Water Use Efficiency of Chinese Pine in Beijing' s Mountainous Areas Based on Tree-Ring 13C Values: A Postprint

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Abstract

Water use efficiency represents a critical node for in-depth investigation of the coupling relationship between water and carbon cycles in forest ecosystems. The Beijing mountainous ecosystem serves as a natural ecological barrier for Beijing Municipality, and studying the dynamics of vegetation water use efficiency and its response to climate change in this region holds significant importance for assessing regional water-carbon coupling relationships and investigating plant responses to global climate change. Employing tree-ring 13C sequences of Chinese pine (Pinus tabuliformis) from the Hongmenchuan watershed in the eastern mountainous area of Miyun County, Beijing, we analyzed the interannual variation of long-term water use efficiency (WUE). Analysis results based on meteorological data from Miyun Station and Shangdianzi Station indicate: (1) From 1952 to 2014, the tree-ring 13C value sequence of Chinese pine in the Hongmenchuan watershed of Beijing' s mountainous area exhibited an upward trend, with a variation range of -23.41‰ to -27.63‰ and an average of -25.56‰; the interannual values of Chinese pine WUE demonstrated a fluctuating downward trend, with a variation range of 5.77–16.53, an average value of 9.6, and an average annual decrease of 0.175. The declining trend was most pronounced around the 1980s, after which it remained at a relatively low level. The minimum value (5.76) occurred in 1994, the maximum value (16.53) occurred in 1976, and the period from 1964 to 1980 exhibited the highest WUE within the study period, with an average value of 13.0. Thus, it is evident that the water use efficiency of Chinese pine forests in the Hongmenchuan watershed has continuously decreased over the past decades, with a concomitant decline in carbon sequestration capacity. (2) Chinese pine WUE exhibited a favorable response to temperature variation, displaying a significant overall negative correlation, with a correlation coefficient of $r^2 = 0.8248$ ($P < 0.01$) with annual mean temperature, and r^2 0.6952 with growing season mean temperature. For every 0.1°C increase in mean temperature, Chinese pine WUE decreased by 0.205. Moreover, the WUE decline rate in years with higher mean temperatures exceeded the WUE increase rate in low-temperature years, leading to the inference that rising temperature exerts a more significant impact on the water-carbon cycle and coupling relationship in Chinese pine forest ecosystems. (3) Chinese pine WUE increased with precipitation, manifesting a certain positive correlation with precipitation, though not statistically significant; following a sudden reduction in precipitation, the WUE values of Chinese pine would subsequently rise, but would decline after persisting for a period, indicating that WUE values possess a certain degree of conservativeness. (4) The response of WUE to temperature variation was more sensitive than its response to precipitation variation. Elevated temperature and reduced precipitation led to decreased leaf stomatal conductance in plants, thereby influencing the carbon sequestration rate of plants.

Full Text

Preamble

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Variation Characteristics of Long-term Water Use Efficiency Based on Tree-ring Carbon Isotope Discrimination in Chinese Pine (Pinus tabulaeformis) in the Beijing Mountainous Area

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Abstract

Water use efficiency (WUE) is a critical parameter for understanding the coupling relationships between water and carbon cycles in forest ecosystems. Investigating the dynamics of vegetation WUE and its response to climate change in the Beijing mountainous area is essential for evaluating regional water-carbon coupling relationships and plant responses to global climate change. This study analyzed long-term WUE using tree-ring 13C values of Chinese pine (Pinus tabulaeformis) in the Hongmenchuan watershed of Miyun County, Beijing, combined with meteorological data from Miyun and Shangdianzi stations.

The results showed that tree-ring 13C values of Chinese pine in the Hongmenchuan watershed exhibited an increasing trend, ranging from -27.63‰ to

-23.41‰ with an average of -25.56‰, decreasing by 0.04‰ annually ($p < 0.01$). The WUE curve showed a quadratic function trend, varying from 5.77 to 16.53 with an average of 9.6, decreasing by 0.175 per year. The WUE of Chinese pine forests in the Hongmenchuan watershed continuously decreased over the past decades, similar to the carbon sequestration capacity of forest ecosystems. The lowest value (5.76) appeared in 1994, while the highest (16.53) appeared in 1976. From 1964 to 1980, WUE remained at a higher level with an average of 13.0.

WUE showed a significant negative correlation with annual temperature ($r^2 = 0.8248$, $p < 0.01$) and growing season temperature ($r^2 = 0.6952$, $p < 0.01$), and a certain but non-significant positive correlation with precipitation. The correlation between WUE and annual temperature was stronger during the growing season, reflecting the influence of non-growing season temperature. WUE increased slightly when temperature decreased, but declined sharply when temperature increased by 0.205 per 0.1℃ temperature rise. After sudden precipitation reduction, WUE increased temporarily and then decreased, indicating that WUE response is more sensitive to temperature change than precipitation change. Increased temperature and decreased precipitation caused a reduction in stomatal conductance of plant leaves that affected the carbon fixation rate.

Keywords: Water use efficiency (WUE); tree-ring 13C; climate change; water-carbon coupling cycle

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Introduction

Water use efficiency (WUE) can be summarized as the ratio of plant-assimilated carbon to water consumed through transpiration. It is an important indicator for measuring plant drought tolerance and a key entry point for studying water-carbon coupling relationships. WUE reflects plant water consumption characteristics and drought adaptation to some extent, representing a plant response to environmental water conditions. Traditional methods for studying WUE mainly include harvest methods, but these are limited by their destructive nature or practical constraints.

With the advancement of isotope technology in ecological research in recent years, measuring stable carbon isotope values (13C) in plant tissues has become a new alternative to traditional methods. Since plant tissue carbon accumulates over time, 13C values represent not instantaneous measurements but the average over the organic matter formation period. This approach better reflects long-term plant water use and adaptation to water stress, with minimal destructive sampling, convenient storage, and easy measurement. Chen et al. analyzed WUE of *Cassia obtusifolia* by measuring leaf stable carbon isotope values, confirming that stable isotope technology is effective for determining plant WUE. Wang et al. studied WUE at the leaf scale through controlled experiments, finding that leaf 13C is a good indicator for evaluating whole-plant WUE. Yin et al. measured 13C in different tissues of poplar trees to analyze WUE at different temporal scales.

Zhang et al. used ecosystem models to study ecosystem-scale WUE in southwestern China and analyze its spatiotemporal dynamics. Most stable isotope studies of plant WUE have focused on the leaf scale, showing significant interannual decreasing trends, but lack long-term scale research. Existing temporal WUE studies mostly use model estimations. Tree-ring isotopes provide an excellent approach for studying long-term WUE. Tree-ring variation is influenced by both genetic characteristics and external environmental conditions. Using tree-ring information such as stable carbon isotope values to study environmental changes or conduct climate reconstruction is highly effective. Since cellulose does not transfer between years in tree rings, intra- and interannual variation information is permanently preserved in tree-ring 13C values, forming a quantitative relationship between carbon isotope information and physiological characteristics. This greatly advances research on plant stable carbon isotope values and water relationships across spatial scales (from individual leaves to complete ecosystems) and temporal scales (from instantaneous gas exchange to paleoecology), enabling understanding of both current physiological status and historical responses to long-term environmental changes, particularly regarding water use and status.

This study used Chinese pine as the research object, measuring stable carbon isotope 13C in tree rings combined with local precipitation and temperature data to explore long-term WUE responses to climate change, thereby improving understanding of water-carbon coupling processes under climate change.

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1. Study Area Overview

The Hongmenchuan watershed is located in the eastern mountainous area of Miyun County, Beijing, representing a typical rocky mountainous area of Beijing. The watershed flows through Miyun County and empties into the Chao River at Dengjiawan, with a length of 20.5 km and an area of 128 km^2. The watershed has complex geomorphology, situated in the transition zone between the North China Plain and Mongolian Plateau, belonging to the Yanshan Mountains with continuous mountains on the east, west, and north sides. The terrain slopes from north to southwest.

The climate is warm temperate semi-humid monsoon continental, with an annual average temperature of 11-12°C and annual precipitation of 650-700 mm, concentrated in July-September. Annual sunshine totals 2801.8 hours. Soils are mainly cinnamon and brown forest soils with prominent skeletal characteristics. The main tree species is Chinese pine (*Pinus tabulaeformis*), accompanied by *Platycladus orientalis*, *Robinia pseudoacacia*, and *Quercus variabilis*.

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2. Experimental Materials and Methods

2.1 Sample Collection

The Hongmenchuan watershed was divided into sampling areas. In October 2014, standard trees with good growth status were selected and two tree cores were taken at breast height along contour lines using an increment borer. Specific sampling methods followed dendroclimatology research standards. To prevent carbon contamination, 48 tree core samples were stored in glass tubes, with 3-4 cores per sampling point to represent 13C values and variation trends at each site. Samples with clear annual rings and few missing rings were selected for stable carbon isotope analysis.

2.2 Sample Processing

Tree core samples underwent standard procedures including natural drying and sanding. Skeleton plots were used for cross-dating each sample, then samples were cut along annual ring lines with a scalpel on a glass plate. Samples from the same year were combined in glass bottles, rinsed twice with deionized water to remove surface carbon contamination, and oven-dried at 70°C for 48 hours. Dried samples were ground with a pulverizer and passed through a 100-mesh sieve. Each annual sample (3-5 mg) was combusted at 950°C in a total organic carbon (TOC) element analyzer in sealed quartz tubes with excess oxygen, converting all carbon to gas. The combustion gas was collected and 13C values were measured using an isotope ratio mass spectrometer with system error less than 0.2‰.

2.3 Calculation of Long-term Plant Water Use Efficiency

Plant WUE is the molar ratio of assimilated CO to transpired water. Plant physiologists measure instantaneous transpiration efficiency (ITE) as the ratio of assimilation rate (A) to transpiration rate (E), expressed as WUE = A/E = (Ca - Ci)/Δe, where Ca and Ci are atmospheric and intracellular CO concentrations, and Δe is leaf vapor pressure difference. Farquhar et al. established the quantitative relationship between carbon isotope discrimination (Δ13C) and Ci/Ca: Δ13C = a + (b - a)Ci/Ca, where a = 4.4‰ is the diffusion fractionation coefficient, b = 27‰ is the Rubisco carboxylation fractionation coefficient, and 13Ca and 13Cp are atmospheric and plant carbon isotope ratios. WUE can be calculated as: WUE = Ca × (13Ca - 13Cp - a)/(b - a).

2.4 Data Statistics and Analysis

Excel and SPSS software were used for correlation analysis, linear regression, and multiple regression analysis. Meteorological data were obtained from Miyun (20 km from sampling site, 116°52 12 E, 40°22 48 N) and Shangdianzi (27 km, 117°07 07 E, 40°39 12 N) stations provided by the National Meteorological Administration. Atmospheric CO concentration data were from the IPCC report.

3. Results

3.1 Statistical Characteristics of Chinese Pine Tree-ring Stable Carbon Isotope Series

The Chinese pine tree-ring stable carbon isotope series (1950-2014) ranged from -27.63‰ to -23.41‰ with an average of -25.56‰, showing an increasing trend of 0.04‰ per year ($r^2 = 0.7181$, $p < 0.01$). The first-order autocorrelation was not significant, indicating tree-ring stable carbon isotope values reflect current-year climate information without significant carryover effects.

3.2 Variation Characteristics of Long-term Water Use Efficiency

WUE in the Hongmenchuan watershed showed an overall decreasing trend, varying from 5.77 to 16.53 with an average of 9.60, decreasing by 0.175 per year. The variation can be divided into three distinct periods: 1952-1964 (increasing trend), 1964-1980 (peak period, maintaining high level with average of 13.0), and 1980-1995 (significant decreasing trend). After 2000, variation amplitude decreased significantly. The lowest value (5.76) appeared in 1994, while the highest (16.53) appeared in 1976.

[Figure 1: see original paper] Tree-ring 13C chronologies of Pinus tabulaeformis in Hongmenchuan watershed

3.3 Response to Temperature Changes

Interannual WUE variation showed significant negative correlation with temperature ($r^2 = 0.8248$ with annual temperature, $r^2 = 0.6965$ with growing season temperature, $p < 0.01$). For every 0.1°C increase in average temperature, WUE decreased by 0.205. In high-temperature years, WUE decline rate was greater than in low-temperature years. During the first half of the study period, large temperature variation amplitude corresponded to significant WUE decline. During several high-temperature periods (1955, 1982), WUE also showed increases, with 82.2% of high-temperature years showing WUE increases of 70.0%.

[Figure 2: see original paper] Inter-annual variations of WUE in Pinus tabulaeformis in Hongmenchuan watershed
[Figure 3: see original paper] Inter-annual variations of temperature and WUE of Pinus tabulaeformis during 1950-2014 in Hongmenchuan watershed
[Figure 4: see original paper] Correlation analysis between WUE of P. tabulaeformis and annual temperature
[Figure 5: see original paper] Correlation analysis between WUE of P. tabulaeformis and growing season average temperature

3.4 Response to Precipitation Changes

Analysis of annual precipitation (ranging from 261.4 to 1404.6 mm) and WUE showed a positive but non-significant correlation ($r^2 = 0.1566$). WUE generally increased with precipitation. After sudden precipitation reduction, 13C values increased and WUE rose temporarily, but after sustained periods, WUE decreased to levels lower than before the reduction. This phenomenon also occurred in 1982.

[Figure 6: see original paper] Inter-annual variations of precipitation and WUE of Pinus tabulaeformis during 1950-2014 in Hongmenchuan watershed
[Figure 7: see original paper] Correlation analysis between WUE of Pinus tabulaeformis and annual precipitation

3.5 Combined Effects of Precipitation and Temperature

Combining temporal variations of precipitation and temperature revealed four periods: (1) 1952-1964: decreasing precipitation (761.2 mm) with relatively good water conditions, increasing temperature (11.58°C) but relatively low mean, WUE showed decreasing trend; (2) 1964-1980: relatively stable precipitation (574.5 mm), decreasing temperature (11.2°C), WUE maintained at relatively high level; (3) 1980-1995: precipitation decreased but remained at 500-600 mm, temperature increased significantly, WUE showed obvious decline; (4) After 2000: temperature stabilized at relatively high level (13.1°C), 2.5°C higher than first period, precipitation decreased, WUE stabilized at lowest mean of study period.

[Figure 8: see original paper] Inter-annual variations of precipitation and temperature

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4. Discussion

4.1 Chinese Pine Tree-ring Stable Carbon Isotope Values and Long-term WUE

Plant tissue stable carbon isotope values are significantly lower than atmospheric values because plants preferentially absorb 12C during photosynthesis, causing carbon isotope fractionation. This carbon isotope effect is influenced by both physiological factors and environmental conditions. From 1950-2014, Chinese pine tree-ring stable carbon isotope values showed a fluctuating increasing trend. When plants experience water stress or high temperature, partial stomatal closure occurs to avoid excessive water loss, reducing internal CO concentration. To maintain high photosynthetic rates, plants increase utilization efficiency of CO entering stomata, leading to increased 13C values. This suggests deteriorating water conditions and rising annual temperatures in recent decades, creating stress on plant growth consistent with local meteorological data.

The overall decreasing WUE trend, particularly significant near the 1980s, indicates that under climate change, Chinese pine ecosystem water use efficiency gradually declined. Plants did not fix more carbon while using equal water mass, showing weakened carbon absorption capacity. Whether as an indicator of plant drought adaptation or as a comprehensive index for evaluating plant growth suitability, its decline indicates plants show some degree of maladaptation to the environment. Studies by Zhang et al. on long-term WUE variation patterns in other regions also showed decreasing trends, with the fastest decline rate in recent decades.

4.2 Response of Long-term WUE to Climate Change

Plant long-term WUE showed significant negative correlation with temperature, with stronger correlation for annual temperature than growing season temperature. This may be because winter low temperatures affect tree photosynthetic capacity, leading to WUE changes. Although evergreen conifers have inhibited photosynthetic capacity during winter, they still respond to environmental changes. The response to temperature change was most significant, with high temperature impacts greater than low temperature impacts. The response to precipitation change was also evident but less significant.

The reason lies in plant stomatal conductance sensitivity to temperature. Related studies show appropriate water stress can improve WUE. CO concentration changes affect plants mainly by altering atmospheric 13C, thereby affecting plant 13C, but without changing plant Pi/Pa, the effect is not significant. Although this process also affects leaf stomatal conductance, the relationships between environmental factors affecting plant tissue stable carbon isotope values are complex, requiring further research.

At the ecosystem scale, WUE is defined as forest net primary productivity (NPP) or ET changes. Environmental changes affect both forest NPP and evapotranspiration, which are significantly positively correlated with temperature but not with precipitation. This study shows temperature change is the most sensitive factor affecting Chinese pine long-term WUE, with temperature rise having more significant impacts on water-carbon cycling and coupling relationships in Chinese pine ecosystems under climate change.

Temperature and precipitation have combined effects on plants. Analysis shows that when annual precipitation decreased but remained at 500-600 mm and annual temperature decreased to 11.2°C, WUE increased, indicating appropriate water reduction actually improved WUE. The optimal environmental condition interval was annual precipitation of 550-600 mm and annual temperature of 11-11.5°C, where WUE was highest. After sudden precipitation reduction, WUE first increased then decreased to lower than pre-reduction levels, suggesting this may be an adaptive strategy to environmental change requiring further study.

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5. Conclusion

(1) Chinese pine tree-ring 13C values in the Hongmenchuan watershed showed an increasing trend of 0.04‰ per year, indicating deteriorating water conditions and rising temperatures creating stress on plant growth.

(2) The WUE curve showed a quadratic function trend with variation range of 5.77-16.53, decreasing by 0.175 per year. The interannual variation can be divided into rising and declining phases, with an advantage interval where WUE was higher when annual precipitation was 550-600 mm and annual temperature was 11-11.5°C, showing early growth stage WUE was higher than later stages.

(3) WUE showed significant negative correlation with temperature ($r = -0.908$, $p < 0.01$) and positive correlation with precipitation, being more sensitive to temperature change than precipitation change. Physiological and ecological changes in stomatal conductance caused by air temperature change are key factors affecting Chinese pine WUE.

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