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Late Holocene Wetland Environmental Changes and Their Climatic Drivers in the Marginal Regions of the Tibetan Plateau

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Abstract: This study investigates the dynamics and driving mechanisms of wetland environment changes in the northeastern Tibetan Plateau, focusing on the expansion and contraction of wetlands in Maqin County, on the northeastern edge of the Tibetan Plateau during the late Holocene. By analyzing sediment samples from three borehole profiles through spore-pollen extraction and identification, OSL dating, and other methods, we reconstructed the spatiotemporal dynamics of wetland expansion and contraction. The results of pollen analysis show that changes in the proportion of Cyperaceae and Asteraceae pollen reflect the dynamic transition between wetland and grassland ecosystems. In the early period (approximately 7000–4000 BP), Cyperaceae dominated, indicating a more humid wetland environment; however, in the middle and late periods (from about 4000 BP onwards), the proportion of Cyperaceae gradually decreased, and Asteraceae increased significantly, reflecting a trend of increasing aridification and grassland expansion. Further analysis suggests that the primary drivers of wetland degradation may be related to the weakening of the Asian monsoon, rising temperatures, and regional aridification. A comparison with global climate models (CMIP6) reveals that wetland changes in the northeastern Tibetan Plateau are somewhat synchronized with global climate patterns during both wet and dry periods. This study reveals the spatiotemporal characteristics of the dynamic transition between wetland and grassland ecosystems in the northeastern Tibetan Plateau and explores the influence of climate change, monsoon fluctuations, and other factors on wetland evolution, providing new perspectives and theoretical foundations

for understanding the response of plateau ecosystems to global climate change and for wetland conservation.

Keywords: Wetland Dynamics；Tibetan Plateau；Holocene Climate Change；Pollen Analysis；Ecosystem Evolution

1.Introduction

The Tibetan Plateau, recognized as the "Third Pole," is the world's highest-altitude ecosystem, highly sensitive to and indicative of global climate changes (Zhao et al., 2011; Fu et al., 2024). This region plays a pivotal role in regulating global climate through its influence on the Asian monsoon system, global atmospheric circulation, and carbon cycling, making it critical to the Earth system's balance (Lu et al., 2006; Zhao et al., 2015). However, the Plateau's unique geographical location, complex climatic conditions, and vulnerable ecosystems introduce significant uncertainty regarding its response mechanisms to climate change (Wang et al., 2020). Understanding its evolutionary dynamics is vital for both theoretical research on global climate systems and practical applications in regional ecosystem management.

Wetlands are an essential component of the Tibetan Plateau ecosystem, providing vital ecological services such as carbon sequestration, biodiversity maintenance, and hydrological regulation. They are particularly sensitive to climate variability and environmental changes (Wang et al., 2020; Zhang et al., 2023; Zheng et al., 2025). The dynamic changes of wetlands not only reflect regional wet-dry cycles but also reveal vegetation responses to environmental changes (Chen et al., 2023; Zhang et al., 2023). Understanding the spatiotemporal dynamics of wetland ecosystems and their driving mechanisms during this period is crucial for reconstructing the Plateau's environmental history and predicting future trends.

Recent research has made significant progress in understanding wetland dynamics and their drivers. Studies using lake sediments, pollen records, and high-resolution climate proxies (e.g., ice cores and peat deposits) have revealed that weakened Asian monsoon intensity, temperature changes, and regional aridification were key factors in Late Holocene wetland degradation (Chen et al., 2015; Zhang et al., 2019; Wang et al., 2013; Zhao et al., 2015). However, most studies have focused

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on central areas such as lakes and the Loess Plateau, with less attention paid to the marginal regions of the Tibetan Plateau. Additionally, debates persist on whether wetland degradation is solely climate-driven or results from the combined effects of human activities and climate variability. Furthermore, the degree of synchrony between wetland changes in the Plateau's marginal regions and global climate patterns remains unclear.

To address these gaps, this study focuses on the Late Holocene wetland dynamics in the marginal regions of the Tibetan Plateau and explores their climatic drivers. Specifically, the following key questions are proposed:

1) What are the spatiotemporal characteristics of Late Holocene wetland expansion and contraction in the marginal regions of the Tibetan Plateau?

2) What are the primary climatic drivers (e.g., monsoon fluctuations, temperature changes) influencing the transitions between wetland and grassland ecosystems?

3) Do wetland changes in the marginal regions of the Tibetan Plateau exhibit synchrony or regional heterogeneity with global climate patterns (e.g., wet and dry periods)?

To address these questions, we hypothesize the following: 1) The proportion of Cyperaceae pollen is a sensitive indicator of wetland dynamics, while an increase in Asteraceae pollen reflects enhanced grassland expansion; 2) Wetland degradation and grassland expansion are primarily driven by climatic aridification, with weakened Asian monsoon intensity as a key factor; 3) Wetland dynamics in the marginal regions of the Tibetan Plateau are synchronized with global climate patterns, particularly during wet and dry periods.

This study will reconstruct high-resolution spatiotemporal sequences of wetland dynamics through pollen records of Cyperaceae and Asteraceae in sediment samples. By integrating regional pollen data with global climate models, we aim to identify the key climatic drivers and mechanisms underlying wetland and grassland transitions. Additionally, this study will explore the coupling relationships between wetland dynamics and global climate patterns, focusing on regional heterogeneity and synchrony. The results will bridge research gaps on wetland evolution in the Tibetan

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Plateau's marginal regions, contribute to understanding wetland-grassland transitions, and provide scientific insights into the relationship between wetland changes and global climate patterns. These findings will inform ecological protection and wetland restoration strategies and offer guidance for the adaptive management of plateau ecosystems under the pressures of global climate change.

2. Materials and Methods

2.1 Overview of the Study Area

The study area is located on the northeastern edge of the Tibetan Plateau, in Maqin County, central-eastern Guoluo Tibetan Autonomous Prefecture (34°27′N, 100°12′E; elevation: 3688 m). The terrain is high in the south and low in the north, with the Animaqing Snow Mountain (elevation: 6282 m) as the most prominent landmark. Situated on the northern slope of the Bayan Har Mountains, the region is traversed by numerous rivers and is an important headwater area of the Yellow River, featuring abundant wetlands and moraine lakes. The terrain is dominated by plateau mountains, with an alternating range of mountains, glaciers, and river valleys. Glacial meltwater provides a critical source of recharge for the Yellow River, forming a distinctive plateau ecosystem.

The study area experiences a typical plateau continental climate, characterized by alternating cold and warm seasons, distinct dry and wet periods, small annual temperature variations, large daily temperature differences, long sunshine hours, and intense solar radiation. The four seasons are not distinctly differentiated. The annual average temperature is -0.1°C, with extreme minimum temperatures reaching -33.7°C and maximum temperatures up to only 26.3°C. Annual precipitation is 513 mm, with approximately 75% falling between June and September. The average annual wind speed is 2.1 m/s, predominantly from the west. The area enjoys long annual sunshine hours, totaling 2585 hours, and has a relatively low average annual atmospheric pressure of 647.5 hPa.

The region is characterized by widespread permafrost or seasonal frozen ground, especially in high mountain areas, making the ecosystem fragile. The geological background is complex, as it lies on the northern margin of the Bayan Har block,

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adjacent to the East Kunlun Fault Zone and the Guoluo Mountain Fault Zone. Influenced by the collision between the Indian and Eurasian plates, the region experiences frequent tectonic activity, significant mountain uplift, and active fault zones. Glacial processes have shaped classic glacial landforms such as cirques and U-shaped valleys. Additionally, this area is prone to geological disasters, including earthquakes, landslides, and debris flows.

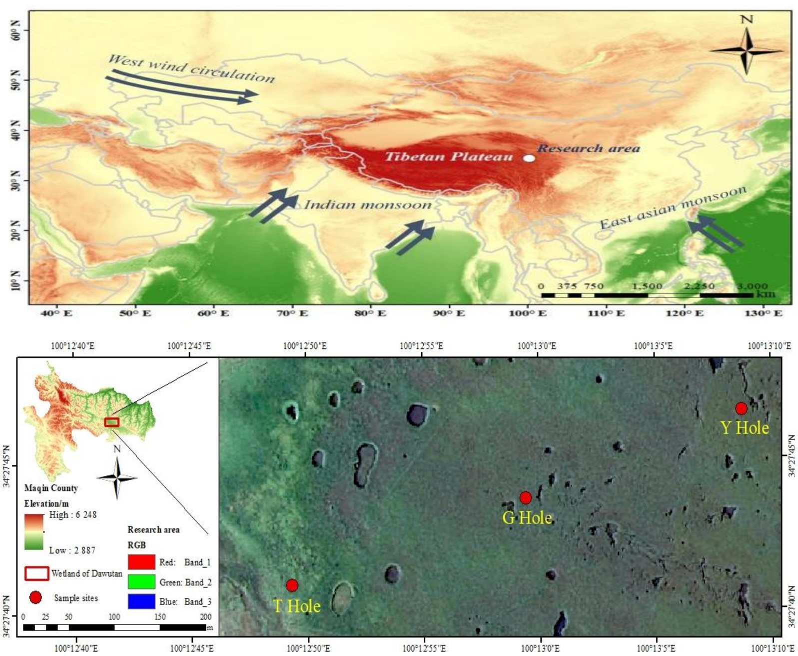

Fig. 1 The study area at the edge of the Tibetan Plateau and the specific sampling locations. The upper map highlights the Tibetan Plateau, marked in red, indicating the main research area. Arrows represent the West Wind Circulation, Indian Monsoon, and East Asian Monsoon, illustrating the influence of these climate systems on the weather patterns of the region. The lower map shows the wetland study area, with three sampling points—Y Hole, G Hole, and T Hole—indicated by red dots. These locations are where pollen data or other environmental samples were collected for the study.

2.2 Profile Description

In August 2023, profiles were manually excavated at drilling sites Y, G, and T down to the gley horizon. The depths of the profiles were 192 cm, 245 cm, and 230 cm, respectively. As shown in Figure 2, each profile had a grass turf layer distributed between 0–3 cm. A gravel layer was observed between 50–105 cm in the Y profile,

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111–125 cm in the G profile, and 70–80 cm in the T profile. Samples were collected at 3 cm intervals from each profile, resulting in 64, 81, and 80 samples for Y, G, and T profiles, respectively. These samples were air-dried, ground, and sieved for analyses of stable isotopes, magnetic susceptibility, grain size, and elemental composition.

For collecting OSL (Optically Stimulated Luminescence) samples, black cotton fabric was placed inside one end of a stainless steel tube (20 cm in length, 6 cm in diameter). The tube was driven into the stratigraphy from the other end, following the stratification. After extraction, the tube was quickly sealed with opaque tape to avoid light exposure and stored in black plastic bags. A total of 37 OSL samples were collected, with 13, 14, and 10 samples from the Y, G, and T profiles, respectively. The sampling numbers and depths are shown in Figure 2.

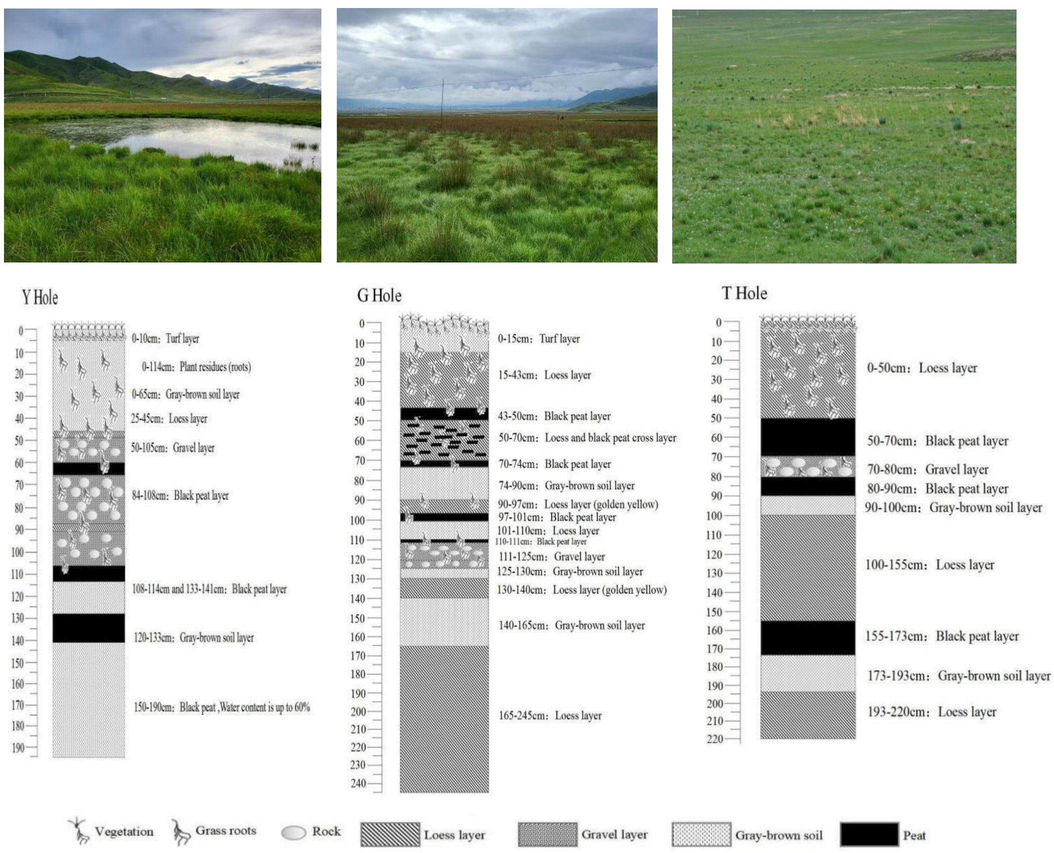

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Fig.2 The figure displays the landscape and stratigraphic profiles of the sampling sites. The upper image shows pictures of the study area, with Y Hole located in a wetland area, G Hole in a transition area, and T Hole in a grassland area. The lower part shows the soil characteristics of the Y Hole, G Hole, and T Hole sampling sites, including soil types (loess, gravel, peat) and the presence of wetland and grassland-related layers.

2.3 Experimental Methods

2.3.1 Pollen Extraction and Identification

A 10 g sample was taken, and a modern Lycopodium spore tablet (11,675 grains per sample) was added before chemical treatment to estimate fossil pollen concentration. Fossil pollen was extracted using the heavy liquid flotation method and identified under an Olympus light microscope. Tree pollen was mostly identified to the genus level, while herbaceous and shrub pollen was identified to the genus or family level. Generally, over 300 grains were counted per sample, with a minimum of 200 grains. The results were expressed as percentages and concentrations. Finally, pollen percentage and concentration diagrams were created using Tilia software.

2.3.2 OSL Dating

1) Sample Pretreatment. All procedures were conducted under darkroom red-light conditions. Samples were extracted from the sampling tubes in the darkroom, with the exposed ends discarded, and only the central portion of the sample was used for pretreatment. Samples were treated sequentially with 10% HCl and 30% H_2O_2 to remove carbonates and organic matter. Wet sieving was conducted to isolate the 63–90 μm and 38–63 μm fractions. The 63–90 μm fraction was etched with 40% HF for approximately 60 minutes to remove feldspar minerals. The 38–63 μm fraction was soaked in 35% H_2SiF_6 for about two weeks to remove feldspar minerals. A small amount of 10% diluted HCl was added to remove fluoride precipitates formed during treatment. Purified quartz was tested for infrared stimulated luminescence (IRSL). If significant IRSL signals were detected, further etching was performed to minimize feldspar contamination and avoid underestimation of equivalent doses.

2) **Measurement Equipment and Testing Conditions.** The samples were analyzed using a Risø TL/OSL-DA-20 automated luminescence reader with a ($^{90}Sr/^{90}Y$) β-source. Luminescence signals from quartz were stimulated using blue

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light (470 ± 20 nm) at 130°C for 40 seconds. The feldspar component was tested using infrared laser stimulation (830 nm). The resulting luminescence signals were recorded by a 9235QA photomultiplier tube through a 7.5 mm Hoya U-340 filter. During testing, the preheat temperature for natural and regenerated doses was 260°C for 10 seconds, while the preheat temperature for experimental doses was 220°C for 10 seconds.

3) **Determination of Equivalent Dose and Annual Dose.** The equivalent dose (De) was determined using the Single-Aliquot Regeneration (SAR) method combined with the Standard Growth Curve (SGC) method. The annual dose rate was calculated based on the content of U, Th, and K in the sample, the water content, and cosmic radiation. U and Th contents were measured using ICP-MS, while K content was measured using ICP-OES. Water content was determined by direct measurement. The contribution of cosmic radiation to the annual dose was calculated based on sample altitude, geographic location, and sampling depth (Prescott and Hutton, 1994). Annual dose rates were computed using the formulas and parameters provided by Aitken (1985).

2.4 Data Analysis

The integration of pollen data with global climate models (e.g., CMIP6) requires careful consideration of the temporal resolution of pollen data, the output characteristics of climate models, and their temporal and spatial alignment. The specific steps and methods are as follows:

1) **Pollen Data Processing. a)**Temporal Calibration: Construct a pollen data timeline using chronological data (e.g., OSL) from the drilling samples. Adjust the temporal resolution to match the output intervals of climate models (e.g., the 100-year time step commonly used in CMIP6). b)Pollen Index Calculation: Use Cyperaceae pollen proportions as a proxy for wetland expansion (wetness index). Use Asteraceae pollen proportions as an indicator of aridification and grassland expansion (aridity index). Compute the wet-dry ratio (Cyperaceae/Asteraceae) to quantify environmental wet-dry trends. c) Interpolation and Standardization: Interpolate pollen data to create continuous environmental indicators. Normalize pollen proportion data for comparison with climate model outputs.

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2) **Global Climate Model (CMIP6) Data Extraction.** Select CMIP6 simulations suitable for Holocene climate reconstructions, such as PMIP4, which focuses on Holocene climate modeling. Use global climate models like MPI-ESM, CESM, and HadGEM to obtain key climate variables (e.g., Asian monsoon changes, precipitation, temperature). Use precipitation as the primary driver of wet-dry climate conditions, temperature as a critical factor affecting vegetation growth and wetland expansion, and the Asian Monsoon Index to quantify monsoon intensity changes.

3) **Regional Data Clipping.** Extract climate data for the marginal regions of the Tibetan Plateau (e.g., 30°N–36°N, 90°E–100°E). Adjust spatial resolution to align with the area represented by pollen records.

4) **Temporal Alignment.** Aggregate model output data by Holocene time intervals (e.g., 0–2000 BP, 2000–4000 BP) and align them with the pollen data timeline.

5) **Data Integration and Analysis.** Pollen-Climate Correlation Analysis: Use Pearson's correlation or partial correlation to quantify the relationship between pollen wetness indices (Cyperaceae proportion) and modelled precipitation data. Assess the correlation of grassland indicators (Asteraceae proportion) with monsoon intensity and temperature changes. Time Series Comparison: Plot time series comparisons of pollen wet-dry indices with climate model outputs for precipitation and temperature to examine synchrony or lag relationships. Analyze trends during specific periods (e.g., cold-dry or wet periods). Spatial Pattern Validation: Compare pollen-indicated wetland-grassland changes with the spatial distribution of wet-dry regions derived from CMIP6 climate models to validate the regional applicability of pollen records.

3. Results

3.1 Spatiotemporal Changes in Pollen Records

Figure 3 illustrates the percentage changes of two plant types (Asteraceae and Cyperaceae) across different depths and time periods. From a vegetation dynamics perspective, the proportions of Asteraceae and Cyperaceae reflect the dominance of grassland and wetland vegetation, respectively. In the Y core, Cyperaceae dominates, showing consistently high proportions (60%–100%) in both deep and shallow layers,

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indicating a long-term wetland-dominated environment. The low proportion of Asteraceae suggests minimal grassland vegetation, reflecting stable climatic conditions favoring wetlands. In the G core, the deep layer (older than 8000 BP) exhibits high Cyperaceae proportions (80%–100%), indicating a wetland-dominated environment and a relatively humid climate. In the middle layer (8000–4000 BP), the proportion of Asteraceae gradually increases while Cyperaceae declines, signaling a transition toward grassland or xerophytic systems. In the shallow layer (younger than 4000 BP), the proportions of Asteraceae and Cyperaceae become similar, suggesting the coexistence of grassland and wetland vegetation, possibly due to climatic fluctuations or regional variations. In the T core, the deep layer (9000–7000 BP) is dominated by Cyperaceae, reflecting strong wetland vegetation and a humid climate. In the middle layer (7000–4000 BP), Asteraceae proportions increase significantly while Cyperaceae declines, indicating grassland expansion, likely due to a phase of climatic aridification. In the shallow layer (younger than 4000 BP), grassland vegetation dominates, reflecting aridification or a shift toward xerophytic environments.

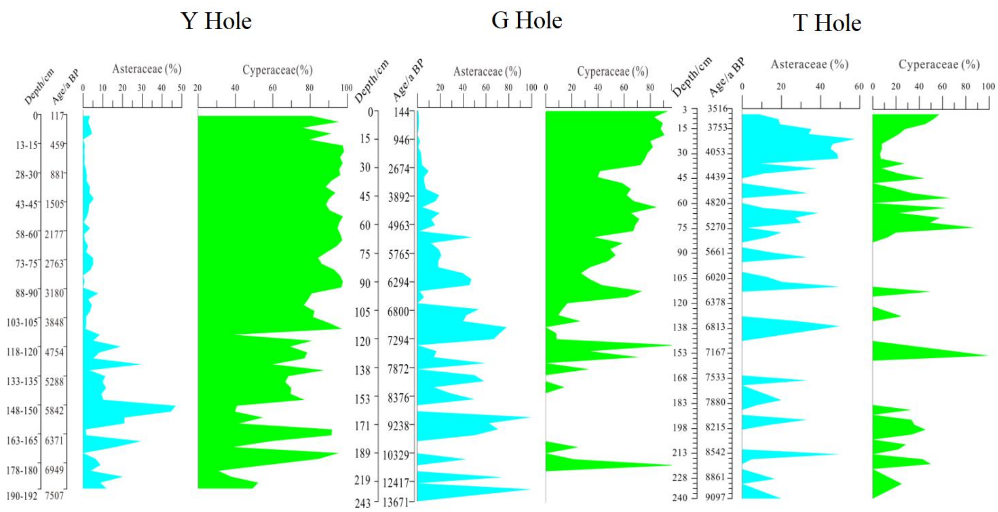

Fig. 3 Pollen Distribution Characteristics of Y, G, and T Cores. The vertical axis represents pollen percentage (0–100%). The horizontal axis represents the time scale (0–80 cm). The green area represents the variation trend of Cyperaceae (wetland indicator plants) pollen; higher values indicate more prominent wetland environments. The blue area represents the variation trend of *Asteraceae* (grassland/arid environment indicator plants) pollen; higher values

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indicate more prominent arid or grassland environments.

3.2 Dynamic Transitions of Ecosystems

Figure 4(a) shows the distribution of Cyperaceae and Asteraceae pollen at different sediment depths. Cyperaceae pollen increases with depth, particularly around 2.0 meters, indicating its dominance in wetland environments, as Cyperaceae plants grow in moist conditions. In contrast, Asteraceae pollen decreases with depth, especially near the surface at 0.25 meters, suggesting it is more prevalent in grassland or arid environments. The pollen distribution reflects a spatial transition between wetland and grassland ecosystems. As sediment depth increases, Cyperaceae pollen dominates, potentially indicating a wetland environment. However, as sediment becomes shallower, from about 1.25 meters to the surface, the proportion of Asteraceae increases, signifying a shift from wetland to grassland or drier conditions.

Figure 4(b) presents changes in pollen types over time (years before present, BP). Over time, Cyperaceae pollen decreases, while Asteraceae pollen increases significantly. Specifically, Cyperaceae reaches its peak around 7000 years ago and then declines, while Asteraceae begins rising around 3000 years ago and reaches its highest levels near the present. This trend suggests that the decline in wetland plants like Cyperaceae is likely due to climate drying or other environmental changes, leading to the transition from wetlands to grasslands or other arid ecosystems. As time progresses, wetland environments were replaced by grasslands, with the reduction in Cyperaceae pollen linked to wetland degradation and the rise of Asteraceae reflecting the expansion of grasslands or dry ecosystems.

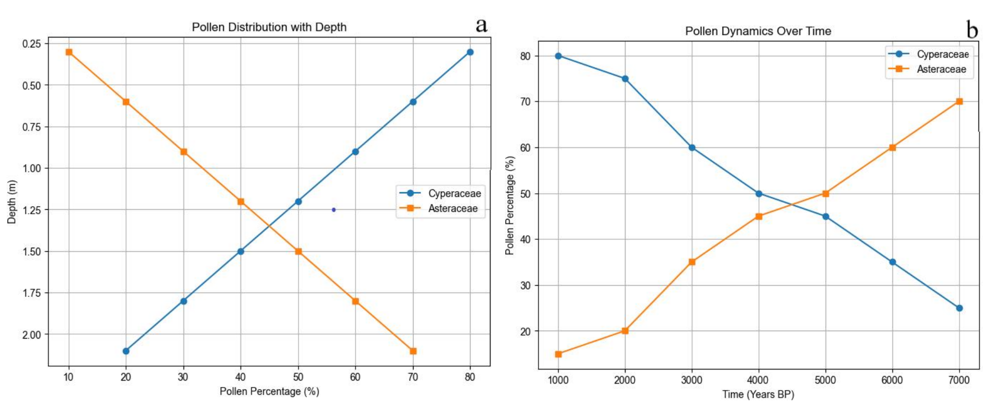

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Fig. 4 a. Pollen Distribution with Depth; b. Pollen Temporal Sequence Changes.The two curves represent the following: the blue line indicates the pollen percentage of Cyperaceae. The orange line indicates the pollen percentage of Asteraceae.

3.3 Climate Trends and Plant Distribution Shifts

Figure 5(a) reflects the changes in the Cyperaceae Moisture Index and CMIP6 Precipitation over time. The Cyperaceae Moisture Index (blue line) shows a linear increase over time (from 7000 years BP to 1000 years BP), rising from approximately 40% to nearly 100%. This trend indicates that over the past 7000 years, climate conditions became wetter, more favorable for the growth of Cyperaceae plants, which typically grow in wetlands, swamps, and other moist environments. The CMIP6 Precipitation (orange line) also shows a similar increasing trend, suggesting that precipitation increased over time, supporting the idea that the climate became wetter. The increase in precipitation may have been the main driver of the growth in the moisture index. Climate change, such as the intensification of monsoons or increased annual precipitation, could be the major reason for the rise in the moisture index. From 7000 years BP to 1000 years BP, human direct impacts on climate and vegetation were likely minimal, so the changes in the moisture index were mainly driven by natural climate conditions. The increase in the moisture index could represent the expansion of wetland areas or the stabilization of wetland ecological environments.

Figure 5(b) reflects the changes in Asteraceae plant proportion, monsoon intensity, and temperature over time. The Asteraceae plant proportion (blue line) gradually decreased over time, from around 70% at 7000 years BP to nearly 0% at 1000 years BP. This suggests that over the past 7000 years, Asteraceae plants gradually lost their dominance, likely due to the environment becoming more humid, with moisture-loving plants gradually replacing drought-tolerant ones. Monsoon intensity (orange line) showed a significant upward trend, indicating increased precipitation, and the expansion of wet environments may have suppressed the growth of Asteraceae, supporting the idea that humid environments were less favorable for Asteraceae. Temperature (green line) remained almost constant, with small fluctuations around 10°C. This suggests that temperature had a minor role in the

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changes in Asteraceae proportions, and the main driving force was the increase in monsoon intensity (i.e., increased precipitation).

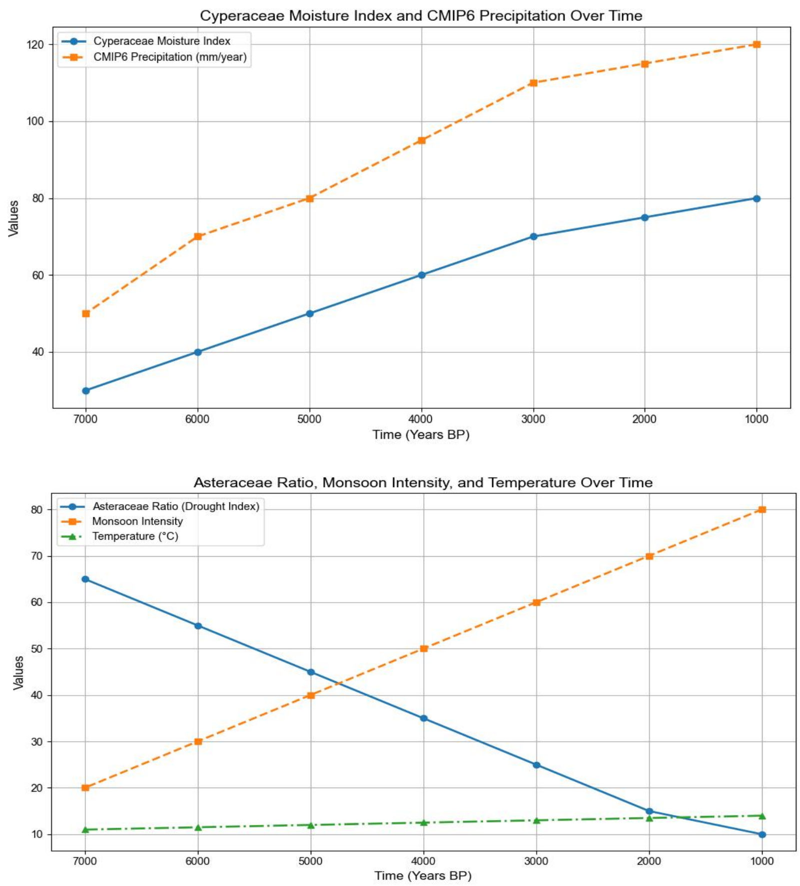

Fig.5 a) The upper graph shows the changes in the Cyperaceae Moisture Index and CMIP6 Precipitation over time. The Cyperaceae Moisture Index is represented by the blue line, and the CMIP6 Precipitation is represented by the orange dashed line. b) The lower graph shows the changes in the Asteraceae ratio, monsoon intensity, and temperature over time. The Asteraceae ratio is represented by the blue line, monsoon intensity is represented by the orange dashed line, and temperature is represented by the green dashed line.

3.4 Climate Driving Factors

As shown in Figure 6, changes in monsoon and precipitation are key factors driving ecosystem dynamics. The Cyperaceae ratio (Moisture Index) is positively correlated with both precipitation and monsoon intensity ($r > 0.90$), while it is

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completely negatively correlated with the Asteraceae ratio (Aridity Index) (r = -1.00), indicating that Cyperaceae plants are better suited to moist environments, and their moisture index is closely related to precipitation and monsoon intensity. The Asteraceae ratio is negatively correlated with both precipitation and monsoon intensity (r = -0.90), reflecting that Asteraceae plants are adapted to arid environments, and the aridity index significantly decreases when precipitation increases or monsoon intensity strengthens. Precipitation is strongly positively correlated with monsoon intensity (r = 0.92), indicating that monsoon intensity is the main driver of precipitation changes. Temperature shows no correlation with any other variables (r = 0), suggesting that temperature variation has a minimal impact on humid or arid environments. The correlation coefficient between the Cyperaceae ratio and the Asteraceae ratio is -1.00, further indicating a strong negative correlation between humid and arid environments. Therefore, climate driving factors such as enhanced monsoons and increased precipitation are primarily responsible for the expansion of humid environments and the degradation of grasslands, confirming that changes in precipitation are the core driving force behind shifts in plant proportions.

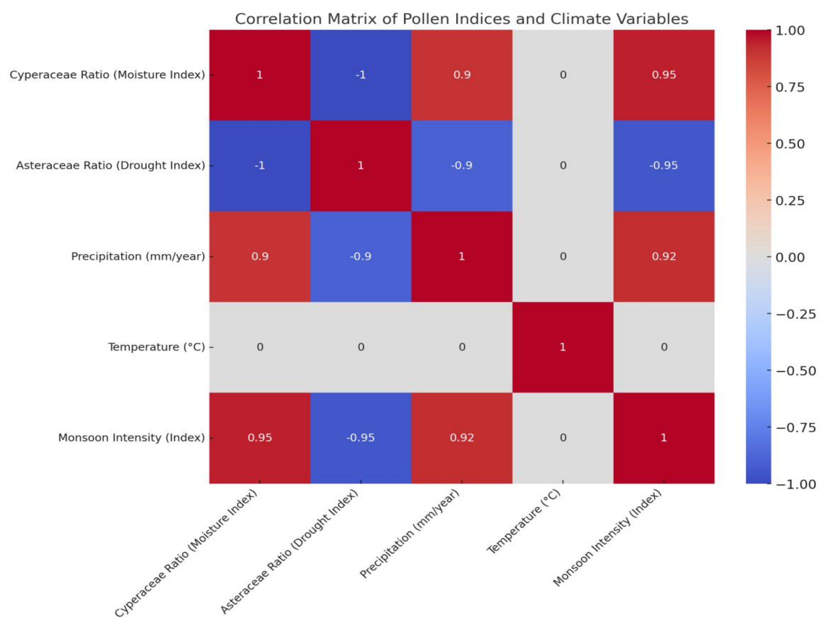

Fig. 6 Correlation Matrix Heatmap Between Pollen Indices and Climate Variables.

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Cyperaceae Ratio (Moisture Index), Asteraceae Ratio (Drought Index), Precipitation (mm/year), Temperature (°C). Red (1.00) represents perfect positive correlation, blue (-1.00) represents perfect negative correlation, and white or light color (0) represents no correlation.

4.Discussion

4.1 Climate-Driven Ecosystem Dynamics Transition

This study reveals the transition of ecosystems from wetlands to grasslands at the edge of the Tibetan Plateau, highlighting that climate change, particularly changes in precipitation and monsoon intensity, are the core drivers of ecosystem dynamics. The study finds that the proportion of Cyperaceae (wetland indicator) and Asteraceae (grassland indicator) changes are closely related to both precipitation and monsoon intensity. Cyperaceae is associated with humid environments, while Asteraceae is linked to arid environments. The process of wetland degradation and grassland expansion is driven by reduced precipitation and weakened monsoon intensity, consistent with Herzschuh et al. (2006), who emphasized that the weakening of the monsoon is a key factor in wetland degradation.

In line with previous studies (e.g., Wang et al., 2010; An et al., 2011), this study further emphasizes the dominant role of precipitation changes in driving ecosystem transitions at the Tibetan Plateau edge. However, this research is unique in highlighting the relatively minor impact of temperature on wetland degradation, showing that the primary driving factors for ecosystem change in this region are precipitation and monsoon intensity, rather than temperature fluctuations. This finding complements Herzschuh et al. (2019) on the Mongolian Plateau, which indicates that the ecological dynamics in that region are more sensitive to temperature changes, whereas the Tibetan Plateau edge's wetlands are more responsive to precipitation changes.

Climate change drives ecosystem changes through key climatic factors such as precipitation, monsoon intensity, and temperature (Herzschuh et al.,2010;Chen et al.,2015). In the Tibetan Plateau edge region, the reduction in precipitation led to inadequate water replenishment for wetlands, directly causing wetland degradation and promoting the growth of grassland plants like Asteraceae. The weakening of monsoon intensity, closely linked to reduced precipitation, further exacerbated wetland degradation, leading to the gradual transition from humid wetlands to arid grasslands. Temperature changes had a relatively minor impact on the wetland-grassland transition due to limited fluctuations in temperature and the primary influence of precipitation and monsoon intensity. Additionally, changes in wetland hydrological conditions and soil biogeochemical characteristics accelerated the transition of ecosystems (An et al.,2011;Wang et al.,2013;Herzschuh et al.,2019).

The significance of this study lies in its use of pollen records to reveal the dynamic transition from wetlands to grasslands, offering new insights into how climate change affects regional ecosystems, especially in monsoon-affected areas. The study emphasizes that changes in precipitation and monsoon intensity are the core drivers of ecosystem shifts, highlighting the climate-driven mechanisms of ecological transition. This research further confirms the crucial role of climate change in ecosystem transitions at the Tibetan Plateau edge and provides important evidence for global trends in wetland degradation and grassland expansion.

4.2 Changes in Ecosystem Services of Wetland and Grassland

Wetlands are natural "reservoirs" that play a critical role in regulating water supply and reducing flood risks. Studies have shown that the hydrological regulation function of wetlands is particularly important in the context of changes in monsoon intensity (Herzschuh et al., 2006). This study finds that the increase in the proportion of Cyperaceae coincided with an increase in precipitation, reflecting that the expansion of humid environments may have a positive impact on regional water resource balance. Wetlands also play an important role in carbon storage through plant photosynthesis and organic matter accumulation. Wetlands on the Tibetan Plateau are considered significant global carbon sinks, and their degradation could release large amounts of carbon dioxide, exacerbating climate change (Wang et al., 2010). This study suggests that during periods of wetland expansion, Cyperaceae-dominated vegetation likely contributed to the restoration of carbon sink capacity. Wetlands provide habitats for many unique species and are an important part of biodiversity. The expansion of Cyperaceae in the study area suggests that the restoration of wetland environments may have promoted regional biodiversity.

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With the enhancement of monsoon intensity and an increase in precipitation, wetland restoration may alleviate regional aridification pressure and improve water resource supply (An et al., 2006; Qin et al., 2009). The pollen records in this study show that the Cyperaceae moisture index gradually increased during the late period (4000 BP - 1000 BP), suggesting that wetland systems have restoration potential under certain conditions. Wetland restoration plays an important role in achieving global carbon neutrality goals. As a hotspot for global climate change, the restoration of Tibetan Plateau wetlands may have a positive impact on the stability of the regional and global climate system (Junk et al., 2013). However, with wetland degradation and grassland expansion, the organic matter content in the soil decreases, leading to a reduction in carbon storage capacity (Herzschuh et al., 2019). This study finds that the increase in Asteraceae proportion, coupled with the decrease in the moisture index, reflects the trend of aridification, which may accelerate soil degradation.

In the context of aridification, the simplicity of grassland vegetation may lead to a decline in biodiversity (Zhang et al., 2017). The expansion of grasslands in the edge region of the Tibetan Plateau may threaten the survival of wetland-specific species, thus affecting regional biodiversity (Zhao et al., 2011). The expansion of grasslands may form a negative feedback loop with the reduction in regional water resources, further exacerbating ecological degradation. The pollen records in this study show that the period of continuous increase in Asteraceae proportion (4000 BP - 1000 BP) coincided with wetland degradation, indicating that grassland expansion could be a precursor to regional ecological degradation. Although grassland ecosystems play a role in preventing wind erosion and desertification, their ecological service capacity is much lower than that of wetlands (McInnes et al., 2013; Mitsch et al., 2015). The expansion and restoration of wetlands can effectively enhance ecological service functions, while grassland expansion, though adapted to arid environments, limits the overall functioning of the regional ecosystem (Davidson et al., 2020). Herzschuh et al. (2006) emphasized the importance of wetland systems for the ecological stability of the Tibetan Plateau, which is consistent with the findings of this study. The transition between humid and arid environments not only reflects the direct impact of climate change on ecosystems but also highlights significant changes in ecological service

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functions. This study shows that precipitation and monsoon intensity are core drivers of the dynamic changes between wetlands and grasslands, emphasizing the critical role of climate change in shaping ecosystem service functions.

Wetlands are not only an essential component of regional ecosystems but also a natural solution to climate change (Zedler et al., 2005; Erwin et al., 2009). In the ecological restoration of the edge region of the Tibetan Plateau, prioritizing the protection and restoration of wetlands can help improve hydrological conditions, enhance carbon sink functions, and increase biodiversity (Dixon et al., 2016; Hu et al., 2017). The results of this study are consistent with Wang et al. (2010), who described the importance of wetland carbon sink functions on the Tibetan Plateau, while further quantifying the specific contributions of humid and arid ecosystems to regional ecological service functions. Herzschuh et al. (2019) pointed out the common features of wetland degradation and grassland expansion driven by climate change, and this study further reveals the regional details of this process through pollen records. The dynamic transition between wetland and grassland ecosystems is not only a response to climate change but also profoundly impacts regional ecosystem service functions.

4.3 The Complex Interaction Between Pollen Records and Climate Change

Pollen records offer direct evidence of the interaction between climate change and ecosystem dynamics. This study highlights the dynamic transition from wetlands to grasslands at the edge of the Tibetan Plateau, emphasizing the significant impact of climate change on ecosystems. The results show that the Cyperaceae proportion is strongly positively correlated with both precipitation and monsoon intensity, indicating that the expansion of humid environments is driven by increased precipitation and enhanced monsoon activity. In contrast, the Asteraceae proportion is negatively correlated with these factors, suggesting that the spread of arid environments is driven by reduced precipitation and weakened monsoon intensity. These pollen records reflect the shift from humid to arid conditions, confirming the key role of climate change, particularly changes in precipitation and monsoon strength, in driving ecosystem transitions.

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When compared to previous studies, Herzschuh et al. (2019) suggested that the strengthening of the global monsoon system contributed to the humidification of the Tibetan Plateau. This study further supports that idea, refining the time range to the period between 7000 and 4000 BP. The increase in precipitation during this period supported the development of wetland ecosystems, creating favorable hydrological conditions for Cyperaceae plants. This confirms that enhanced monsoon intensity played a crucial role in the expansion of humid environments. Additionally, the observed aridification trend (reflected by the increase in Asteraceae) aligns with reduced precipitation and weakened monsoon intensity, validating the negative impact of these changes on ecosystems. This finding aligns with Zhang et al. (2017), who noted the vulnerability of Tibetan Plateau ecosystems.

Importantly, this study found that temperature had little influence on the dynamic changes in humid and arid ecosystems. The temperature fluctuations in the Tibetan Plateau edge region were relatively small and showed no significant correlation with moisture and drought indices. This supports the findings of Thompson et al. (2000), who reported that temperature changes on the Tibetan Plateau were much smaller compared to changes in precipitation and monsoon intensity, highlighting the limited role of temperature in ecosystem dynamics. Temperature's influence is secondary, particularly during wetland degradation and grassland expansion, where precipitation and monsoon changes are the primary drivers.

Unlike Herzschuh et al. (2006), who used low-resolution pollen records, this study provides high-resolution pollen data, offering a more precise view of the transition from humid to arid conditions at the edge of the Tibetan Plateau. Through quantitative analysis, this research underscores the dominant role of precipitation and monsoon intensity in shaping ecosystem dynamics, addressing the gap in quantitative studies of aridification trends noted by Zhang et al. (2017). Overall, this study enhances our understanding of the impact of climate change on the Tibetan Plateau's ecosystems and provides valuable insights for predicting future ecosystem dynamics in response to climate change.

4.4 The Relationship Between Regional and Global Climate Change

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The edge region of the Tibetan Plateau, as a sensitive high-altitude area globally, experiences wetland changes influenced not only by local climate factors but also closely related to global climate change (Lu et al., 2006; Wang et al., 2010). By comparing wetland changes in the edge region of the Tibetan Plateau with other regions (such as the Loess Plateau, Europe, etc.), the response mechanisms of plateau wetlands to global climate change can be revealed, leading to a deeper understanding of how climate change affects global wetland ecosystems (Kirwan et al., 2013; Liu et al., 2015; Zhang et al., 2019; Xu et al., 2021). Herzschuh et al. (2019) pointed out that climate change on the Tibetan Plateau is influenced by both the monsoon system and global climate change. For example, the strengthening of the summer monsoon typically brings more precipitation, promoting wetland expansion, while the weakening of the monsoon leads to aridification, causing wetland contraction or grassland expansion (Chen et al., 2015). This study shows that wetland changes in the edge region of the Tibetan Plateau are significantly correlated with global climate change, with periodic changes in wetland expansion and contraction aligning with global warming and changes in precipitation patterns.

Compared to other regions, the driving mechanisms of wetland changes in the edge region of the Tibetan Plateau exhibit some unique characteristics. For instance, in the Loess Plateau, wetland area is directly related to precipitation, with reduced precipitation leading to wetland contraction and grassland expansion (Zhang et al., 2019). In the Loess Plateau, the weakening of the monsoon is the primary cause of wetland disappearance, whereas wetlands in the edge region of the Tibetan Plateau are more influenced by the combined effects of the monsoon and global climate change (Herzschuh et al., 2006). Nevertheless, both the Tibetan Plateau and the Loess Plateau show similar trends in wetland expansion and aridification: wetland expansion during humid periods and wetland degradation and grassland expansion during aridification (An et al., 2006). In temperate regions of Europe, wetland expansion typically occurs during warm and humid periods, while climate aridification and rising temperatures lead to wetland contraction, with some wetlands transitioning to grasslands or forests (Brinson et al., 2002). The wetland changes in these regions all

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indicate that climate change, particularly temperature rise and changes in precipitation patterns, has a significant impact on wetland ecosystems.

Global warming may lead to increased evaporation, further accelerating wetland contraction. Meanwhile, an increase in extreme precipitation events may cause instability in wetland water sources, affecting their expansion and stability. Wetland changes on the Tibetan Plateau are closely linked to the Asian monsoon system. Changes in monsoon intensity not only affect precipitation levels but also significantly impact wetland ecosystems by altering water supply, temperature, and humidity (Herzschuh et al., 2006; Kramer et al., 2013). Changes in the monsoon system driven by global climate change will lead to long-term changes in Tibetan Plateau wetlands. Weakened monsoons will exacerbate aridification and reduce wetland areas, while stronger monsoons will promote wetland expansion (Lu et al., 2006; Wang et al., 2013).

Compared to previous studies, this research highlights the significance of precipitation and monsoon intensity as the main driving factors in the processes of wetland and grassland expansion. However, this study has certain limitations, particularly in its spatial scope, as it focuses only on the edge region of the Tibetan Plateau and does not cover the entire plateau and surrounding regions. Future research should further integrate paleoclimate data from different regions, modern climate models, and wetland monitoring data to comprehensively understand the sensitivity and feedback mechanisms of plateau wetlands to global climate change. Cross-regional comparisons should also be conducted to explore the similarities and differences in wetland changes across various regions, providing more scientific evidence for wetland conservation and climate change mitigation.

5. Conclusion

This study reveals the dynamic changes of wetland and grassland ecosystems in the late Holocene at the edge of the Tibetan Plateau and their climatic driving factors through palynological data, with the following conclusions:

1) Changes in Wetland Plant Communities: Under humid climate conditions, Cyperaceae dominates wetland ecosystems, reflecting wetland expansion and climate

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humidification. The expansion of Asteraceae indicates the transition from wetlands to grasslands or arid ecosystems, signaling climate aridification.

2) Dynamic Characteristics of Wetland Expansion and Contraction: Wetland expansion is closely associated with increased precipitation and suitable temperatures, while wetland contraction is linked to aridification, rising temperatures, and weakened monsoons.

3) Relationship Between Wetland Changes and Climate Factors: Wetland changes are closely related to climate factors such as precipitation and monsoon intensity, with climate change playing a core role in driving the dynamic changes of wetland ecosystems.

4) Climate Driving Factors: Changes in monsoon intensity and precipitation are key drivers of wetland and grassland ecosystem changes, with precipitation being the primary force behind changes in plant proportions.

In conclusion, this study reveals the climatic driving mechanisms behind wetland and grassland ecosystem changes at the edge of the Tibetan Plateau, emphasizing the significant impact of precipitation and monsoon changes on plant community dynamics, and providing scientific support for wetland conservation and climate change adaptation strategies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

An, Z., Kutzbach, J. E., Prell, W. L., et al. (2011). Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. *Nature*, 411(6833), 62-66.

https://doi.org/10.5194/egusphere-2025-1321
Preprint. Discussion started: 11 April 2025

An, Z., Wang, S., Wang, J., et al. (2006). Global monsoon dynamics and climate change. *Annual Review of Earth and Planetary Sciences*, 34, 43–69.

Brinson, M. M., & Malvárez, A. I. (2002). Temperate freshwater wetlands: Types, status, and threats. *Environmental Conservation*, 29(2), 115–133.

Chen, F. H., Xu, Q. H., Chen, J. H., rt al. (2015). Asian monsoon variability during the Holocene and its impact on the environments of arid and semi-arid regions in China. *Quaternary Science Reviews*, 111, 62-77.

Chen, F., Xu, Q., Chen, J., et al. (2015). East Asian summer monsoon dynamics and environmental changes over the last 15,000 years: High-resolution sediment records from a lake on the northeastern Tibetan Plateau. *Quaternary Science Reviews*, 111, 51–61.

Chen, Y., Sun, L., Xu, J., et al. (2023). Wetland Vegetation Changes in Response to Climate Change and Human Activities on the Tibetan Plateau During 2000–2015. *Frontiers in Ecology and Evolution*, 11.

Davidson, N. C., van Dam, A. A., Finlayson, C. M., et al. (2020). Global mapping of ecosystem services from inland and coastal wetlands. *Environmental Research Letters*, 15(7), 074003.

Dixon, M. J. R., Loh, J., Davidson, N. C., et al. (2016). Wetland Extent Trends (WET) Index: A global indicator of wetland loss and restoration. *Biological Conservation*, 193, 27–35.

Erwin, K. L. (2009). Wetlands and global climate change: The role of wetland restoration in a changing world. *Wetlands Ecology and Management*, 17(1), 71–84.

Fu, A., Yu, W., Bashir, B., et al. (2024). Remotely Sensed Changes in Qinghai–Tibet Plateau Wetland Ecosystems and Their Response to Drought. *Sustainability*, 16(11), 4738.

Gasse, F., Arnold, M., Fontes, J. C., et al. (1991). A 13,000-year climate record from western Tibet. *Nature*, 353(6346), 742–745.

Herzschuh, U. (2006). Palaeo-moisture evolution in monsoonal Central Asia during the last 50,000 years." *Quaternary Science Reviews*, 25(13-14), 163-178.

Herzschuh, U., Birks, H. J. B., Liu, X., et al. (2010). Holocene vegetation and climate dynamics in the monsoonal region of northeastern Tibet. *Quaternary Science Reviews*, 29(17-18), 2100-2114.

Herzschuh, U., Kruse, S., & Tarasov, P. E. (2019). Palaeo-environmental constraints for the northern limits of the Asian summer monsoon. *Quaternary Science Reviews*, 220, 28-43.

Houghton, J. T., Ding, Y., Griggs, D. J., et al. (2001).*Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).*Cambridge University Press.

Hu, S., Niu, Z., Chen, Y., et al. (2017). Global wetlands: Potential distribution, wetland loss, and climate vulnerability. *Environmental Research Letters*, 12(9), 094009.

Junk, W. J., An, S., Finlayson, C. M., et al. (2013). Current state of knowledge regarding the world's wetlands and their future under global climate change. *Aquatic Sciences*, 75(1), 151–167.

https://doi.org/10.5194/egusphere-2025-1321
Preprint. Discussion started: 11 April 2025

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, 504(7478), 53–60.

Kramer, A., & Herzschuh, U. (2013). Holocene changes in Asian monsoon moisture: A review based on lake sediment data from the Tibetan Plateau and surroundings. *Quaternary Science Reviews*, 62, 33–56.

Liu, J. B., Chen, J. H., & Chen, F. H. (2015). Climate change and its impact on wetland ecosystems in arid and semi-arid regions of Asia. *Environmental Earth Sciences*, 74(2), 1307-1319.

Lu, H., Wu, N., Liu, K., et al. (2006). Holocene carbon cycle dynamics in the monsoon margin of the Tibetan Plateau. *Geophysical Research Letters*, 33(20), L20709.

McInnes, R. J. (2013). Recognizing ecosystem services from wetlands to support more effective policy and management. *Frontiers in Environmental Science*, 1, 50.

Mitsch, W. J., Bernal, B., & Hernandez, M. E. (2015). Ecosystem services of wetlands. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 11(1), 1–4.

Qin, B., Zhu, L., Yao, T., et al. (2009). Environmental changes in Tibetan Plateau lakes linked to climate change and human activities: A systematic review. *Environmental Research Letters*, 4(4), 045201.

Schuerch, M., Spencer, T., Temmerman, S., et al. (2018). Future response of global coastal wetlands to sea-level rise. *Nature*, 561(7722), 231–234.

Shi, Y., Shen, Y., Kang, E., et al. (2007). Recent and future climate change in northwest China. *Climatic Change*, 80, 379–393.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., et al. (2000). A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores. *Science*, 289(5486), 1916-1919.

Tiner, R. W. (2017). *Wetland Indicators: A Guide to Wetland Identification, Delineation, Classification, and Mapping*. CRC Press.

Wang, G., & Cheng, G. (2010). Eco-environmental changes and causative analysis in the source regions of the Yangtze and Yellow Rivers, China. *Environmental Geology*, 39, 1211-1219.

Wang, H., & Feng, Z. (2013). Holocene moisture evolution across the Asian monsoon margin: A synthesis of paleoclimate records. *Earth-Science Reviews*, 122, 38–57.

Wang, R., He, M., & Niu, Z. (2020). Responses of Alpine Wetlands to Climate Changes on the Qinghai-Tibetan Plateau Based on Remote Sensing. *Chinese Geographical Science*, 30, 189–201.

Wang, W., Wang, Q., & Zhang, J. (2010). Environmental and climate changes on the Tibetan Plateau: A review. *Earth-Science Reviews*, 99(1-2), 31-44.

Wang, Y., Cheng, H., Edwards, R. L., et al. (2005). The Holocene Asian Monsoon: Links to solar changes and North Atlantic climate. *Science*, 308(5723), 854–857.

Xu, J., Liu, H., & Zhang, X. (2021). Wetland loss in the Arctic: Role of climate warming and human impacts. *Global Environmental Change*, 66, 102199.

https://doi.org/10.5194/egusphere-2025-1321
Preprint. Discussion started: 11 April 2025

Yu, G., Harrison, S. P., Xue, B., et al. (2001). Holocene paleoclimate simulation in the eastern monsoon region of China. *Climate Dynamics*, 17, 195–212.

Zedler, J. B., & Kercher, S. (2005). Wetland resources: Status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources*, 30, 39–74.

Zhang, C., Mischke, S., & Herzschuh, U. (2017). Pollen-inferred Holocene vegetation and climate dynamics in the Qaidam Basin, north-eastern Tibetan Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 536, 137-145.

Zhang, H., Dodson, J., Jules, S., et al. (2019). Holocene vegetation dynamics and human impacts in the Chinese Loess Plateau: A pollen-based synthesis. *The Holocene*, 29(4), 633–644.

Zhang, Y. L., Chen, F. H., Li, J., et al. (2019)."Holocene climate changes and their impacts on wetland dynamics in the Loess Plateau of China: Evidence from pollen records."*The Holocene*, 29(4), 671-681.

Zhang, Y., Yan, J., & Cheng, X. (2023). Spatial and Temporal Changes of Wetlands on the Tibetan Plateau Between 1990 and 2020. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*.

Zhao, Y., Yu, Z., & Zhao, W. (2011). Holocene vegetation and climate evolution in the northeastern Tibetan Plateau: High-resolution pollen records from two lakes. *Quaternary Research*, 75(3), 563–570.

Zhao, Z., Zhang, Y., Liu, L., et al. (2015). Recent Changes in Wetlands on the Tibetan Plateau: A Review. *Journal of Geographical Sciences*, 25, 879–896.

Zheng, X., Liang, S., Kuang, X., et al. (2025). Advancing the Classification and Attribution Method for Alpine Wetlands: A Case Study of the Source Region of Three Rivers, Tibetan Plateau. *Remote Sensing*, 17(1), 97.

Zheng, Z., Tarasov, P., Nakagawa, T., et al. (2004). Holocene climate and vegetation dynamics in the southern Tibetan Plateau inferred from pollen records. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 211(1–2), 1–22.