Postprint: Variations in Pollen Type Diversity in Arid Central Asia under the Holocene Westerly Mode

Authors: Zhang Dongliang

Date: 2022-06-01T00:00:00+00:00

Abstract

Climate warming poses a significant threat to vegetation in the arid regions of Central Asia. Due to limited observation periods, we cannot adequately understand the relationship between plant diversity and climate change in arid regions over long timescales. However, pollen preserved in geological records provides an opportunity to understand the existence, distribution, and diversity characteristics of past vegetation. Taking the Altai Mountains as an example, three pollen sequences at different altitudes (high altitude–Halasazi peat, mid-altitude–Narenxia peat, and low altitude–Kanas Lake) were selected to investigate variation characteristics of pollen type diversity and its response patterns to Holocene climate change. The results show: (1) Variation in pollen type diversity in the Altai Mountains during the Holocene exhibits a unique pattern. Specifically, during the early Holocene, as climate warmed, the forest upper limit began to migrate upward, resulting in increased pollen type diversity at high altitudes. (2) During the mid-Holocene, the climate was warm and humid; upward and downward migration of both the forest upper and lower limits led to relatively high pollen type diversity at high and low altitudes, but pollen type diversity in the taiga-dominated forest belt was relatively low, mainly attributable to a decline in species evenness. (3) During the late Holocene, the climate became colder and more humid; the downward shift of the forest belt upper limit led to a significant increase in pollen type diversity at mid-altitudes. During the Holocene, the forest belt exhibited the greatest magnitude of change in pollen type diversity, making this region the most sensitive and vulnerable area to climate response. This study helps us grasp the response patterns of mountain vegetation belts to Holocene climate change and provides crucial evidence for exploring the migration history of mountain vegetation.

Full Text

Changes of Pollen Taxa Diversity in the Arid Central Asia under the Holocene Westerlies Mode: A Case Study of the Altai Mountains

ZHANG Dongliang1,2,3

1 Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
2 Research Center for Ecology and Environment of Central Asia, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
3 University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Climate warming poses a significant threat to vegetation in the arid Central Asia. However, the short duration of instrumental observations limits our understanding of long-term relationships between plant diversity and climate change in this region. Pollen records from geological archives provide an opportunity to investigate past plant presence, distribution, and diversity characteristics. This study examines pollen taxa diversity changes and their response patterns to Holocene climate variability using three pollen sequences from different elevations in the Altai Mountains: Halasazi Peat (high elevation), Narenxia Peat (mid-elevation), and Kanas Lake (low elevation). The results reveal a distinctive pattern of pollen taxa diversity change in the Altai Mountains. Specifically, during the early Holocene, warming climate caused the upper forest limit to migrate upward, increasing pollen diversity at high elevations. In the middle Holocene, warm and humid conditions drove both upward and downward migration of forest limits, resulting in higher diversity at high and low elevations but lower diversity within the taiga-dominated forest belt, primarily due to decreased species evenness. During the late Holocene, cooling and wetting climate forced the upper forest limit downward, significantly enhancing pollen diversity at mid-elevations. The forest belt exhibited the greatest magnitude of diversity change throughout the Holocene, identifying it as the most climate-sensitive and vulnerable zone. This study advances our understanding of mountain vegetation belt responses to Holocene climate change and provides critical evidence for reconstructing mountain vegetation migration history in arid Central Asia.

Keywords: Holocene; pollen taxa diversity; Altai Mountains; arid zone; Central Asia

1. Introduction

Global mean temperatures are approaching the upper limit of the past 10,000 years [1], with profound impacts on every biome across the planet [2]. These changes pose severe threats to fragile ecosystems in arid regions, causing tree growth decline and mortality [3]. Recent projections indicate that arid and semi-arid regions will experience significant warming and aridification, leading to habitat fragmentation and increased uncertainty in vegetation ecosystem evolution [4]. As climate change intensifies in the coming decades, protecting biodiversity and the services ecosystems provide to nature and humanity must be prioritized on international policy agendas [5]. Effective interventions require reliable predictions and evidence-based solutions, yet short-term observations make it difficult to forecast species- to ecosystem-level responses to climate change [6]. Consequently, evidence of biodiversity evolution from geological history has become critically important [7].

Pollen from geological records represents the most abundant paleoecological archive, offering evidence of past plant presence and distribution, and serving as highly effective material for paleo-diversity studies [8]. The Tianshan-Altai Mountains region in arid Central Asia represents a global biodiversity hotspot. Recent warming in this region has far exceeded the global average, increasing the frequency of extreme climate events [9]. This creates an urgent need to investigate relationships between pollen taxa diversity and climate using palynological methods. Previous studies have examined pollen diversity and mountain forest belt dynamics in the Tianshan Mountains [10, 11], particularly under the Holocene "Westerlies Mode" (characterized by low precipitation in the early Holocene and high precipitation in the mid-to-late Holocene) [12, 13]. However, pollen diversity patterns and vegetation belt migration processes remain unclear for the Altai Mountains.

Numerous pollen assemblage studies have been conducted across different altitudes in the Altai Mountains [14-20], providing data to assess whether past climate changes increased or decreased pollen taxa diversity and how they affected vegetation belt dynamics. This study selects three high-resolution pollen sequences from different elevations (Halasazi Peat, Narenxia Peat, and Kanas Lake) to investigate pollen taxa diversity responses to the Holocene Westerlies Mode. We address two scientific questions: (1) How did pollen taxa diversity evolve at different elevations during the Holocene? (2) How did Holocene pollen taxa diversity respond to temperature and precipitation changes?

1.1 Study Area

The Altai Mountains lie at the boundary between Siberian taiga and Central Asian deserts, with unique topography creating distinctive vegetation landscapes. The region has a mean annual temperature of -8 to 4°C and mean annual precipitation of 300-500 mm [21]. During cold seasons, Siberian High development dominates the region with cold-dry conditions, while westerly winds transport North Atlantic moisture during warm seasons [22]. Precipitation decreases eastward and continentality increases eastward across the Altai Mountains [23], a pattern clearly reflected in modern vegetation.

The southern slope of the Altai Mountains, approximately 750 km long, exhibits clear vertical vegetation zones [24, 25]: (1) Desert-steppe belt (<800 m), dominated by *Chenopodiaceae* and *Artemisia* desert types, with dominant species including *Ceratocarpus*, leguminous *Trifolium*, asteraceous *Cousinia*, *Artemisia*, *Polygonaceae*, and grasses; (2) Steppe belt (800-1400 m), primarily containing rosaceous *Spiraea*, *Ephedra*, grasses, sedges, legumes, and labiates; (3) Forest belt (1400-2300 m), dominated by mixed forests of Siberian larch and Siberian spruce, occasionally accompanied by poplar and birch; (4) Alpine meadow belt (2300-2700 m), dominated by sedges, grasses, rosaceous and caryophyllaceous herbs; and (5) Alpine tundra belt (2700-3200 m), dominated by mosses and lichens [Figure 2: see original paper].

1.2 Data Sources

This study utilizes three high-resolution pollen sequences from different elevations across the Altai Mountains: Halasazi Peat, Narenxia Peat, and Kanas Lake [Figure 1: see original paper].

Halasazi Peat (48°07 N, 88°22 E; 2450 m) is located in the alpine meadow belt. The core has AMS 14C dating with ~80-year resolution, analyzing 85 samples with >300 pollen grains per sample [26].

Narenxia Peat (48°48 N, 86°54 E; 1760 m) lies within the forest belt. The core has AMS 14C dating with ~70-year resolution, analyzing 95 samples with >300 pollen grains per sample [27].

Kanas Lake (48°43 N, 87°01 E; 1340 m) is near the lower forest limit. The core has AMS 14C dating with ~90-year resolution, analyzing 65 samples with >300 pollen grains per sample [28].

All three sites cover the entire Holocene period.

1.3 Pollen Diversity Index Calculation

We selected the Shannon-Wiener index (H) to quantify pollen taxa diversity. This index measures uncertainty in assigning randomly sampled individuals to taxa [29, 30]. Greater pollen taxon richness produces higher uncertainty, indicating higher diversity. The index is calculated as:

$$H = -\sum_{i=1}^{S} P_i \log(P_i)$$

where the logarithm can use base e; S represents pollen taxon richness; P_i is the proportion of individuals belonging to the ith taxon; n_i represents the count of each pollen taxonomic unit; and N is the total number of individuals across all pollen groups.

To examine relationships between different pollen types and diversity, we classified pollen into four components: taiga, tundra, steppe, and desert [31, 32]. The taiga component represents woody taxa, while the latter three represent non-woody components.

2. Results

2.1 Halasazi Peat

Correlation analysis between pollen components (tundra, taiga, steppe, desert) and the Shannon-Wiener index shows taiga component has the strongest correlation ($R^2 = 0.21$, $p < 0.01$), followed by desert and tundra components ($R^2 = 0.10$, $p < 0.01$), while steppe component shows no significant correlation ($R^2 = 0.00$, $p > 0.05$). These results indicate that taiga and desert vegetation contributed to pollen diversity at Halasazi Peat during the Holocene, with taiga making the largest contribution, while steppe vegetation contributed minimally.

The Holocene Shannon-Wiener index at Halasazi Peat averaged 1.77, showing no significant trend [Figure 4a: see original paper]. Periods above the mean occurred around 11,500-10,000 and 6,000-2,000 cal yr BP, with the remaining period below the mean. The highest value appeared around 2,500 cal yr BP, and the lowest around 11,000 cal yr BP.

Further tracking of woody and non-woody Shannon-Wiener indices reveals both follow the overall trend, but the woody index remains lower. The entire Holocene can be divided into three stages: early Holocene (11,500-8,500 cal yr BP) with low index values (mean = 1.68); middle Holocene (8,500-4,200 cal yr BP) with high values (mean = 1.85); and late Holocene (4,200 cal yr BP to present) with gradually declining values (mean = 1.78).

2.2 Narenxia Peat

Correlation analysis shows all four pollen components contributed to diversity at Narenxia Peat, with steppe component showing the strongest contribution ($R^2 = 0.92$, $p < 0.01$), followed by taiga ($R^2 = 0.57$, $p < 0.01$) and desert components ($R^2 = 0.20$, $p < 0.01$). Tundra component shows a negative correlation ($R^2 = 0.12$, $p < 0.01$) [Figure 3b: see original paper].

The Holocene Shannon-Wiener index at Narenxia Peat averaged 1.88, with clear trend changes dividing into three stages: early and late Holocene with high index values (mean = 1.95), and middle Holocene with low values (mean = 1.78). Both woody and non-woody indices follow the overall trend, but non-woody indices show greater variation amplitude than woody indices [Figure 4b: see original paper].

2.3 Kanas Lake

Correlation analysis indicates taiga, tundra, and desert components contributed to pollen diversity at Kanas Lake, with taiga showing the strongest contribution ($R^2 = 0.53$, $p < 0.01$), followed by desert ($R^2 = 0.40$, $p < 0.01$) and tundra components ($R^2 = 0.21$, $p < 0.01$). Steppe component shows significant negative correlation ($R^2 = 0.42$, $p < 0.01$) [Figure 3c: see original paper].

The Holocene Shannon-Wiener index at Kanas Lake averaged 1.75, with three distinct stages: middle Holocene with high values (mean = 1.85), and early and late Holocene with low values (mean = 1.68). Woody indices follow the overall trend, while non-woody indices show significant declining trends ($R^2 = 0.42$, $p < 0.01$) [Figure 4c: see original paper].

3. Discussion

Analysis of relationships between different pollen components (tundra, taiga, steppe, desert) and the Shannon-Wiener index across three altitudes reveals that taiga component positively affects diversity at all elevations, while other components show varying patterns [Figure 3: see original paper]. Steppe component contributes weakly to diversity at the upper forest limit, positively at mid-elevations, but negatively at the lower forest limit. These results demonstrate that Shannon-Wiener index calculations can reflect Holocene forest belt migration characteristics in the Altai Mountains.

The three study sites show inconsistent Shannon-Wiener index trends during the Holocene [Figure 4: see original paper]. During the early Holocene (11,500-8,500 cal yr BP), regional climate became warmer and drier. Halasazi and Narenxia peats show high index values, while Kanas Lake shows low values. For woody pollen, Halasazi and Kanas Lake show low values, while Narenxia shows high values, indicating the forest belt primarily occupied mid-elevations (Narenxia region) without expanding to Halasazi and Kanas Lake areas. As climate gradually warmed, the upper forest limit shifted upward, and with increasing humidity, the lower limit began moving downward. This forest belt migration gradually increased woody pollen diversity at Halasazi and Kanas Lake, while Narenxia, located within the forest belt, maintained high woody diversity.

During the middle Holocene (8,500-4,200 cal yr BP), the regional climate was warmest and wettest. Halasazi and Kanas Lake show high Shannon-Wiener indices, indicating rich pollen diversity, while Narenxia shows declining diversity. This pattern suggests that continued warming and wetting drove forest belt expansion both upward and downward, gradually occupying previously non-forested areas (Halasazi and Kanas Lake), thereby increasing woody pollen diversity in these regions. However, Narenxia recorded the lowest diversity of the entire Holocene, evident in both woody and non-woody indices. This decline likely resulted from: (1) warm-wet climate increasing spruce and larch areas within the forest belt [33], decreasing other tree species' area and evenness

[34], ultimately reducing woody diversity; and (2) forest belt expansion reducing interstitial grassland area, consequently decreasing non-woody diversity.

During the late Holocene (4,200 cal yr BP to present), climate became cooler and wetter. Halasazi and Narenxia peats show high Shannon-Wiener indices, while Kanas Lake shows declining diversity. For woody pollen, Halasazi index declines slowly, indicating downward forest belt migration under cooling-wetting conditions should increase diversity at mid-low elevations. However, Kanas Lake records decreasing diversity, contrary to expectations. This discrepancy may arise from: (1) continued cooling reducing taiga area migrating to lower elevations, decreasing woody diversity; and (2) intensified human activities and frequent fires at low elevations reducing pollen diversity.

Overall, under combined Holocene temperature and precipitation influences, Altai vegetation belts show unique patterns: early Holocene warming-drying drove upward forest belt migration, increasing high-elevation diversity; middle Holocene warming-wetting widened the forest belt, expanding upward and downward and significantly increasing woody diversity at high and low elevations, but decreasing diversity within the forest belt due to reduced species evenness; late Holocene cooling-wetting drove downward upper forest limit migration, significantly increasing mid-elevation diversity. These results demonstrate that forest belts move upward along elevation to obtain more moisture during warm-dry periods, and vice versa, while also adjusting belt width by moving downward to respond to warm-wet conditions [35].

Altai pollen diversity patterns reveal that mid-elevation areas (Narenxia region) show the largest vegetation diversity changes [Figure 4: see original paper], indicating the forest belt is the most climate-sensitive and vulnerable zone. Given moisture-sensitive taxa's limited climatic niche space and restricted habitat, water loss threatens the relatively narrow forest belt. When aridity exceeds thresholds, some forest belt taxa may disappear. For example, as a global biodiversity hotspot, the narrow vegetation belt in the eastern Andes is highly vulnerable to warming because expected climate velocities may shift narrowly distributed plant taxa beyond their climatic niches within centuries [36]. Notably, under current warming, the study region faces increasing drought risk with rising intensity and duration [37], potentially causing immeasurable threats to forest belt plant taxa in arid regions. Enhanced protection and maintenance of mountain forest belts are needed, particularly for moisture-sensitive species.

Although pollen-based paleo-diversity reconstruction may have biases due to identification precision, production, dispersal capacity, representation, and depositional environment differences [24, 32], pollen analysis remains a powerful method for reconstructing plant diversity, providing key evidence for studying mountain vegetation belt responses to Holocene climate change [8].

4. Conclusion

Analysis of altitude-based pollen taxa diversity changes recorded in Altai pollen sequences reveals: during the warm-dry early Holocene, the upper forest limit began migrating upward, gradually increasing high-elevation pollen diversity; during the warm-wet middle Holocene, the forest belt widened, expanding both upward and downward, significantly increasing woody pollen diversity at high and low elevations, but decreasing diversity within the forest belt due to reduced species evenness; during the cool-wet late Holocene, the upper forest limit migrated downward, significantly increasing mid-elevation diversity. These results demonstrate that Holocene temperature and moisture (or precipitation) jointly influenced forest belt migration, consequently affecting pollen diversity changes across elevations.

References

[1] Steffen W, Rockström J, Richardson K, et al. Trajectories of the earth system in the Anthropocene[J]. Proceedings of the National Academy of Sciences, 2018, 115(33): 8252-8259.

[2] Dawson T P, Jackson S T, House J I, et al. Beyond predictions: Biodiversity conservation in a changing climate[J]. Science, 2011, 332(6025): 53-58.

[3] Urban M C, Bocedi G, Hendry A P, et al. Improving the forecast for biodiversity under climate change[J]. Science, 2016, 353(6304): aad8466.

[4] Foden W B, Young B E, Akçakaya H R, et al. Climate change vulnerability assessment of species[J]. Wiley Interdisciplinary Reviews: Climate Change, 2019, 10(1): e551.

[5] Fordham D A, Jackson S T, Brown S C, et al. Using paleo archives to safeguard biodiversity under climate change[J]. Science, 2020, 369: eabc5654.

[6] Weng C Y, Hooghiemstra H, Duivenvoorden J F. Challenges in estimating past plant diversity from fossil pollen data: Statistical assessment, problems, and possible solutions[J]. Divers Distribution, 2006, 12: 310-318.

[7] Liu H Y, Park Williams A, Allen C D, et al. Rapid warming accelerates tree growth decline in semi-arid forests of Inner Asia[J]. Global Change Biology, 2013, 19: 2500-2510.

[8] Weng C, Hooghiemstra H, Duivenvoorden J F. Response of pollen diversity to the climate driven altitudinal shift of vegetation in the Colombian Andes[J]. Philosophical Transactions of the Royal Society B: Biological Sciences, 2007, 362(1478): 253-262.

[9] Franco A M, Hill J K, Kitschke C, et al. Impacts of climate warming and habitat loss on extinctions at species latitude range boundaries[J]. Global Change Biology, 2006, 12: 1545-1553.

[10] Huang J P, Yu H, Guan X D, et al. Accelerated dryland expansion under climate change[J]. Nature Climate Change, 2016, 6: 166-171.

[11] Zhang D L, Feng Z D. Holocene climate variations in the Altai Mountains and the surrounding areas: A synthesis of pollen records[J]. Earth Science Reviews, 2018, 185: 847-869.

[12] Chen F H, Yu Z, Yang M, et al. Holocene moisture evolution in arid Central Asia and its out-of-phase relationship with Asian monsoon history[J]. Quaternary Science Reviews, 2008, 27: 351-364.

[13] Cheng Y, Liu H, Wang H, et al. Climate-driven Holocene migration of forest-steppe ecotone in the Tien Mountains[J]. Forests, 2020, 11(11): 1139.

[14] Zhang Y, Kong Z C, Yan S, et al. Paleo-biodiversity at the northern piedmont of Tianshan Mountains in Xinjiang during the Middle to Late Holocene[J]. Acta Phytoecologica Sinica, 2005, 29(5): 836-844.

[15] Zhang D L, Chen X, Li Y M, et al. Holocene moisture variations in the arid Central Asia: New evidence from the southern Altai Mountains of China[J]. Science of the Total Environment, 2020, 735: 139487.

[16] Wang W, Zhang D L. Holocene vegetation evolution and climatic dynamics inferred from an ombrotrophic peat sequence in the southern Altai Mountains within China[J]. Global and Planetary Change, 2019, 172: 10-22.

[17] Zhang D L, Chen X, Li Y M, et al. Holocene vegetation dynamics and associated climate changes in the Altai Mountains of the arid Central Asia[J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2020, 550: 109744.

[18] Feng Z D, Sun A Z, Abdusalih N, et al. Vegetation changes and associated climatic changes in the southern Altai Mountains within China during the Holocene[J]. Holocene, 2017, 27(5): 683-693.

[19] Huang X Z, Peng W, Rudaya N, et al. Holocene vegetation and climate dynamics in the Altai Mountains and surrounding areas[J]. Geophysical Research Letters, 2018, 45(13): 6628-6636.

[20] Zhang D L, Yang Y P, Ran M, et al. Vegetation dynamics and its response to climate change during the past 2000 years in the Altai Mountains, northwestern China[J]. Frontiers of Earth Science, 2021, doi.org/10.1007/s11707-021-0906-9.

[21] Zhang D L, Lan B, Yang Y P. Comparison of precipitation variations at different time scales in the northern and southern Altai Mountains[J]. Acta Geographica Sinica, 2017, 72(9): 1569-1579.

[22] Blyakharchuk T, Chernova N. Vegetation and climate in the western Sayan Mts according to pollen data from Lugovoe Mire as a background for prehistoric cultural change in southern Middle Siberia[J]. Quaternary Science Reviews, 2013, 75: 22-42.

[23] Yuan G Y. The vertical zonation of the western Altai MTS[J]. Acta Geographica Sinica, 1986, 41(1): 32-40.

[24] Prentice I, Cramer W, Harrison S, et al. A global Biome model based on plant physiology and dominance, soil properties and climate[J]. Journal of Biogeograph, 1992, 19(2): 117-134.

[25] Prentice I, Guiot J, Huntley B, et al. Reconstructing biomes from palaeoecological data: A general method and its application to European pollen data at 0 and 6 ka[J]. Climate Dynamics, 1996, 12(3): 185-194.

[26] Walker M J C, Berkelhammer M, Björck S, et al. Formal subdivision of the Holocene series/epoch: A discussion paper by a working group of INTIMATE (integration of ice core, marine and terrestrial records) and the subcommission on Quaternary stratigraphy (international commission on stratigraphy)[J]. Journal of Quaternary Science, 2012, 27: 649-659.

[27] Marcott S, Shakun J, Clark P, et al. A reconstruction of regional and global temperature for the past 11300 years[J]. Science, 2013, 339: 1198-1201.

[28] Zhang D L, Huang X Z, Liu Q, et al. Holocene fire records and their drivers in the westerlies-dominated Central Asia[J]. Science of the Total Environment, 2022, 833: 155153.

[29] Hammer O, Harper D A, Ryan P D. Palaeontological statistics software package for education and data analysis[J]. Palaeontologia Electronica, 2001, 4(1): 9.

[30] Giesecke T, Wolters S, Jahns S, et al. Exploring Holocene changes in palynological richness in northern Europe–Did postglacial immigration matter?[J]. PLoS One, 2012, 7(12): e51624.

[31] Li Q, Zhao Y. Quantitative methods and progress of paleofloristic diversity reconstruction based on pollen assemblages[J]. Quaternary Sciences, 2018, 38(4): 821-829.

[32] Bush M B, Silman M R, Urrego D H. 48,000 years of climate and forest change in a plant species diversity hot spot[J]. Science, 2004, 303: 827-829.

[33] Li H, Li Z, Chen Y, et al. Drylands face potential threat of robust drought in the CMIP6 SSPs scenarios[J]. Environmental Research Letters, 2021, 16(11): 114004.

Note: Figure translations are in progress. See original paper for figures.