South American tree rings show declining $\delta^{13}C$ trend

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ABSTRACT

A composite, 290-year tree-ring $\delta^{13}C$ chronology was developed from a site in Chile where 5 *Fitroya cupressoides* (alerce) trees were sampled, 2 increment cores per tree, and the holocellulose component was analyzed in 5-year ring groups. This chronology shows a decreasing $\delta^{13}C$ trend of approximately $1.2°/_{oo}$, primarily since the turn of this century. This $\delta^{13}C$ decline is similar to that of major tree-ring studies in the Northern Hemisphere, but it is the only major Southern Hemisphere study which clearly exhibits a $\delta^{13}C$ trend. This is the first evidence for any interhemispheric reproducibility of tree-ring $\delta^{13}C$ chronologies, and furthermore, the *Fitzroya* $\delta^{13}C$ trend conforms well to that of $\delta^{13}C$ of atmospheric CO_2 determined from ice cores and direct measurements. This correspondence suggests the alerce $\delta^{13}C$ trend has not been substantially influenced by systematic changes in environmental factors such light, relative humidity and soil moisture or by changing atmospheric CO_2 concentration, all of which are, in theory, capable of altering C_i/C_a ratios and obscuring the atmospheric $\delta^{13}C$ record contained in the tree rings.

1. Introduction

Efforts have been made to reconstruct changes in $\delta^{13}C$ of atmospheric CO_2 as important to constraining global carbon cycle models and deriving the history of biospheric CO_2 emissions (Siegenthaler and Oeschger, 1987; Leuenberger et al., 1992). Such reconstructions (compared for post-1900 in Fig. 1) have employed $\delta^{13}C$ measurements in tree rings (Peng et al., 1983; Freyer and Belacy, 1983; Stuiver et al., 1984; Leavitt and Long, 1988, 1989a), and more recently $\delta^{13}C$ measurements in C_4 plants (Marino and McElroy, 1991) and direct measurements of $\delta^{13}C$ in ice cores (Friedli et al., 1986). In theory, C_4 plants are more reliable atmospheric $\delta^{13}C$ monitors because plant $\delta^{13}C$ is much less influenced by the ratio of intercellular to atmospheric CO_2 concentrations (C_i/C_a) than is the case for C_3 plants

(trees). In addition to C_i/C_a and atmospheric CO_2 $(\delta^{13}C_{air})$, the $\delta^{13}C$ of C_3 plants also depends on constants a and b representing CO_2 diffusion and RuBP carboxylase fractionation, respectively (Farquhar et al., 1982):

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

In principle, the C_i/C_a term is governed by rates of stomatal conductance and carbon assimilation, and can be influenced by conditions of water, light and relative humidity. Because of this C_i/C_a dependence, it is possible for $\delta^{13}C_{plant}$ to shift even if $\delta^{13}C_{air}$ is constant.

One of the characteristics of the above $\delta^{13}C$ chronologies is that they show a decline in $\delta^{13}C$ of approximately $1–2°/_{oo}$ from the beginning of the industrial revolution to the present, frequently inferred to represent inputs of ^{13}C-depleted CO_2 to the atmosphere from fossil-fuel burning and biospheric activities largely related to land-use changes. Although major Northern Hemisphere
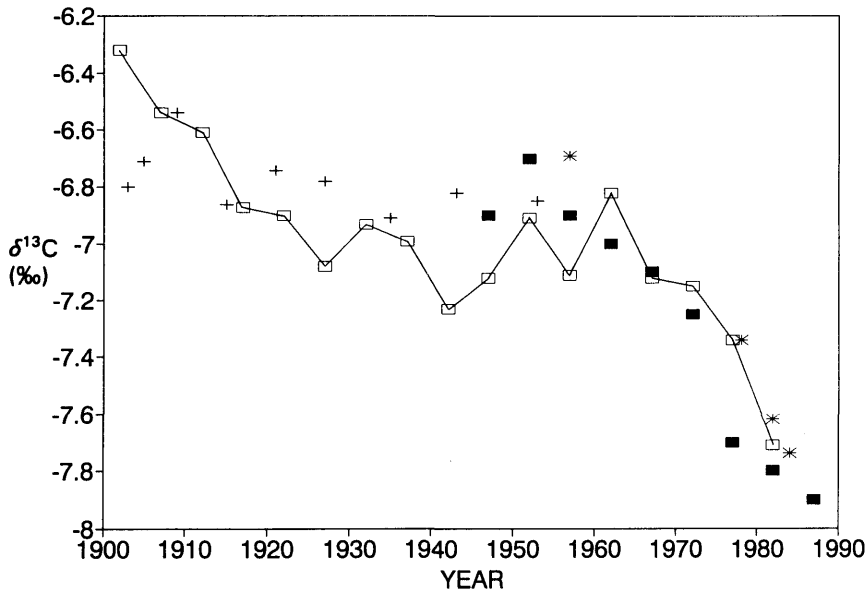
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Fig. 1. Post-1900 comparison of δ^{13}C trends from C_3 tree rings ($\square$, Leavitt and Long, 1989), C_4 corn ($\blacksquare$, Marino and McElroy, 1991), ice cores ($+$, Friedli et al., 1986), and direct atmospheric measurements ($*$, Friedli et al., 1986; Keeling et al., 1979, 1980) as 5-year averages. The tree-ring curve is adjusted into place by assigning the 1978 measured air value of $-7.34°/_{oo}$ to the 1975–79 pentad.

tree-ring chronologies show such a decline, Francey (1981a, 1981b) found no trend of δ^{13}C in rings of seven trees from Tasmania. Subsequently, Francey and Farquhar (1982) inferred that knowledge of C_i/C_a variation is critical to calculating $\delta^{13}C_{air}$ from tree rings, and can account for differences in trends and absolute δ^{13}C change among tree-ring chronologies.

In this study, we report a new, site-representative δ^{13}C chronology at a locale in southern Chile. We also test this chronology as representative of the atmosphere by means of the $\delta^{13}C_{air}$ chronologies now available from ice core measurements. The species analyzed, *Fitzroya cupressoides* (locally known as alerce), is a large, long-lived conifer endemic to southern Chile and adjacent portions of Argentina, similar in habitat to the North American coastal redwoods (*Sequoia sempervirens*) (Veblen et al., 1976). *Fitzroya* can grow up to 5 m in diameter, 50 m in height, and achieve an age of up to 3,622 years (Veblen et al., 1976). *Fitzroya* has recently been used to develop a 3620-year temperature reconstruction (Lara and Villalba, 1993).

2. Methods

Tree cores were collected from within a forested area of approximately 1 km^2 in Alerce Andino National Park near Puerto Montt (41°30'S, 72°33'W) at an elevation of 450 m. Soils at Alerce Andino National Park have high organic matter content (30–100% in the upper horizon), low pH (4.0–5.1), and high C/N ratios (CONAF, 1985). Climate of the study area is characterized by high annual precipitation with somewhat reduced rainfall in summer, classified as oceanic wet temperate with mild Mediterranean influence (Fuenzalida, 1950; Di Castri and Hajek, 1976). Meteorological records for Lago Chapo located within 13 km of the study site at 240 m elevation indicate 4140 mm of annual precipitation and a mean annual temperature of 10.3°C (ENDESA, 1990). The sampled *Fitzroya cupressoides* trees were the dominant species in these mixed, old-growth forests, with a crown cover of approximately 50%.

For this study, 2 cores from each of 5 *Fitzroya* trees were collected with increment borers in

March 1989. Leavitt and Long (1984) have demonstrated the importance of taking such multiple samples to accurately represent the $\delta^{13}C$ chronology of a site. Diameter at breast height of the cored trees ranged from 100 to 260 cm and their minimum age ranged from approximately 608 to 996 years. Cores were surfaced, crossdated for the period 1700–1987 and ring widths were measured following standard methods (Stokes and Smiley, 1968; Robinson and Evans, 1980; Holmes, 1983). Schulman's (1956) convention of assigning the date of the tree ring to the calendar year in which ring growth begins was adopted, i.e., the 1987 ring was formed from around October 1987 through March 1988. The 10 cross-dated cores were split longitudinally, with one half taken for stable-carbon isotope analysis. Each core was then carefully separated into successive tree-ring pentads (1700-04, 1705-09, etc.) with a razor knife. The pentads were pooled from all 10 cores with the exception that around every 50 years the pentads from each tree were processed separately to determine the variability of isotopic composition among trees.

Samples were ground to 20 mesh. The holocellulose component of the wood was isolated by first removing extractives with toluene and ethanol, and finally delignifying with sodium chlorite (Leavitt and 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 ($^\circ/_{oo}$) units with respect to the PDB standard. Repeated combustion and analysis during the period of this experiment gave a standard deviation of $0.38\,^\circ/_{oo}$. This value was uncustomarily high (our usual overall precision is 0.15–$0.20\,^\circ/_{oo}$) and poses a potential for inducing trends in the data even if none are present. However, the variability was random and there is no evidence for any systematic biasing of the $\delta^{13}C$ chronology developed, e.g.,, the $\delta^{13}C$ difference between the 1820-24 and 1985-87 pentads was initially measured as $1.55\,^\circ/_{oo}$, and when cellulose of these two pentads were selectively combusted and analyzed again after the full chronology was developed, the difference was $1.23\,^\circ/_{oo}$. This suggests the gross trends in the $\delta^{13}C$ chronology are real, but care should be exercised if one

attempts to ascribe significance to the subtle features of the curve.

3. Results and discussion

The 300-year *Fitzroya* $\delta^{13}C$ curve shows a long-term decreasing trend, falling most rapidly after AD 1900 (Fig. 2). The decline from a plateau of approximately $-22.8\,^\circ/_{oo}$ maintained during the 1800's to AD 1985 is approximately 1.2 to $1.7\,^\circ/_{oo}$ depending upon whether the change is determined from the 5-pentad running average or from the individual points. Every 50 years from 1700-04 to 1900-04, the individual $\delta^{13}C$ values of each tree are plotted; in general, $\delta^{13}C$ of trees #3 and 4 tend to be most negative, whereas trees #1, 2 and 5 are least negative. The $\delta^{13}C$ values of the individual trees span 1.5 to $2.5\,^\circ/_{oo}$ for a common pentad, which is similar to the variability seen among southwestern USA pinyon individuals at a site (Leavitt and Long, 1989b) despite a moisture regime very different from the alerce site. Another *Fitzroya* at an elevation of 200 m near Valdivia, Chile, and from which a $\delta^{13}C$ chronology was already developed from a single radius (Stuiver et al., 1984), is also included in Fig. 2, and it shows many similarities with the curve of this study. The 1800s generally have a fairly uniform $\delta^{13}C$ and an initially slow decline begins in the late 1800s. The Stuiver curve ends in 1975–79 just prior to the steep decline seen in our curve thereafter. Elevated $\delta^{13}C$ values in the mid-1700s but distinctly lower values in the early 1700s occur in both curves, and may therefore represent real changes.

For further comparison, the mean pinyon curve (Leavitt and Long, 1989a) is also plotted in Fig. 2. However, it represents 56 trees from 14 sites in the southwestern United States whereas Alerce Andino is a single site. Furthermore, the pinyon trend had been normalized for climate effects by significant ring-width index versus $\delta^{13}C$ relationships. We tested our *Fitzroya* chronology for such relationships but found no significant correlations between mean ring-width indices of each pentad with $\delta^{13}C$, nor between first differences of mean indices and $\delta^{13}C$.

The *Fitzroya* chronology clearly shows a downward trend which differs from the flat trend in Tasmanian tree rings reported by Francey (1981a). Three additional South American trees
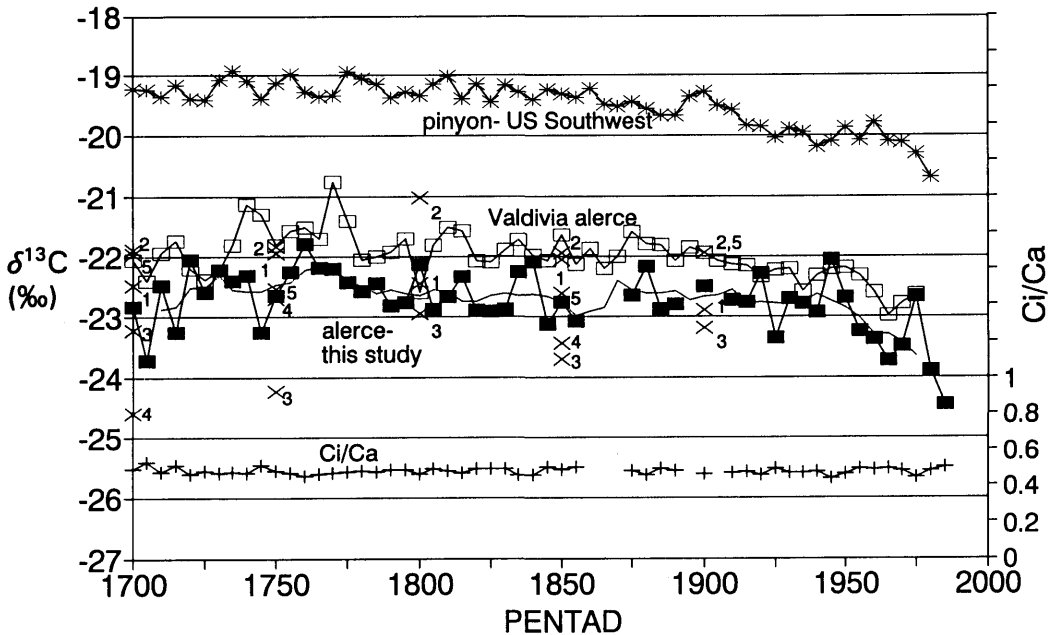
Fig. 2. The δ^{13}C curves of alerce from this study (the $\times$'s represent values of individual trees when analyzed separately), of Valdivia alerce from Stuiver et al. (1984), and of pinyon from the southwestern US (Leavitt and Long, 1988, 1989a). A 5-pentad moving average has been fitted to the alerce data. Plotted C_i/C_a values ($+$'s) are derived from the alerce δ^{13}C chronology using the $\delta^{13}C_{air}$ values from ice cores and direct measurements, and the plant carbon isotope fractionation equation (see text).

(in addition to that depicted in Fig. 2) of Stuiver et al. (1984) and 3 individual trees from Tasmania, New South Wales and New Zealand reported by Epstein and Krishnamurthy (1990) also show little or no δ^{13}C decline since AD 1800. Freyer (1981) suggested a rainforest environment (as in Tasmania) with important canopy and respired CO_2 effects could mask global effects. Even if sub-canopy respired CO_2 influence is inconsequential at canopy level as suggested by measurements of Francey et al. (1984), there are potentially other subtle mechanisms to induce $\delta^{13}C_{plant}$ differences among trees and sites. These could include pest infestations, changes (perhaps long-term) in competition and availability of light and nutrients, and soil microfaunal changes.

We can compare the *Fitzroya* $\delta^{13}C_{plant}$ chronology to the $\delta^{13}C_{air}$ chronology derived from ice cores and direct air measurements. By using the $\delta^{13}C_{air}$ chronology of Friedli et al. (1986) to represent the value of pentads and by interpolating intermediate $\delta^{13}C_{air}$ values with a smoothed curve, the history of C_i/C_a ratios of the *Fitzroya* trees can

be calculated. This C_i/C_a chronology is plotted in Fig. 2 and shows a mean of 0.477 and standard deviation of 0.017. Regression of C_i/C_a with year gives an r^2 of 0.029 and slope of $-3.4 \times 10^{-5}\,{}^{\circ}/_{\circ\circ}$ year^{-1}, i.e., this chronology is indistinguishable from a horizontal line. This is strong evidence that the *Fitzroya* δ^{13}C curve is tracking $\delta^{13}C_{air}$ and its trend is not being altered by any shifts in environmental parameters and atmospheric CO_2 concentration which could affect $\delta^{13}C_{plant}$. The pentad-to-pentad fluctuations of up to $1^{\circ}/_{\circ\circ}$, however, are too large to represent rapid global δ^{13}C changes and suggest some local ecophyhsiological influence, perhaps related to microclimate.

4. Conclusions

The pooled trees at the Alerce Andino site show a clear decrease of mean δ^{13}C in tree-ring cellulose, like that seen in some Northern Hemisphere chronologies but in contrast to Tasmanian trees which showed no δ^{13}C trend. This is the first major

chronology in the Southern Hemisphere to show such a decline, and evidences that such trends are not exclusive to the Northern Hemisphere, although complexities in plant carbon isotope fractionation related to different histories of C_i/C_a from one tree to the next are likely responsible for differences among trends. Comparison of the *Fitzroya* $\delta^{13}C$ chronology with atmospheric estimates from ice cores indicates that the $\delta^{13}C$ trend in these trees is following atmospheric $\delta^{13}C$. The long-term trend of C_i/C_a ratios calculated from the *Fitzroya* is constant and suggests constancy of the net influence of changing atmospheric CO_2 concentrations and environmental factors which could alter site-averaged C_i/C_a. Rapid $\delta^{13}C_{plant}$ changes from one pentad to the next, however, are unlikely attributable to sudden $\delta^{13}C_{air}$ changes, but reveal short-term changes of C_i/C_a. Why this chronology reflects $\delta^{13}C_{air}$ when the Tasmanian chronology does not, is not clear; perhaps the climate of the Alerce Andino site with high rainfall and low moisture stress, the fairly

open rain-forest canopy allowing easier access to free air, and the location on the west coast of a continent combine to provide favorable circumstances. Success of *Fitzroya* as a $\delta^{13}C_{air}$ proxy for the past 300 years is promising to longer reconstructions at this pentad time resolution, but caution must still be exercised because of possible variation in C_i/C_a ratios over thousand of years.

5. Acknowledgments

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