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Tree-Ring Carbon Isotopic Constraints on Carbon-Water Exchanges between Atmosphere and Biosphere in Drought Regions in Northwestern China

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Abstract The comparison between the carbon isotope and the index of ring width of a pine disc from the Tuomuer Peak region in Xinjiang shows that the effects of climate changes on the tree-ring growth and carbon isotopic fractionation varies with time. The reason is probably relative to the characters of climate changes and adaptability of the tree-ring growth to climate changes. The relationships between the atmospheric CO_2 level and the revised $\delta^{13}C_{air}$ by the tree-ring carbon isotope indicate that the carbon cycle is not in a steady state, but under a stage-change condition in this area. It also can be concluded that the ratio of CO_2 from the terrestrial eco-system has increased, and the flux of CO_2 exchange between the atmosphere and the biosphere was gradually increasing over the past century. In addition, the results also confirm the validity and superiority of the carbon isotope to the research of the water-use efficiency.

Key words: tree ring, carbon isotope, CO_2 exchange, water-use efficiency

1 Introduction

Recently more and more attention has been put on the terrestrial ecosystem in researching the global carbon cycle (Cao et al., 1998a, b, 1999). Besides its direct influences on the life and the future concentration of atmospheric CO_2, an important reason is that terrestrial ecosystem plays a key role in the interaction between the atmospheric CO_2 and climate changes. Tree rings not only can reflect the changes of past climate and plants (Farquchare et al., 1982), but also can record the information about the carbon and water cycle (Stuiver et al., 1984; Leavitt et al., 1989; Feng, 1999), hence providing a powerful and good method to synthetically study the geochemical integration of the atmospheric CO_2, land biota and climate.

2 Samples and Analytic Methods

The tree-ring samples analyzed here are pine discs sampled at 3200 m a.s.l. in the Qiongtelian Valley in the Tuomuer Peak region, Xinjiang. The sampling site is very close to the Qiongtelian glacier, but it is not located on the tree line. The tree rings grew from the year of 1904 to 1978. The local geographical and climate conditions were discussed in detail previously (Wan, 1992). An index series was obtained after the widths of tree rings of 5 different radii were measured and fitted by linear and negative exponential functional regressions.

In order to simultaneously measure $\Delta^{14}C$ and $\delta^{13}C$ of the tree rings, each annual ring was separated to extact cellulose by the standard chemical method, and then the cellulose was oxidized by copper oxide to become CO_2. Carbon isotopic analyses were performed with a Mat-252 mass-spectrometer. Results are expressed in the standard δ notation with respect to the PDB standard with a precision of 0.1‰. The first step of the $\Delta^{14}C$ analysis is that cellulose was transformed into benzene, and then was determined in a Liquid Scintillation Analyzer. The result was corrected by isotopic fractionation and radio decay with a precision of 3‰.

3 Results

In Fig. 1, the vertical axis stands for the correlation coefficient between the index of ring width and the

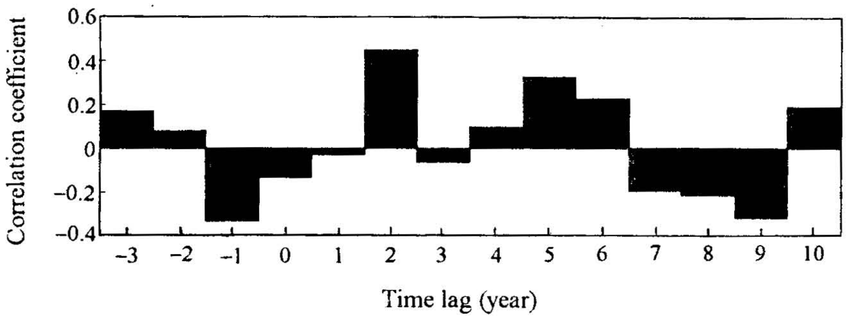

Fig. 1. The correlation coefficient between the index of width and the annual mean precipitation.

found by the linear regression that a remarkable positive correlation between the annual mean temperature and the $\delta^{13}C$ of tree rings exits with a confidence level of 99 percent. It is suggested that the tree-ring $\delta^{13}C$ is mainly affected by the temperature change, thus can be viewed as an index of temperature.

annual averaged precipitation from 1956–1978 and the horizontal axis represents the time lag of the year tree-ring represents to precipitation record. It is very obvious that the index of ring width is not correlative to the mean precipitation of the year (with a zero time lag). However, they are significantly correlative if the time lag is two years. This time lag is probably relative the state of groundwater supply points to the local climate condition two years before.

$\Delta^{14}C$ of tree rings approximately decreased by 10 ‰ from 1925 to 1937. The analytic result of tree-ring $\delta^{13}C$ shows an evident fall of about 0.7‰ from 1925 to 1978 (Fig. 2). The slope of –0.015 is slightly larger than that of the Chinese pine (–0.024) in Huangling of Shaanxi Province, obtained by Leavitt (1995), and lower somewhat than that from Eagle Peak (–0.010) (Leavitt, 1995). This decreasing trend is definitely caused by the "Suess" effect resulting from the anthropogenic CO_2 emissions from fossil fuel combustion.

The high-frequency change of $\delta^{13}C$ is completely consistent with the fluctuation of annual averaged temperature observed in the Akesu Meteorological Observatory near the sampling site (Fig. 2). It is

4 Discussion

4.1 Adaptability of the tree-ring growth to the climate changes

Stuiver (1984) found highly significant correlations between ring areas and $\delta^{13}C$ of tree rings. Leavitt and Long (1989) made full use of this type of correlation to model $\delta^{13}C$ of atmospheric CO_2. In this paper, the aforesaid results clearly show that the index of ring width is positively correlative to the annual mean precipitation, and the precipitation is negatively correlative to the carbon isotope of tree rings. Thus, it might be deduced that the index of ring width is probably negatively correlative to the carbon isotope of tree rings. However, a wholly opposite relationship does not arise when the index of ring width is directly compared with the carbon isotopic composition of tree rings (Wang et al., 1999a). Instead, it changes with time. Prior to the border of 1961, the index of ring width is completely opposite to the carbon isotopic composition of tree rings. The maximum of the former

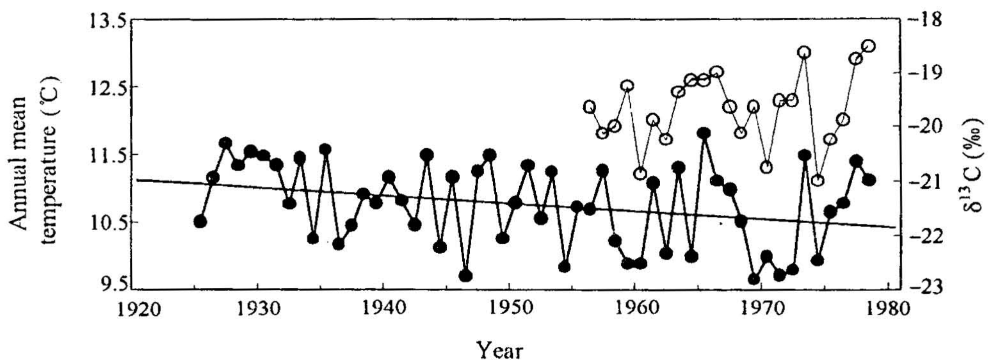

Fig. 2. Tree-ring $\delta^{13}C$ (PDB, ‰) (•) and annual mean temperature (°C) (o).
Upper: annual mean temperature (dotted line) and $\delta^{13}C$ of tree rings (solid line); bottom: 3-year running average (thin line) and polynomial fitting line of Δ (‰) (thick line).

is corresponding to the minimum of the latter, while the minimum of the former to the maximum of the latter. The fluctuations of the both cases, however, have turned to be synchronous after 1961.

This kind of relationship is demonstrated more clearly in the figure below (Fig. 3), in which the correlation coefficients in a 5-year and 10-year periods are shown. Such relationship can be explained only by the integration of temperature and precipitation. Before 1961, the opposite relationship was mainly caused by the precipitation change because higher mean precipitation must result in a larger index of ring width and lower carbon isotope, and lower precipitation corresponds to a smaller index and higher carbon isotope. Inversely, the positive correlation from 1961–1978 indicates that the growth of tree rings was chiefly affected by temperature changes in this period because higher temperatures will cause higher carbon isotope ratios and larger indexes of ring width, but lower temperatures will lead to lower carbon isotopes and smaller indexes.

Briffa et al. (1998) have notified that the sensitivity of recent tree growth to temperature reduced at high northern latitudes (Briffa et al., 1998). The reason remains unknown. As revealed in this study, a similar change has also occurred in the tree-ring carbon isotope. We guess that this transformation of correlation is probably relative to the style of climate changes in the past century and the response of tree-ring growth to this kind of climate changes. The environmental factors influencing isotopic compositions of trees are numerous (Stuiver et al., 1984) and vary with sites (Saurer et al., 1995). Also, it varies probably with time in the light of the result present here. This is very important to reconstruct and model the climate variability based on tree rings. The transfer function, commonly derived in the period of predictant, will inevitably produce a bias when applied to the predictor time series because the relationships between climate parameters, tree-ring growth and carbon isotope compositions change with time.

4.2 Carbon dioxide exchanges

C_i/C_a, the ratio of intercellular to ambient CO_2 partial pressure, is internally controlled by the stomatal conductance and assimilation rate and externally affected by the atmospheric CO_2 concentration and climate changes. C_i/C_a can be only estimated by the isotopic fractionation equation of Farquchar et al. (1982). However, this method was limited by the very little observation of atmospheric $\delta^{13}C$ before 1980. Leavitt had to interpolate the atmospheric $\delta^{13}C$ by means of the polynomial (Stuiver et al., 1984). A geochemical method to model C_i/C_a by tree-ring $\delta^{13}C$ was devel-

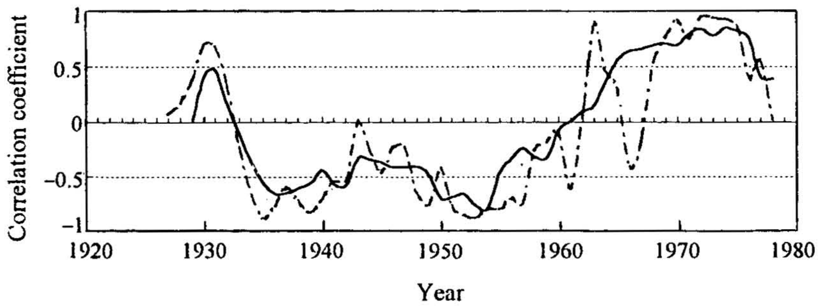

Fig. 3. Correlation coefficient between index of ring width and carbon isotope Δ (‰). $\Delta = \delta C_{plant} - \delta C_{air}$, dotted and solid lines correspond to the coefficients in 5-year and 10-year periods, respectively.

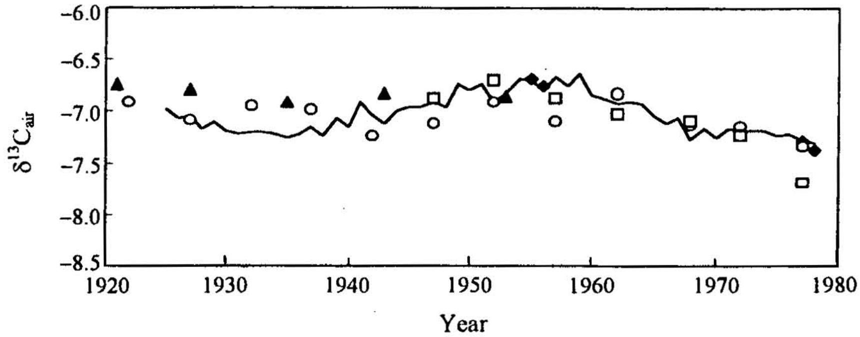

Fig. 4. Variations of $\delta^{13}C_a$ of atmospheric CO_2.
▲: Results from ice core dating (Friedli, 1986); ◆: observations after 1955 (Keeling, 1979, 1989); ○: results based on tree-ring carbon isotopes (Leavitt, 1989); □: results based on C4 plant isotopes (Marino, 1991); line : results reported in this paper.

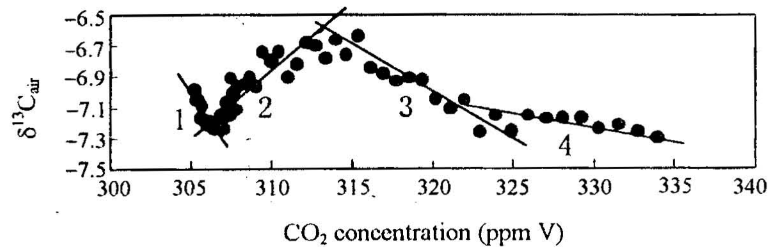

Fig. 5. Plot of interpolated CO_2 concentrations against modeled atmospheric $\delta^{13}C$.

oped to reduce the dependence (Wang et al., 1999b). We can approximate the annual change of $\delta^{13}C$ of atmospheric CO_2 by substituting the modeled C_i/C_a of tree rings into the carbon isotopic fractionation equation. This modeled atmospheric $\delta^{13}C$ is in excellent agreement with the results obtained by other researchers (Fig. 4).

By the estimated tree-ring C_i/C_a, the authors discussed CO_2 and water exchanges between the atmosphere and biosphere that greatly influence the climate change (Wang et al., 1999c). In Fig. 5 the annual change of $\delta^{13}C$ of atmospheric CO_2 is plotted against the interpolated CO_2 concentration. The evolution of the atmospheric CO_2 can be clearly divided into 4 stages in this figure. We hypothesize that the carbon cycle in each stage is in a steady state, meanwhile suppose that the atmospheric CO_2 just has an average input in each stage. Based on the relationship between the atmospheric $\delta^{13}C$ and CO_2 concentration, we can get CO_2 mixing equations as follows:

(1) 1925–1939 $\delta^{13}C = -28.59 + 6551/C$ (‰)

(2) 1940–1960 $\delta^{13}C = 5.46 - 3827/C$ (‰)

(3) 1960–1970 $\delta^{13}C = -22.42 + 4928/C$ (‰)

(4) 1971–1978 $\delta^{13}C = -12.82 + 1850/C$ (‰)

where $\delta^{13}C$ means atmospheric $\delta^{13}C$, and C denotes the atmospheric CO_2 concentration.

In stages (1), (3) and (4), $\delta^{13}C$ is negatively correlative to CO_2 concentration, which is similar to the diurnal and seasonal changes and to the trend change over the past two centuries. We found that the $\delta^{13}C$ of CO_2 input into atmosphere in stage (1) is about −28.59 ‰, which is in excellent agreement with the global average $\delta^{13}C$ of CO_2 from fossil fuel emission (−28.5 ‰) (Zondervan, 1996). It suggests that CO_2 input into atmosphere in this period is mainly from the fossil fuel emission. The CO_2 input into atmosphere in stages (3) and (4) has isotopic ratios of −22.42 ‰ and −12.82‰, respectively. It is clear that the ratio of CO_2 from the terrestrial eco-system is increasing, and the ratio of anthropogenic CO_2 retained in atmosphere decreasing in comparison with stage (1). These conclusions could be drawn on the assumption that ocean carbon reservoirs have kept unchanged. The hypothesis undoubtedly produces some bias in case of long-term changes. However, it is certain that the carbon cycle is not in a steady state, but has been under a stage-change condition over the past century. It also can be indicated that the flux of CO_2 exchange between the atmosphere and the biosphere was gradually increasing from 1920 to 1978 because the ratio of CO_2 from terrestrial ecosystem has increased.

4.3 The long-term change of water-use efficiency

The equation to illuminate the process of water loss during photosynthesis was simplified (Polley, 1993) as $W = fC_a(1 - C_i/C_a)$, where $f = 1/1.6$.

It is obvious that W is chiefly influenced by the atmospheric CO_2 content and climate changes. The effect of atmospheric CO_2 is expressed as follows:

$$\frac{dW}{dC_a} = f(1 - C_i/C_a) - fC_a\frac{d(C_i/C_a)}{dC_a}$$

According to the interpolated C_a and estimated C_i/C_a (Wang et al., 1999c), the following equation is easily obtained

$W = 0.25\,C_a + 31.2$

This equation stands for the contribution of the elevated CO_2 content to the water-use efficiency of tree-ring growth during a long term. It is in agreement with the experimental reѕult on C3 plant (Polley, 1993).

The quantitativ study of the effect of climate changes on the water-use efficiency has been done very little. The formula $W_c = W - W_{CO_2}$ was taken to assess the influence. The estimated W_c fluctuates at the same pace with the change of tree-ring $\delta^{13}C$. This suggests that the water-use efficiency mainly is affected by temperature with a little impact from precipitation. It is in good agreement with the experimental result, too (Woodward, 1987). The change of W_c shows that the magnitude of effect resulting from the temperature change is larger than that from the increase of CO_2 concentration over the past century.

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Wang Shilu Graduated from the Department of Geology, Changchun University of Earth Science in 1991 and acquired his Ph.D for environment geochemistry at the Institute of Geochemistry, CAS in 1998. Dr. Wang works now as Associate Professor in this Institute. Main research interests include global and local environmental changes, biogeochemical cycle of carbon and geochemical trace of ^{13}C and ^{14}C.