Paleoenvironmental Significance of Carbon and Oxygen Isotopes in α-Cellulose from Altai Mountain Peat: A Case Study of Heiyangpo Peat (Postprint)

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Abstract

The westerly wind-dominated Altai Mountains represent one of the key regions for paleoclimate research. To assess the validity of directly applying modern process studies of peat plant carbon and oxygen isotopes (δ^{13}Ccell and δ^{18}Ocell) from the Altai Mountains to centennial- or millennial-scale paleoclimate reconstructions, we analyzed the correlations between temperature, precipitation, and relative humidity from the Kaba River Meteorological Station during the cold season (October–April of the following year), warm season (May–September), and at annual scales from 1962 to 2017 with the δ^{13}Ccell and δ^{18}Ocell values of peat from Heiyangpo, based on reliable ^{210}Pb and ^{137}Cs dating. Results indicate that the δ^{13}Ccell of Heiyangpo peat is significantly negatively correlated with relative humidity from May to August ($r = -0.52$, $P < 0.05$), while δ^{18}Ocell is significantly positively correlated with precipitation from November to January of the following year ($r = 0.49$, $P < 0.05$). Variations in δ^{13}Ccell and δ^{18}Ocell of Heiyangpo peat can thus be regarded as proxy indicators for relative humidity from May to August and precipitation from November to January of the following year, respectively. This study provides multi-year-scale data support for the paleoclimatic interpretation of α-cellulose isotope records from Altai Mountain peat, not only enriching modern instrumental process studies of peatland isotopes in China, but also holding significant importance for conducting long-term quantitative paleoclimate research using peat cellulose isotopes in the study area.

Paleoenvironmental Implications of α-Cellulose Carbon and Oxygen Isotopes from Heiyangpo Peatland in the Altai Mountains

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Abstract

The Altai Mountains, perennially influenced by westerly winds, represent a key region for paleoclimate research. To investigate the validity of applying modern process studies of peat plant carbon and oxygen isotopes directly to centennial- or millennial-scale paleoclimate reconstructions, we analyzed the relationships between α-cellulose carbon and oxygen isotopes (δ^{13}Ccell and δ^{18}Ocell) from Heiyangpo peatland and meteorological parameters (temperature, precipitation, and relative humidity) from Habahe station spanning 1962–2017. The analysis covered cold-season (October–April), warm-season (May–September), and annual timescales. Results reveal that δ^{13}Ccell values correlate significantly negatively with May–August relative humidity (r = -0.52, $P < 0.05$), while δ^{18}Ocell values correlate significantly positively with November–January precipitation (r = 0.49, $P < 0.05$). Thus, δ^{13}Ccell and δ^{18}Ocell can serve as reliable proxies for May–August relative humidity and November–January precipitation, respectively. This study provides multi-year scale data support for interpreting Holocene climate information recorded by peat cellulose isotopes in the Altai Mountains, enriching modern observational process studies of peat isotopes in China and offering important implications for quantitative paleoclimate reconstruction using peat cellulose isotopes over long timescales.

Keywords: Heiyangpo peatland; carbon and oxygen isotopes; observed interval; Altai Mountains

1. Introduction

Peat ecosystems, covering 3% of global land area, are hotspots for terrestrial carbon storage research. Since the Last Glacial Maximum, peatlands have sequestered approximately 600 Gt of organic carbon. Peat deposits provide valuable archives for paleoenvironmental analysis and climate reconstruction. Various climate proxies—including dry density, humification degree, testate amoebae, plant macrofossils, pollen, and biomarkers—have been widely applied in peat-based paleoenvironmental reconstructions. For classical peat core analyses, stable carbon and oxygen isotopes in peat plant residues serve as important complementary proxies.

Previous studies have demonstrated that the paleoclimatic significance of peat plant cellulose carbon and oxygen isotopes (δ^{13}Ccell and δ^{18}Ocell) varies significantly across regions. In China' s low-latitude, semi-humid/semi-arid, and arid zones—spanning 451,084 ± 2,014 km^2 and influenced by westerly and monsoon (Indian and East Asian) systems—research shows divergent patterns. In monsoon-affected regions, δ^{13}Ccell from vascular plants has been used as a proxy for summer monsoon precipitation or regional humidity. However, studies in New Zealand indicate that δ^{13}Ccell from single vascular plants correlates significantly with temperature rather than humidity, a finding supported by recent modern process investigations in Dajiuhu peatland, Hubei Province.

In the westerly-influenced Altai Mountains of northwestern China, previous research based on modern process studies at Halasazi peatland suggested that δ^{13}Ccell and δ^{18}Ocell from sedge correlated positively with warm-season and cold-season temperatures, respectively, implying that positive isotopic trends in the peat core indicated Holocene warming. However, this temperature reconstruction contradicted temperature declines indicated by woody pollen content from the same core, raising a critical question: Can modern process studies of peat plant cellulose carbon and oxygen isotopes be directly applied to centennial- or millennial-scale research? The lack of investigation into relationships between δ^{13}Ccell/δ^{18}Ocell and multi-year modern environmental factors limits interpretation of Holocene climate signals in Altai peat records.

To bridge modern process studies with centennial- to millennial-scale changes, this study focuses on Heiyangpo peatland in the Altai Mountains. We aim to establish quantitative or semi-quantitative relationships between peat plant δ^{13}Ccell/δ^{18}Ocell and meteorological parameters during the observational period, and to explore how peat plant isotopes respond to measured climate and hydrological data. This research will determine the multi-year environmental significance of carbon and oxygen isotopes in this region, address gaps in interpreting Altai peat cellulose isotope records at multi-year scales, and provide robust data support for more reasonable paleoclimate information interpretation.

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2. Study Area

The Altai Mountains extend over 2,000 km in a northwest-southeast orientation across China, Kazakhstan, Russia, and Mongolia. The Chinese portion lies on the southern slope of the middle segment, located in northernmost Xinjiang between 46°33 35 -49°10 45 N and 85°31 37 -91°01 15 E. Modern cold-season climate in the Altai region is controlled by interactions between the "prevailing westerly-North Atlantic Oscillation coupled system" and the "Siberian High system," while warm-season climate is dominated by the "Asian Low system" over inland Asia and the "Azores High system" extending to southwestern Siberia. These systems provide abundant precipitation and favorable intermontane basins for diverse peatland development.

Heiyangpo peatland (48.34°N, 87.18°E, 1,353 m a.s.l.) is situated on the southern slope of the Altai Mountains [Figure 48: see original paper]. Fed primarily by atmospheric precipitation and snowmelt, the water table remains below 0.5 m. The Habahe meteorological station (48.03°N, 86.24°E, 532.6 m), located 70 km away, provides 56 years of observational data (1962-2017). The region experiences cold, long winters (mean January temperature: -14.7°C) and cool, short summers (mean July temperature: 22.3°C). Annual mean temperature is 5.0°C, with mean annual precipitation of 197.9 mm. Relative humidity ranges from 52.9%-55.4% in the cold season and 47.2%-72.2% in the warm season, with relatively uniform intra-annual precipitation distribution and cold-season precipitation accounting for 30-40% of the annual total. The living vegetation at Heiyangpo is dominated by Cyperaceae (sedge), forming a eutrophic swamp surrounded by coniferous forests at higher elevations or shady slopes, and grasslands at lower elevations or sunny slopes.

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3. Methods

3.1 Sample Collection In July 2017, a 30 cm peat core was drilled at Heiyangpo. The core was sectioned at 1 cm intervals in the field, with samples sealed in labeled bags and stored at -4°C. Plant residue analysis revealed that the core was dominated by Cyperaceae (Carex), similar to the modern vegetation.

3.2 Chronology and Depth-Age Model The chronology was established using ^{137}Cs and ^{210}Pb data. The ^{137}Cs peak at 11 cm (324.70 $\text{Bq} \cdot \text{kg}^{-1}$) corresponds to the 1986 CE Chernobyl accident, while the peak at 16 cm (1963 CE) represents maximum fallout from atmospheric nuclear testing. ^{210}Pb activity shows an exponential decline from 22.20 $\text{Bq} \cdot \text{kg}^{-1}$ at the top to 3.20 $\text{Bq} \cdot \text{kg}^{-1}$ at the bottom. Using the Constant Rate of Supply (CRS) model, we constructed the depth-age model [Figure 2: see original paper]. The core spans 1962-2017 CE, with an average accumulation rate of 0.29 $\text{cm} \cdot \text{a}^{-1}$. The rate increased over time, varying substantially between 30-12 cm (0.18 $\text{cm} \cdot \text{a}^{-1}$) and 12-1 cm (0.48 $\text{cm} \cdot \text{a}^{-1}$).

3.3 Cellulose Extraction and Isotope Analysis Cellulose extraction followed the method of Huang et al. [38]: (1) Humic substances were removed by boiling samples in 5% HCl; (2) Carbonates and easily hydrolyzed substances (pectin) were removed with 7.5 mL of 1% HCl; (3) Lignin was eliminated using

0.5 g $NaClO_2$ and 0.5 mL CH_3COOH, repeated until samples turned white; (4) Hemicellulose and polysaccharides were removed with 7.5 mL of 17.5% NaOH at 80°C; (5) Residual alkali was neutralized with 1% HCl. The final residue was freeze-dried.

Carbon isotope analysis: 30-50 g cellulose samples were combusted with excess CuO under vacuum using Pt catalyst, converting cellulose to CO_2. After purification, δ^{13}C was measured on a Delta V MAT isotope ratio mass spectrometer.

Oxygen isotope analysis: 300-500 g samples were pyrolyzed at 1,090°C in high-purity helium. The resulting CO was separated from impurities and measured on a Delta V MAT mass spectrometer. Analytical precision was better than \$±\$0.2‰ for both isotopes.

δ^{13}C correction: Since the Industrial Revolution, fossil fuel combustion has caused atmospheric CO_2 δ^{13}C to decline continuously. To extract climate signals, we corrected δ^{13}Ccell values using the method of McCarroll and Loader [40] [Figure 3: see original paper].

3.4 Climate Correlation Analysis To match isotope signals with meteorological data, we calculated arithmetic means of climate parameters corresponding to each core layer based on deposition rates. Because sedge growth concentrates in the warm season, we further analyzed correlations between isotopes and monthly relative humidity/precipitation combinations. Statistical significance was assessed using Origin 2018, with $P < 0.05$ indicating significant correlation.

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4. Results

4.1 Isotope Variation Characteristics δ^{13}Ccell values range from -22.30‰ to -21.30‰ (mean: -21.77‰). The most positive value (-21.30‰) occurs at 16 cm (2009 CE), while the most negative (-22.30‰) appears at 17 cm (1961-1966 CE). The overall trend is positive ($r = 0.67$, $P < 0.001$), with a notable negative shift at 15-1 cm (1967-2017 CE) and a minor negative excursion at 5-4 cm (2004-2009 CE) [Figure 3: see original paper].

δ^{18}Ocell values range from 18.60‰ to 21.30‰ (mean: 20.08‰), showing an overall positive trend ($r = 0.63$, $P < 0.001$). The most positive value (21.30‰) occurs at 16 cm (2000-2003 CE), while the most negative (18.60‰) appears at 16-14 cm (1963-1972 CE), with a clear negative shift at 5-4 cm (2009 CE) [Figure 3: see original paper].

4.2 Correlations between δ^{13}Ccell and Meteorological Factors δ^{13}Ccell shows no significant correlation with temperature (cold season: $r = 0.16$, $P = 0.53$; warm season: $r = 0.54$, $P = 0.08$; annual: $r = -0.04$, $P = 0.89$) or precipitation (cold season: $r = -0.37$, $P = 0.14$; warm season: r = -

0.46, $P = 0.06$; annual: $r = -0.19$, $P = 0.46$). However, δ^{13}Ccell correlates significantly negatively with May-August relative humidity ($r = -0.52$ to -0.60, $P < 0.05$) [FIGURE:4, FIGURE:5], with May-July humidity showing the strongest correlation ($r = -0.60$, $P = 0.01$).

4.3 Correlations between δ^{18}Ocell and Meteorological Factors

δ^{18}Ocell shows no significant correlation with temperature (cold season: $r = 0.29$, $P = 0.26$; warm season: $r = 0.34$, $P = 0.17$; annual: $r = -0.08$, $P = 0.75$) or warm-season precipitation ($r = 0.48$, $P = 0.07$). However, it correlates significantly positively with cold-season precipitation ($r = 0.49$, $P < 0.05$), particularly November-January precipitation ($r = 0.48$, $P = 0.03$) [FIGURE:6, FIGURE:7].

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5. Discussion

Our correlation analysis reveals that Heiyangpo peat δ^{13}Ccell correlates significantly negatively with May-August relative humidity, while δ^{18}Ocell correlates significantly positively with November-January precipitation. Since Altai peat plants grow primarily during May-September, the δ^{13}Ccell signal reflects growing-season humidity control. Plant δ^{13}C is determined by the ratio of intercellular to atmospheric CO_2 concentration (c /c). Low humidity induces stomatal closure to prevent excessive water loss, reducing c /c and increasing δ^{13}Ccell. High humidity opens stomata, increasing c /c and decreasing δ^{13}Ccell. This negative δ^{13}Ccell-humidity relationship has been applied in regional paleoclimate reconstructions, such as at Narenxia peatland (48.8°N, 86.9°E, 1760 m) and Chaiwopu peatland (43.48°N, 87.93°E, 2168.5 m) on the northern Tianshan slope, where δ^{13}Ccell records indicate Late Holocene moisture variations consistent with other proxies.

The δ^{18}Ocell signal reflects precipitation isotopic composition. Peat plants absorb water primarily from soil, which is sourced from atmospheric precipitation. Thus, δ^{18}Ocell mainly records precipitation δ^{18}O. During November-January, precipitation falls as snow, which contributes significantly to the water available for plant uptake during the growing season. Modern hydrological investigations at Halasazi peatland (2450 m) support this, showing that winter snowmelt accounts for 71% of peat water sources, making δ^{18}Ocell a signal of cold-season precipitation. Similarly, tundra peat in the western Ural Mountains fed by snowmelt shows δ^{18}Ocell strongly correlated with cold-season precipitation ($r = 0.73$, $P < 0.001$).

Notably, our results differ from high-altitude Halasazi peatland studies, which found δ^{13}Ccell correlated with warm-season temperature. This discrepancy likely reflects altitude differences: at higher elevations, temperature may dominate plant isotopic variation, whereas at lower elevations like Heiyangpo (1353 m), humidity and precipitation are primary controls. Both sites share consistent westerly moisture sources, but local environmental factors differ due to elevation.

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6. Conclusion

Based on 56 years of observational data (1962–2017), this study establishes that: 1. Heiyangpo peat δ^{13}Ccell values correlate significantly negatively with May–August relative humidity ($r = -0.52$, $P < 0.05$), serving as a reliable proxy for growing-season humidity. 2. δ^{18}Ocell values correlate significantly positively with November–January precipitation ($r = 0.49$, $P < 0.05$), serving as a reliable proxy for cold-season precipitation. 3. These relationships provide essential multi-year scale data for interpreting Holocene climate signals in Altai peat cellulose isotope records, addressing previous interpretation uncertainties.

Future work should strengthen seasonal-scale investigations of peat δ^{13}Ccell and δ^{18}Ocell to enhance understanding of regional climate change mechanisms.

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