2002). We expect these inter-annual variations in precipitation to be recorded in the $\delta^{18}O$ values of tree rings. Interannual and decadal variations in the North American monsoon can have significant impacts on both ecosystem function (Kim 2002) and human activities (Dettinger et al. 1998).

Precipitation arriving during the warm months of summer will be more enriched in the heavy isotopes of hydrogen and oxygen than winter precipitation (Dansgaard 1964, Mazor 1991). Therefore, plants that receive and rely on summer rain-fall inputs would be expected to have higher $\delta^{18}O$ values in their organic matter (Weiguo et al. 2004). Growth rings of long-lived trees, subfossil wood and archaeological remains provide a valuable record of variation in monsoonal precipitation (Fritts 1976, 1991), and can be subdivided into seasonal components (Fritts 1976). The latewood portion of a tree ring is produced near the end of the growing season and is expected to reflect summer water inputs.

However, the $\delta^{18}O$ in organic matter is a function of both water source and humidity (Edwards et al. 1986, Lipp et al. 1996, Roden and Ehleringer 1999b). Humidity strongly influences the output of a mechanistic model that predicts cellulose $\delta^{18}O$ values from environmental inputs (Roden et al. 2000). Thus, if summer rains bring reduced vapor pressure deficits and less evaporative enrichment, the increase in tree ring $\delta^{18}O$ with enriched summer water inputs could be less than ex-pected. In one recent study along a precipitation transect, Roden et al. (2005) found that differences in vapor pressure deficits between inland juniper and coastal spruce sites masked large differences in stem water $\delta^{18}O$ (> 5‰) producing nearly identical latewood $\delta^{18}O$ values. Precipitation amount may also affect organic matter $\delta^{18}O$ (Saurer 2003). Thus, to de-termine how precipitation timing and amount modifies cellulose $\delta^{18}O$ values, we studied sites that differed in summer water inputs but were similar in total precipitation, as well as sites that were similar in summer water inputs but differed in total precipitation.

Roden et al. (2005) found that their ability to de-convolute the information in the $\delta^{18}O$ of latewood cellulose could be en-hanced by including carbon isotope data. The $\delta^{13}C$ of organic matter is strongly related to water status and humidity (Comstock and Ehleringer 1992, Saurer et al. 1995, Stewart et al. 1995, Hemming et al. 1998). Stomatal closure associated with water stress or high vapor pressure deficits will reduce intercellular CO_2 concentrations and reduce discrimination against ^{13}C by Rubisco (Farquhar et al. 1982, 1989). Thus, $\delta^{13}C$ in organic matter has been used to estimate plant wa-ter-use efficiency (Hubick et al. 1986, Farquhar et al. 1989, Feng 1999). Summer rainfall amounts and timing may amelio-rate seasonal drought stress (Schwinning et al. 2002) and po-tentially affect organic matter $\delta^{13}C$. We expect the measure-ment of both carbon and oxygen isotopes to provide a useful approach to delineating source water and water status contri-butions to variations in isotopic composition of tree-ring cellu-lose.

The goal of our study was to assess how $\delta^{18}O$ and $\delta^{13}C$ of tree-ring cellulose respond to variation in summer precipita-tion inputs. We selected to study ponderosa pine (*Pinus pon-derosa,* Dougl.), a widely distributed, relatively long-lived co-nifer that produces easily distinguishable annual growth rings. It is the most common tree species at high elevations in the southwestern USA and occurs in extensive stands in eastern Oregon and California (Harlow et al. 1979). Our hypothesis was that trees growing at sites that differ in summer rainfall in-puts differ in their carbon and oxygen isotopic composition of latewood cellulose. Specifically, we predicted that: (1) trees in areas exposed to monsoonal precipitation inputs have higher latewood cellulose $\delta^{18}O$ values with increasing summer rain-fall inputs representing increased use of a water source more enriched in ^{18}O; (2) trees in areas exposed to monsoonal pre-cipitation inputs have lower values of latewood cellulose $\delta^{13}C$ because of reduced water stress and water-use efficiency dur-ing summer months; (3) trees in areas with little summer rain are less responsive to variation in summer rain in terms of both $\delta^{18}O$ and $\delta^{13}C$; (4) variation in relative humidity modifies both $\delta^{18}O$ and $\delta^{13}C$ values in tree ring cellulose through modifica-tions of evaporative enrichment (for $\delta^{18}O$) and water-use effi-ciency (for $\delta^{13}C$); and (5) between-site variation in total pre-cipitation (with similar summer inputs) affects cellulose $\delta^{13}C$ more strongly than $\delta^{18}O$.

Materials and Methods

Site locations, descriptions and sampling

In a preliminary study in 1997, cores were obtained from trees on three sites: one in Arizona (near the city of Show Low, 34°16′ N, 110° W, 1935 m a.s.l.); a second in California (near Bridgeport 38°26′ N, 119°26 W, 1900 m a.s.l.); and the third in Oregon (near Black Butte, 44°24′ N, 121°40′ W, 1090 m a.s.l.). In 2002, different locations (Table 1) were chosen for sampling that were better matched for precipitation inputs and temperature. They represented: (a) high annual precipitation sites, with high versus low proportions of summer rainfall (Ar-izona vs. California, Table 1); and (b) low summer precipita-tion sites with high versus low annual precipitation (California vs. Oregon). All sites were dominated by *Pinus ponderosa* of various ages (Table 1). The sites where chosen on slopes well above riparian zones to minimize the potential for ground wa-ter access. At each site, we sampled four healthy-looking trees between 40 and 75 cm in diameter that were either canopy dominants or subdominants. Cores (12 mm diameter) were obtained from the four cardinal directions near the base of each tree.

Sample processing and cellulose extraction

Annual growth increments over 40–45 years were measured to the nearest 0.01 mm on all cores. Cores were cross-dated based on total ring width (using the COFECHA program, Grissino-Mayer 2001, data not shown), and any ring anoma-lies were noted. Isotopic analysis was conducted on the tree rings from the three cores (analyzed separately) from each site that produced the highest correlations from the cross-dating

Table 1. Site descriptions. Mean and range precipitation data for the Arizona, California and Oregon sites were derived from 58, 47 and 40 years of weather station observations, respectively. The weather stations were located 3, 4 and 15 km from, and were offset 25, 160 and 42 m in elevation from, the trees at the Arizona, California and Oregon sites, respectively. Abbreviations: MAP, mean annual precipitation; MSP, mean summer precipitation; and MSP (%), the proportion of MAP occurring in the summer.

Site	Location	Elevation (m)	Approx. tree age (years)	Location of weather station	MAP (mm) (range)	MSP (mm) (range)	MSP (%) (range)
Arizona	33°51′ N, 109°10′ W	2493	40–250	Alpine, AZ	529.1 (282–799)	253.0 (140–542)	47.8 (25–70)
California	39°24′ N, 120°07′ W	1860	30–150	Boca, CA	567.7 (131–1078)	42.9 (0–173)	7.6 (0–26)
Oregon	44°24′ N, 121°40′ W	1090	25–200	Sisters, OR	351.5 (129–611)	32.8 (3–75)	9.3 (1–25)

analysis. Annual rings were subdivided into earlywood and latewood based on position and visual estimates of wood density (with the aid of a 20× dissecting microscope). The latewood cellulose from the annual rings was excised with a scalpel, and the samples from the four cardinal directions on a single tree were pooled and cut into small pieces with a razor blade. The samples were dried at 70 °C for 48 h and ground to a fine powder with a ball mill (Wig-L-Bug, Crescent, Elgin, IL). For the preliminary (1997) study, only 6 years were sampled (non-consecutive years chosen for differences in climate), whereas for the 2002 study, all the rings from the last 35 years were sampled.

About 50–100 mg of ground sample was loaded into fiber filter bags (ANKOM, Fairport, NY) that were then heat sealed for cellulose extraction. The procedure is modified from Leavitt and Danzer (1993, see also Gaudinski et al. 2005). Briefly, the filter bags were placed in a Soxhlet apparatus to reflux a 2:1 (v/v) mix of toluene:ethanol for 24-h, followed by a period of drying and another 24-h extraction (for lipids and resins) with 95% ethanol. The bags were dried and then boiled for 1 h to extract soluble sugars and low molecular mass polysaccharides. The samples were then "bleached" with a sodium chlorite:acetic acid solution that was periodically replaced over a 4-day extraction to remove lignin and other N containing compounds. To obtain pure α-cellulose, the sample was exposed to 17% (w/v) NaOH, followed by an acetic acid solution to neutralize the pH and extensive rinsing with double distilled water (Gaudinski et al. 2005). The α-cellulose was dried at 70 °C for 48 h.

Analysis of stable carbon and oxygen isotope ratios

For $\delta^{18}O$ measurements, 0.09–0.11 mg of α-cellulose was loaded into silver capsules and converted to CO by pyrolysis (Saurer et al. 1998) in a hot (1400 °C) alumina:glassy carbon reactor (Thermo-Finnigan TC/EA) and separated from other gases in a 0.6-m molecular sieve 5A gas chromatography (GC) column connected to a Finnigan MAT deltaPlus XL isotope ratio mass spectrometer. The mass spectrometers were located at the Stable Isotope Ratio Facility for Environmental Research at the University of Utah.

For $\delta^{13}C$ measurements, about 1 mg of α-cellulose was loaded into tin capsules and combusted in an elemental analyzer (Carlo-Erba 1110) coupled to a Finnigan MAT delta Plus isotope ratio mass spectrometer. The precision of α-cellulose standards run with the samples was 0.23‰ for $\delta^{18}O$ (standard deviation, $n = 36$) and was 0.16‰ for $\delta^{13}C$ ($n = 13$).

Climate data

Historical climate data were obtained from the Western Regional Climate Center (associated with the Desert Research Institute, www.wrcc.dri.edu). Monthly climate summaries were obtained for the weather station closest to each site. For the 1997 study, the stations were located in Show Low, AZ, Bridgeport, CA and Sisters, OR. For the 2002 study, the weather stations and general precipitation summaries are listed in Table 1. A water year, rather than a calendar year, was used to determine total annual precipitation. The water year was defined as October of the previous year through September of the current year. This definition relates best to the water inputs available to support tree growth associated with the current year's tree ring. Summer precipitation was defined as that recorded for the months of July through September. This clearly matches the greatest water inputs associated with monsoonal storm systems at the Arizona site (Figure 1). The three sites for the 2002 study were well matched in temperature, despite the great distances between them (about 1700 km between the Oregon and Arizona sites). Mean annual maximum temperatures were 16.1, 16.3 and 16.1 °C for the Arizona, California and Oregon sites, respectively. The sites were also similar in mean annual (< 1.5 °C between sites), mean growing season (< 1.4 °C, April to September), growing season mean maximum (< 1.6 °C) and growing season mean minimum (< 2.4 °C) temperatures.

Weather stations near our sites did not record relative humidity, so we used PRISM spatial climate layers (http://www.ocs.orst.edu/prism/index.phtml; Daly et al. 2002) to estimate mean dew point temperature at our site coordinates for each month of the growing season from 1967 to 2002. Relative humidity was then calculated from PRISM-derived air temperatures for spring (April to June) and summer (July to September) months. Regional Palmer Drought Severity Index
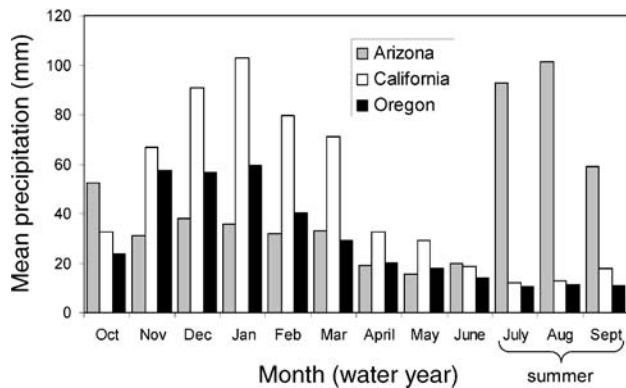
Figure 1. Mean monthly precipitation recorded at the weather stations closest to each site.

(PDSI; Palmer 1965) data for each site were obtained from the National Climate Data Center (NOAA, http://lwf.ncdc.no-aa.gov/oa/ncdc.html). Information on monthly snow depth from nearby stations was obtained from SNOTEL datasets (USDA, Natural Resource Conservation Service, http://www-.wcc.nrcs.usda.gov/snow). Correlation analysis based on Pearson's correlation coefficients was performed with SPSS 11.0 software (SPSS, Chicago, IL).

Results

Time series of tree ring and environmental measurements

Trees at the Arizona site had consistently more ^{18}O-enriched latewood cellulose than trees at either the Oregon or California site (Figure 2A). Mean (and range) latewood $\delta^{18}O$ was 35.1 (3.2), 30.8 (2.9) and 29.6 (3.9)‰ for trees growing at the Arizona, California and Oregon sites, respectively. The maximum variation in latewood $\delta^{18}O$ between two consecutive years was between 3 and 4‰ for trees at all sites, indicating that tree ring $\delta^{18}O$ records interannual variation in environmental inputs. Tree-ring $\delta^{13}C$ was less variable between sites than $\delta^{18}O$ (Figure 2B). Mean (and range) latewood $\delta^{13}C$ was –22.4 (2.0), –22.0 (2.3) and –23.2 (1.9)‰ for trees growing at the Arizona, California and Oregon sites, respectively. Trees growing at the Arizona site had the greatest interannual variation in ring widths, whereas trees growing at the Oregon site produced the least (Figure 2C). Mean (and range) ring width was 2.40 (2.77), 2.29 (1.32) and 2.00 (0.99) mm for trees growing at the Arizona, California and Oregon sites, respectively.

In general, the Oregon site experienced higher relative humidities than the other sites (Figure 3A), with the exception of the summer months when the Arizona site was normally more humid (data not shown). Mean (and range) growing season relative humidity (PRISM modeled) was 18.7 (7.1), 21.6 (11.5) and 27.7 (10.8)% for the Arizona, California and Oregon sites, respectively. Water year precipitation (Figure 3B and Table 1) was more variable at the California site than at the other sites. Interannual variation in water year precipitation between consecutive years was as high as 517, 747 and 353 mm for the Ari-
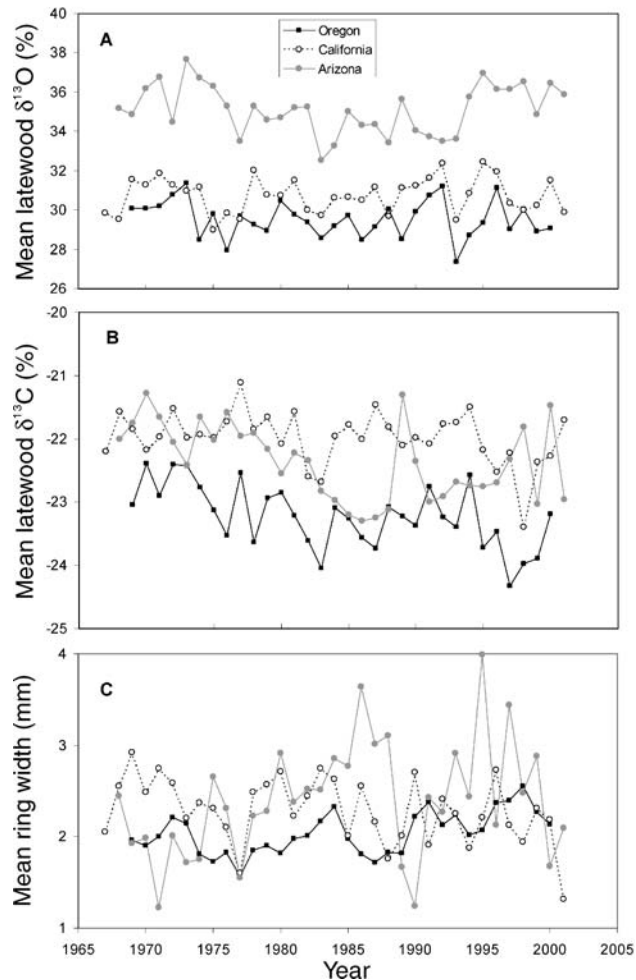

Figure 2. Time series of the mean ($n = 3$) latewood cellulose $\delta^{18}O$ (panel A), $\delta^{13}C$ (panel B) and annual growth increment (panel C) for ponderosa pine trees growing at three sites in the western USA. Mean between-tree variation (standard deviation) was 1.85, 0.81 and 1.07 for $\delta^{18}O$ (panel A); 0.99, 0.34 and 0.64 for $\delta^{13}C$ (panel B); 0.86, 0.59 and 0.75 for ring width (panel C) for the Oregon, California and Arizona sites, respectively.

zona, California and Oregon sites, respectively. Trees growing at the Arizona site received a greater proportion of their total water inputs as summer rain (Figure 3C and Table 1). Interannual variation in the amount of summer rain as a percent of total precipitation was also greater at the Arizona site, with differences from one year to the next as high as 46.5%.

Correlations between tree ring measurements and precipitation inputs

Table 2 presents correlation coefficients between rainfall parameters and tree ring isotope and width measurements. The correlation between summer rain as a percent of total water year precipitation and cellulose $\delta^{18}O$ was significant for trees at the Arizona site (slope = 0.038‰ %$^{-1}$) but not for trees at sites with minimal summer rainfall inputs (Oregon and Cali-
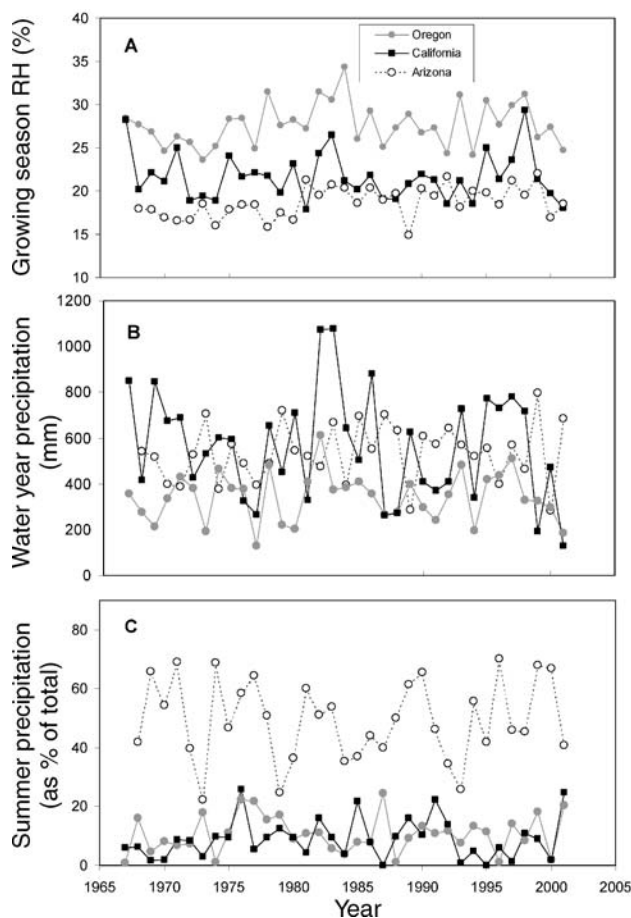
Figure 3. Time series of the growing season (April to September) relative humidity as estimated by the PRISM model (panel A), water year precipitation (panel B) and the amount of summer precipitation inputs as a proportion of total water year precipitation (panel C) for three sites in the western USA.

fornia). There were no significant correlations between the absolute amount of summer rainfall and $\delta^{18}O$ in latewood cellulose for trees at any site. Thus, the amount of summer rain as a percentage of total water year precipitation appears to be a more valuable indicator of summer water use than the absolute amount.

There was a significant decline in latewood cellulose $\delta^{18}O$ in trees at the Arizona site for years with high total water year precipitation (Table 2; slope $= -0.0038$‰ mm^{-1}). No significant correlations between total water year precipitation and tree ring $\delta^{18}O$ were observed for trees at the Oregon and California sites. Preliminary data from 1997 showed no trends in $\delta^{18}O$ of latewood cellulose with total water year precipitation (data not shown), but showed an increase in cellulose $\delta^{18}O$ with increased amounts of summer rain for the Arizona site only (Figure 4). Although the sites sampled during 2002 were better matched in total precipitation and proportion of summer rain than the sites included in the preliminary 1997 study, the similarity of the results in these studies imply that our findings may be general and apply on broad regional as well as local

scales.

Latewood cellulose $\delta^{13}C$ values were higher for trees at the Arizona site for years in which trees received a greater proportion of their annual water inputs as summer rain (Table 2, slope $= 0.021$‰ %$^{-1}$). However, there appeared to be no relationship between latewood cellulose $\delta^{13}C$ values and summer rain (as a percent of total precipitation) for trees at the Oregon and California sites. For all three sites, there was a significant negative correlation between total water year precipitation and latewood cellulose $\delta^{13}C$. The slopes were -0.0033, -0.0010 and -0.0025‰ mm^{-1} for the Arizona, California and Oregon sites, respectively. Trees at all sites exhibited a negative relationship (significant for the Oregon and California sites) between $\delta^{13}C$ in latewood cellulose and total summer rain (Table 2).

Carbon isotope discrimination ($\Delta^{13}C$) was calculated (Farquhar et al. 1982) to correct for changes in atmospheric $\delta^{13}C$ (estimated from Francey et al. 1999). Although using $\Delta^{13}C$ changed the sign of correlations ($\Delta^{13}C$ values are positive, whereas $\delta^{13}C$ values are negative) with precipitation patterns and amounts, there were only minor changes in correlation coefficients or their significance (data not shown). This was expected because the $\Delta^{13}C$ correction should have a greater influence on low frequency (decadal to millennial) variation in atmospheric conditions than high frequency (annual and seasonal) variation in precipitation patterns.

Ring widths of trees at the Arizona site were negatively correlated with summer rain as a percent of total water year precipitation (Table 2; slope $= -0.026$ mm %$^{-1}$). Changes in summer precipitation did not seem to alter ring width of trees at the Oregon and California sites. There was no significant correlation between absolute summer rainfall amount and mean ring width for trees at any site. Trees growing at the Arizona and California sites had significant positive correlations between total water year precipitation and mean ring width, but the relationship was not strong at either site (slopes $= 0.0022$ and 0.0008 mm mm^{-1} for Arizona and California trees, respectively).

Although there were significant positive correlations between the amount of summer rain and total water year precipitation (Table 2), there were significant negative correlations between summer rain as a percent of total precipitation and total water year precipitation. This implies that years that have a higher proportion of water inputs in the summer months are years that tend to be drier than normal. This relationship was particularly strong for the Arizona site.

An often-used indicator of water stress is the Palmer Drought Severity Index (PDSI; Palmer 1965). The only significant correlations of monthly PDSI estimates and tree-ring $\delta^{18}O$ were observed for the summer period and for trees at the Arizona site (Figure 5A). For all sites, correlations of monthly PDSI and tree ring $\delta^{13}C$ were consistently negative. The correlations were significant for virtually every month for trees at the Arizona and California sites, whereas trees at the Oregon site produced fewer significant correlations with PDSI (Figure 5B). Latewood cellulose $\delta^{13}C$ values were also negatively correlated with both the maximum winter and April snow-pack measurements (from SNOTEL stations nearest to

Table 2. Correlation between rainfall parameters from nearby weather stations and the latewood cellulose $\delta^{18}O$ and $\delta^{13}C$ values as well as mean ring width of trees growing on three sites that differed in the amounts of summer precipitation inputs. Summer rain (SR) refers to the sum of the precipitation received at that site during the months of July, August and September. Summer rain as a percent of total is calculated as a percentage of annual water year precipitation (WYP), which is the sum of monthly values starting with October of the previous year and ending with September of the current year. Values are Pearson's correlation coefficients with the P value in parentheses. Significant correlations are indicated by asterisks: **, $P < 0.01$; and *, $P < 0.05$.

Arizona			California			Oregon		
SR	SR (% of total)	WYP	SR	SR (% of total)	WYP	SR	SR (% of total)	WYP
$\delta^{18}O$ of latewood cellulose								
−0.004	0.457**	−0.431*	−0.147	−0.163	0.011	−0.151	−0.040	−0.191
(0.984)	(0.010)	(0.015)	(0.398)	(0.350)	(0.950)	(0.410)	(0.827)	(0.296)
$\delta^{13}C$ of latewood cellulose								
−0.215	0.437*	−0.668**	−0.395*	−0.028	−0.583**	−0.450**	−0.004	−0.505**
(0.245)	(0.014)	(< 0.01)	(0.019)	(0.875)	(< 0.01)	(0.010)	(0.983)	(< 0.01)
Mean ring width								
−0.050	−0.526**	0.427*	0.095	−0.322	0.521**	−0.029	−0.092	0.072
(0.791)	(< 0.01)	(0.017)	(0.586)	(0.059)	(< 0.01)	(0.874)	(0.610)	(0.692)
Water year precipitation								
0.466**	−0.458**		0.405*	−0.250		0.315	−0.363*	
(< 0.01)	(0.010)		(0.016)	(0.147)		(0.074)	(0.038)	

our sites); however, the correlations were significant for the California site only (data not shown).

Tree ring measurements and relative humidity

Table 3 presents the Pearson correlation coefficients between humidity parameters and tree-ring isotope and ring width mea-

Figure 4. Effect of summer rain as a percent of total water year precipitation on the $\delta^{18}O$ of latewood cellulose of pine trees. This preliminary dataset was collected in 1997 at different field sites to those of the 2002 study. The tree rings sampled for the 1997 study were not consecutive, but were chosen from years with distinct differences in summer rainfall.

surements. All correlation coefficients for the relationship between latewood cellulose $\delta^{18}O$ and relative humidity (spring, summer or entire growing season) were negative, indicating that the reduction in leaf evaporative enrichment due to increased humidity was recorded in tree-ring $\delta^{18}O$. However, correlations with summer humidity were significant for the Oregon and California sites only. The greatest slope ($-0.142‰\ \%^{-1}$) was for trees at the California site, indicating that for every 10% increase in summer relative humidity, the $\delta^{18}O$ of latewood cellulose declined by 1.42‰.

All correlation coefficients for the relationship between latewood cellulose $\delta^{13}C$ and relative humidity were significant and negative (Table 3), indicating that the effect of increased humidity on enhanced water-use efficiency in leaves was recorded in tree-ring $\delta^{13}C$. The slopes ranged from -0.101 to $-0.216‰\ \%^{-1}$, implying that for a 10% increase in relative humidity (irrespective of season), $\delta^{13}C$ of latewood cellulose declined between 1 and 2‰.

Diameter growth of ponderosa pine trees located at the Oregon and California sites was unresponsive to changes in relative humidity (Table 3). Trees at the Arizona site increased ring width in response to increased relative humidity, especially during spring. The hyperarid period (from April to June) is particularly important for the hydrology of plants growing in Arizona, and any increase in moisture during spring could increase plant growth. Relative humidity was positively correlated with precipitation inputs (data not shown), as expected because the PRISM model (Daly et al. 2002) uses meteorological data, including precipitation, from local weather stations to make interpolations of dew point temperature at different locations.
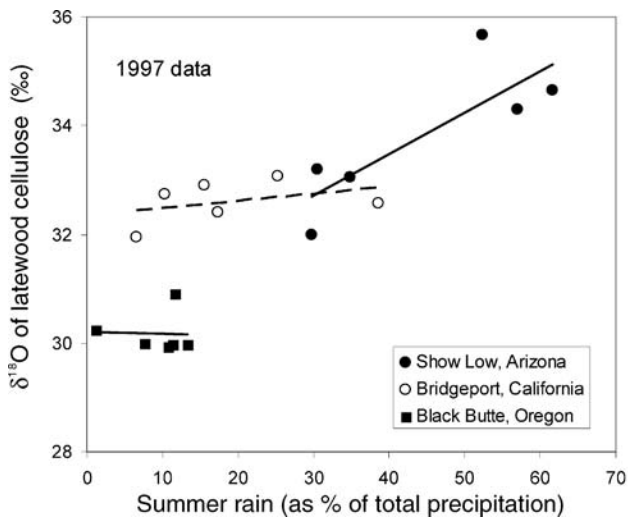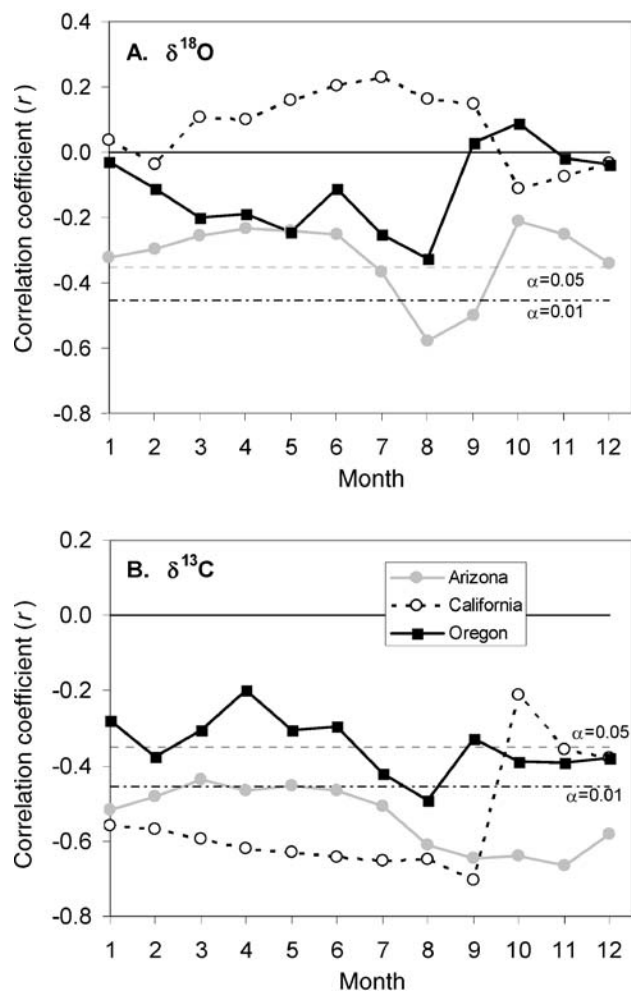
Figure 5. Pearson's correlation coefficients between latewood cellulose $\delta^{18}O$ (A) or $\delta^{13}C$ (B) and monthly Palmer Drought Severity Index for each site. Horizontal lines indicate significance of correlations. Symbols: ●, Arizona; ○, California; and ■, Oregon.

Discussion

Tree-ring chronologies are a valuable resource for probing climate variation. Chronologies can use variation in ring widths (Schulman 1956), ring density (Fritts 1976, Schweingruber 1990), ring structure (false latewood bands; Wright et al. 1998, Meko and Baisan 2001), and the carbon, hydrogen and oxygen isotopic composition of organic matter (Edwards and Fritz 1986, Saurer et al. 1995, Anderson et al. 1998, Hemming et al. 1998, Pendall, 2000, Robertson et al. 2001) as proxies for a variety of climate parameters (e.g., temperature, precipitation, humidity). Our study extends the use of tree ring information to examination of seasonal water inputs and their importance to tree water balance.

Comparison of preliminary results (1997 sampling) with those from our larger dataset (2002 sampling) showed a consistent pattern in cellulose $\delta^{18}O$ values. Trees from regions that received a larger fraction of their total precipitation as summer rain produced cellulose in the latewood region of the tree ring that was more enriched in ^{18}O. These results support our hypothesis that summer rainfall inputs enriched in ^{18}O will be recorded in latewood cellulose. The lack of relationship between latewood cellulose $\delta^{18}O$ and total water year precipitation was also relatively consistent between the 1997 and 2002 studies. In contrast, Weiguo et al. (2004) found a positive correlation between annual precipitation and tree-ring $\delta^{18}O$ in Chinese pine; however, whole rings were measured in their study rather than latewood. Although our preliminary study lacked sufficient statistical power to allow definite conclusions about summer water use, the similarity in patterns among sites separated by over 100 km (e.g., Show Low versus Alpine Arizona) demonstrate that the results from the 2002 study were not simply a local phenomenon.

For the Arizona site, significant correlations were observed between latewood cellulose $\delta^{18}O$ values and the proportion of total precipitation that came in summer months, but not with

Table 3. Correlation between relative humidity (RH) developed from the PRISM model and the latewood cellulose $\delta^{18}O$ and $\delta^{13}C$ values as well as mean ring width of trees growing on three sites that differed in the amounts of summer precipitation inputs. Spring RH values represent mean PRISM estimates for April, May and June. Summer RH values represent mean PRISM estimates for July, August and September, and growing season RH values represent mean estimates for all six months. Values are Pearson's correlation coefficients with the P value in parentheses. Significant correlations are indicated by asterisks: **, $P < 0.01$; and *, $P < 0.05$.

Arizona			California			Oregon		
Spring RH	Summer RH	Growing Season RH	Spring RH	Summer RH	Growing Season RH	Spring RH	Summer RH	Growing Season RH
$\delta^{18}O$ of latewood cellulose								
−0.291	−0.209	−0.334	−0.117	−0.381*	−0.251	−0.056	−0.377*	−0.255
(0.112)	(0.259)	(0.067)	(0.503)	(0.024)	(0.145)	(0.759)	(0.031)	(0.153)
$\delta^{13}C$ of latewood cellulose								
−0.574**	−0.386*	−0.639**	−0.548**	−0.639**	−0.678**	−0.361*	−0.566**	−0.600**
(< 0.01)	(0.032)	(< 0.01)	(< 0.01)	(< 0.01)	(< 0.01)	(0.039)	(< 0.01)	(< 0.01)
Mean ring width								
0.566**	0.196	0.496**	0.086	0.210	0.154	0.216	0.028	0.186
(< 0.01)	(0.291)	(< 0.01)	(0.625)	(0.226)	(0.378)	(0.227)	(0.877)	(0.300)

the absolute amount of summer rain. This implies that it is not simply the amount of ^{18}O-enriched rain that falls in the summer that causes enrichment in cellulose $\delta^{18}O$, but how important that rain is to whole-plant water balance. The effect of precipitation events on the water balance of a tree depends on the amount of soil water present at the beginning of each event (Landsberg and Gower 1997). In addition, the intensity and duration of summer storm events can determine whether precipitation inputs infiltrate soils deeply and become a usable resource, or whether they are mainly lost to evaporation or runoff. Studies in desert ecosystems have shown that the ability of plants to utilize a pulse of water (a significant rain event) varies depending on species (functional type), rooting depth and season (Ehleringer et al. 1999).

Overall, the latewood cellulose of trees at the Arizona site was enriched in [18]O by 5‰ compared with the Oregon or California sites, indicating that reliance on summer rain is recorded in tree-ring cellulose. Site differences in relative humidity may have have influenced cellulose $\delta^{18}O$ through its effects on leaf evaporative enrichment (Roden and Ehleringer 1999*a*). However, growing season humidity was only 9% lower at the Arizona site compared with the Oregon site. A mechanistic model developed to predict $\delta^{18}O$ in organic matter using environmental inputs (Roden et al. 2000) predicts that a 9% decrease in relative humidity would modify cellulose $\delta^{18}O$ values by 2‰. This approximation may be high because minimal differences in relative humidity between sites were estimated during summer months when latewood cellulose would have been constructed ($< 5\%$, with the Arizona site having the highest summer humidity). This analysis does not take into consideration the effects of humidity on secondary evaporation of water sources that can influence needle cellulose $\delta^{18}O$ (Wright and Leavitt 2005). However, secondary evaporation during summer months further enriches summer precipitation, more clearly distinguishing it from predominately winter sources (Oregon and California). Oxygen isotope ratios of precipitation and resulting organic matter can be correlated with temperature; however, this cannot explain the differences between sites because there were minimal differences in maximum and mean temperatures among sites. In addition, correlation analysis of the interannual variation in latewood cellulose $\delta^{18}O$ with mean, maximum and minimum temperatures over an annual growing season or summer period were not statistically significant (with the one exception of growing season mean temperature at the California site, data not shown). Although it cannot be ruled out that other environmental differences between the sites played a role in modifying cellulose $\delta^{18}O$ values, the similarity between the sites in humidity, temperature and total water year precipitation, as well as comparable results for tree-ring cellulose $\delta^{13}C$ and ring widths, indicate that precipitation inputs enriched in [18]O are likely the major cause of higher $\delta^{18}O$ values in trees at the Arizona site. Thus, differences in the timing of precipitation events appear to be recorded in the differences in the $\delta^{18}O$ of latewood cellulose for these trees. This alone suggests that long-term tree-ring $\delta^{18}O$ records may contain valuable information about changes in monsoonal precipitation patterns in the southwestern United States.

Ponderosa pine trees growing at the Oregon and California sites responded (in organic matter $\delta^{18}O$, $\delta^{13}C$ and ring widths) similarly to changes in environmental inputs, whereas trees growing at the Arizona sites were more distinct. The Oregon and California sites received similar amounts of summer rain, but the Oregon site had substantially less total annual precipitation, which implies that it is geographic differences in summer rainfall inputs, not total precipitation, that mainly determines tree-ring isotopic variation. The data also support our predictions that sites with more limited summer rainfall inputs are less responsive (especially in terms of latewood cellulose $\delta^{18}O$) to summer rainfall variation.

In contrast to our predictions, the $\delta^{13}C$ values of latewood cellulose for trees at the Arizona site increased when the trees received a greater proportion of their water inputs as summer rain. However, as predicted from carbon isotope theory (Farquhar et al. 1989) and found in other studies (Saurer et al. 1995, Stewart et al. 1995, Leavitt et al. 2002), $\delta^{13}C$ values in trees at all sites declined with increasing water status as measured by total water year precipitation (Table 2) or PDSI (Figure 5). Years with a high proportion of total precipitation coming in the summer months tended to be years with low total precipitation. This implies that, when winter recharge of soil water is less than normal, the summer precipitation inputs become increasingly important, but plants may still be conservative in water use because of an overall water deficit. We speculate that as needles age they may become less responsive to late summer increases in soil water, especially if they developed under water-limited conditions.

The $\delta^{13}C$ values of latewood cellulose were negatively correlated with the absolute amount of summer rainfall and that relationship was strongest for the Oregon and California sites. Negative correlations between $\delta^{13}C$ and summer precipitation have also been found in spruce latewood cellulose (Treydte et al. 2001) and cellulose from post-false latewood bands in pine (Leavitt et al. 2002). Our results indicate that, at sites with minimal summer rainfall inputs, greater than normal summer rain events can have a larger impact on tree water status than in regions that normally receive a large portion of their water inputs in the summer. A study in the Pacific Northwest (Peterson and Peterson 2001) showed that the growth of mountain hemlock was positively correlated with summer precipitation for dry sites but not for wet sites.

Our ring width measurements indicate that the absolute amount of summer rain is less important to diameter growth than overall water deficit. Ring width was negatively correlated (for trees at the Arizona site) with the proportion of total precipitation that came in the summer months and positively correlated with total water year precipitation (for trees at the Arizona and California sites). Positive relationships between ring widths and precipitation are common in the southwest USA (Schulman 1956, Fritts 1976), and some studies have demonstrated that the width of the latewood band may be a more sensitive indicator of summer rainfall inputs than total ring width (Meko and Baisan 2001, Leavitt et al. 2002, Watson and Luckman 2002).

The arid land ecosystems dominating regions of the southwest USA are sensitive to the variability and timing of rainfall events (Ehleringer et al. 1999). Thus, changes in precipitation patterns or shifts in the monsoon climatic boundary, or both, would impact ecosystem function and plant distribution in this region. Monsoonal precipitation patterns may be influenced by teleconnections with sea surface temperature in the Pacific Ocean (Carleton et al. 1990, Higgins et al. 1998, Wright et al. 1998) and different phases of the ENSO cycle may affect summer precipitation patterns in the desert southwest (Andrade and Sellers 1988, Carleton et al. 1990). Thus, global change and associated modifications of the frequency and strength of ENSO events (Wang 1995, Trenberth 1997) are likely to have important impacts on the hydrologic cycle in this region. For example, shifts in precipitation anomalies associated with the North American Monsoon may have occurred in the middle of the 20th century (Kim 2002). However, the cause of these changing precipitation patterns since 1960 is unclear because of the lack of long-term records (Kim 2002).

Historical records of precipitation patterns for this region could be provided by tree-ring analysis of ancient trees, especially *Pinus ponderosa*, because of its wide distribution and longevity. However, ring widths alone may not provide a clear picture of summer rainfall inputs. Our results demonstrate that stable isotope analysis of latewood cellulose can provide another way to probe historic precipitation patterns. Other studies (Feng et al. 1999, Weiguo et al. 2004) have successfully used tree-ring hydrogen isotope ratio (δD) and $\delta^{18}O$ values as a proxy for monsoon intensity in Asia. Pendall (2000) found that δD composition of cellulose from piñon pine (*Pinus edulis* Engelm.) needles collected from New Mexico, USA, were correlated with summer rainfall amounts as well as with ENSO events. Wright et al. (1998) found a strong relationship between summer rainfall $\delta^{18}O$ and cellulose $\delta^{18}O$ extracted from false latewood bands in ponderosa pine in Arizona. In addition, Leavitt et al. (2002) showed that $\delta^{13}C$ of pine tree rings can be correlated to summer precipitation amount, drought severity and ENSO events. These studies in combination with our results confirm the usefulness of stable isotope analysis of latewood cellulose for documenting historic variation in the North American monsoon climate system.

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