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RESEARCH ARTICLE

Vegetation stability during the last two centuries on the western Tibetan Plateau: a palynological evidence

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Abstract Investigating the dynamics of vegetation is an essential basis to know how to protect ecological environments and to help predict any changes in trend. Because of its fragile alpine ecosystem, the Tibetan Plateau is a particularly suitable area for studying vegetation changes and their driving factors. In this study, we present a high-resolution pollen record covering the last two centuries extracted from Gongzhu Co on the western Tibetan Plateau. Alpine steppe is the predominant vegetation type in the surrounding area throughout the past 250 years with stable vegetation composition and abundance, as revealed by pollen spectra dominated by *Artemisia*, Ranunculaceae, Cyperaceae, and Poaceae. Detrended canonical correspondence analysis (DCCA) of the pollen data reveals low turnover in compositional species (0.41 SD), suggesting that the vegetation in the Gongzhu catchment had no significant temporal change, despite climate change and population increases in recent decades. We additionally ran DCCA on ten other pollen records from the Tibetan Plateau with high temporal resolution (1–20 years) covering recent centuries, and the results also show that compositional species turnover (0.15–0.81 SD) is relatively low, suggesting that the vegetation stability may have prevailed across the Tibetan Plateau during recent centuries. More high-resolution pollen records and high taxonomic-resolution palaeo-vegetation records (such as sedaDNA), however, are needed to confirm the vegetation stability on the Tibetan Plateau.

Keywords pollen, compositional species turnover, vegetation change, ecological stability

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1 Introduction

The stability of ecosystems is an important concept in ecology, and is key to maintaining the ecosystem service function of the Earth (Holling, 1973; Radchuk et al., 2019; Chen et al., 2021). Nowadays, due to climate change and human disturbance, ecosystems are under stress and some have been severely damaged and thus will be difficult to restore (Pennekamp et al., 2018). To help protect ecosystems and their functioning, it is necessary to research the resilience of the ecosystem, particularly fragile ecosystems.

The Tibetan Plateau is an alpine ecosystem at high elevation (average elevation exceeds 4000 m a.s.l. (above sea level)), with a complex climate and fragile vegetation (Qiu, 2008; Miehe et al., 2019). It is a significant study area for past and recent ecosystem changes (Piao et al., 2019). Vegetation is an important part of terrestrial ecosystems and can respond to changes in the ecosystem rapidly and directly (Chen et al., 2020). The driving factors of vegetation change on the Tibetan Plateau have been widely investigated, primarily focused on the Holocene (Miehe et al., 2011b; Shen et al., 2015; Cui et al., 2021; Li et al., 2021). Due to the increase in human population and grazing activities during recent decades, several studies have attributed the degradation of vegetation on the Tibetan plateau to anthropogenic causes (Chen et al., 2013; Wang et al., 2015). However, it has been argued that current vegetation changes are still largely influenced by climate (Miehe et al., 2011a; Wang et al., 2017). For example, Wang et al. (2017) conclude that their vegetation survey method found that vegetation changes in pastoral area were mainly the result of changes in the climatic environment rather than of intensified grazing. Evidence from observational studies shows that the driving factors of vegetation change are contested and should continue to be researched. The above studies focus on recent vegetation change over the last few decades, but their baseline may already be unnatural vegetation communities. It is therefore necessary to study terrestrial ecosystem change from further back in time, using an indicator approach for example, to assess whether any change has exceeded the ecosystem's tolerance threshold or whether it is still in a stable state.

Pollen data derived from lake sediments can be used to analyze vegetation change over long-term scales of continuity (Cao et al., 2019, 2023; Liu et al., 2022; Wang et al., 2022). Numerous studies have used pollen analysis to discuss the response of vegetation to climate and human activities (Zhao et al., 2008; Cui et al., 2021; Cao et al., 2022; Zhang et al., 2022), though the size of lakes could also affect the sensitivity of the vegetation to environment change (Tarasov et al., 2007; Tian et al., 2014). Additionally, high-resolution pollen data are also an important factor for analyzing vegetation change, which can provide more detailed information (Tian et al., 2014). Many of the high-resolution studies already carried out on the Tibetan Plateau, have mainly been used to reconstruct changes in precipitation and temperature, while few have studied the terrestrial ecosystem (Li et al., 2017; Sun et al., 2020). These short-scale, high-resolution vegetation change studies are mainly concentrated on the eastern Tibetan Plateau, and are scarce in the western region, thus preventing a comprehensive understanding for the entire Tibetan Plateau.

In this study, we present a high-resolution fossil pollen record from Gongzhu Co on the western Tibetan Plateau covering the past 250 years. We analyzed the fossil pollen assemblages to reconstruct the history of the regional vegetation and estimated selected diversity metrics. We then collated additional high-resolution pollen records covering the past 1000 years to assess ecosystem stability. We aim to determine i) the main drivers of change in vegetation composition in Gongzhu Co during the past 250 years; and ii) whether the ecosystem was stable on the Tibetan Plateau during recent centuries.

2 Study area

Gongzhu Co (82.15°E, 30.39°N, 4786 m a.s.l.) is located in Pulan County, Ngari Prefecture on the western Tibetan Plateau (Fig. 1). The lake, with an area of 66.2 km^2, is an inland lake and mainly recharged by inflowing rivers. The climate of the study area is alternately affected by Westerlies and the Indian Summer Monsoon. According to meteorological data of Pulan meteorological station (30.28°N, 81.25°E, ~100 km to the south-west of Gongzhu Co, 3900 m a.s.l.), the mean annual precipitation (MAP) was 159 mm and the mean annual air temperature (MAT) was 3.5°C (1973–2015 data). Within the lake catchment area, the main vegetation type is alpine steppe (Fig. 1(a)), and the dominant species are *Artemisia*, *Stipa*, *Kobresia*, *Saussurea*, *Heteropappus Suaeda*, *Potentilla*, and *Oxytropis* (Fabaceae) (Jin et al., 2022). In the hilly areas of the catchment, there is a small amount of shrub vegetation with *Caragana spinosa*.

3 Material and methods

3.1 Sampling and dating

A 30.5-cm-long sediment core was collected in 2016 using a UWITEC gravity corer with a 6-cm diameter. The core was sub-sampled continuously at 0.5-cm intervals in the laboratory. Prior to analysis, all sub-samples were freeze-dried.

The chronology of the sediment core was determined using a combination of ^{210}Pb and ^{137}Cs dating and quadratic polynomial extrapolation. ^{210}Pb is a naturally produced radionuclide, which can exist in lake sediment for nearly two hundred years (Appleby et al., 1997). ^{137}Cs is an artificially produced radionuclide generated from nuclear weapons testing (Cremers et al., 1988). The combined dating method of ^{210}Pb and ^{137}Cs is the preferred method for the study of centennial-scale lake sedimentary records (Gao et al., 2021). We weighed and filled 7 mL centrifuge tubes with lyophilized samples and sealed them for 3 weeks before testing on a machine. The dating was conducted at 1-cm intervals for the upper part (0–22.25 cm) at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS). An age-depth model was constructed using *Plum* software, which is a new Bayesian model and can provide a more robust and objective chronology and better estimates of uncertainties (Aquino-López et al., 2018).

3.2 Pollen analysis and numerical analyses

A total of 54 sediment samples were selected for pollen analysis. Pollen samples were treated using the modified acetolysis procedure (Fægri and Iversen, 1989), including HCl (10%), NaOH (10%), HF (40%), and acetolysis (9:1 mixture of acetic anhydride and sulphuric acid), fine sieving (7 μm mesh), and then mounted on slides in glycerine for counting. A tablet of *Lycopodium* spores (27,560 grains tablet^{-1}) was added to each sample before processing to calculate the absolute pollen concentration (Maher, 1981). All samples were counted using a ZEISS optical microscope at 400 × magnification. The main references for identification are the modern pollen reference slides from the Tibetan Plateau and published reference books and photographs (Wang et al., 1995; Tang et al., 2016; Cao et al., 2020). More than 500 terrestrial pollen grains were counted for each sample; although for a few samples (about 10) with low pollen concentration, more than 2000 grains of *Lycopodium* spores were counted to ensure the reliability of the

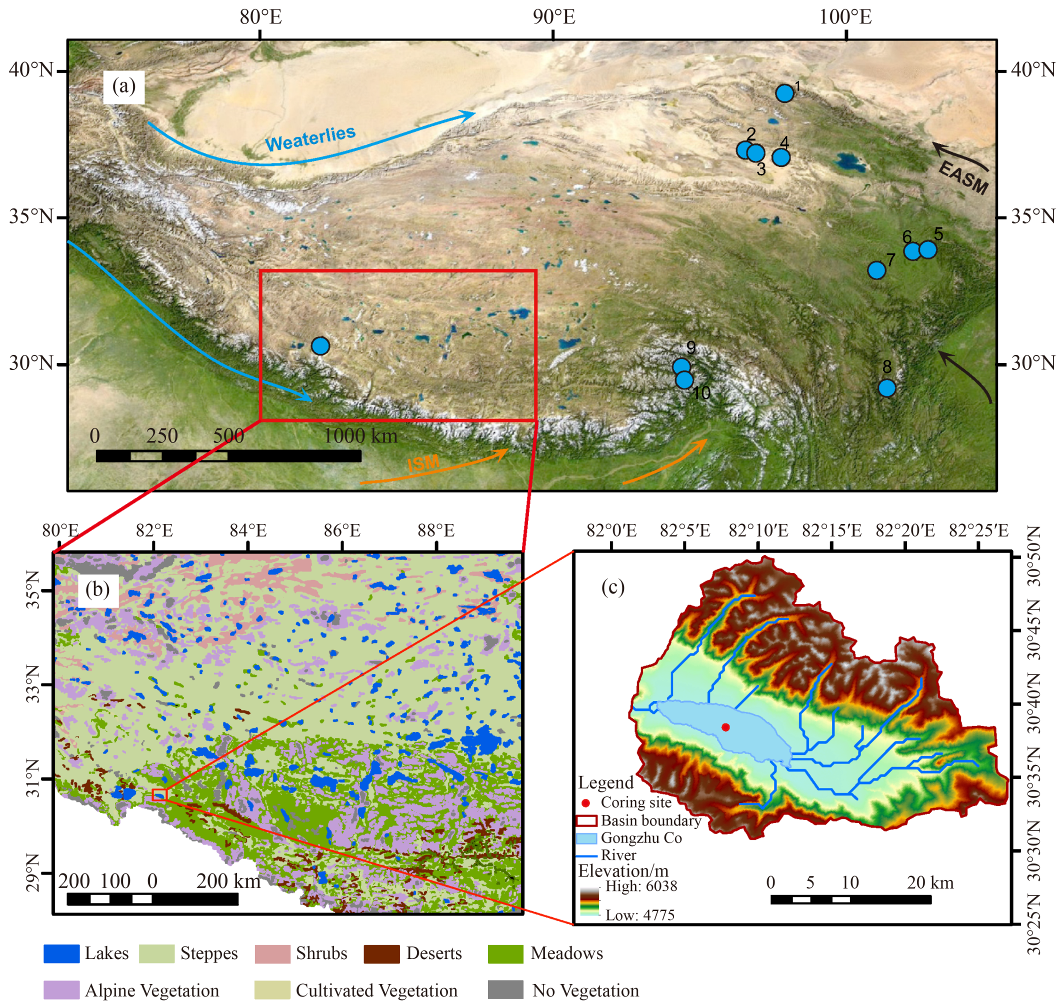

Fig. 1 (a) Location of Gongzhu Co on the Tibetan Plateau. The archives mentioned in the discussion section are also marked (blue dots): (1) Tian'E Lake, (2) Hurleg Lake, (3) Toson Lake, (4) Gahai Lake, (5) Flower Swamp, (6) Xing Co, (7) Dongerwuka Lake, (8) Wuxu Lake, (9) Lake LC6, (10) Basomtso. (b) Vegetation types around Gongzhu Co. (c) Topography of Gongzhu Co catchment.

numerical analyses. The percentages of terrestrial pollen taxa were calculated based on the sum of terrestrial pollen counts. Concentrations of pollen were calculated based on their counts together with the ratio of counted and total grains of *Lycopodium* spores. Pollen zones were classified by a constrained incremental sum of squares (CONISS) cluster analysis based on the square-root transformed percentages of all terrestrial taxa using Tilia software (Grimm, 2004).

Pollen taxa present in at least 2 samples and with a maximum $\geqslant 2\%$ in at least one sample ($n = 17$) were selected and their percentages were square-root transformed to stabilize variances and optimize the signal-to-noise ratio (Prentice, 1980). Detrended correspondence analysis (DCA) was first used to determine the gradient length of the data (Hill and Gauch, 1980). Since the gradient length of the first axis was less than 2 standard deviations, a linear method of principal component analysis (PCA, ter Braak and Prentice, 2004) was chosen to explain the variations in pollen assemblages. DCA and PCA were performed using the *decorana* and *rda* functions in the *vegan* package (version 2.6-4; Oksanen et al., 2022) for R.

Pollen diversity and richness were estimated using Hill numbers (Hill, 1973; Jackson and Blois, 2015). Diversity was calculated using the iNEXT package version 2.0.12, which includes rarefaction (Chao et al., 2014; Hsieh et al., 2016) for R (R Core Team, 2022). The results are given as the effective number of taxa. Richness (N0) is the total number of taxa in a community, while evenness, which is a measure of the relative frequency of species in the community, was calculated as the N2/N0 ratio, where N2 is the number of very abundant taxa in the sample (Jost, 2007; Rudaya et al., 2020). Detrended canonical correspondence analysis (DCCA) was applied to estimate the overall compositional species turnover measured in standard deviation (SD) units (as beta diversity), which provides an estimate of compositional change along a temporal gradient (ter Braak and Verdonschot, 1995; Wang and Herzschuh, 2011; Cao et al., 2019; Felde et al., 2020). DCCA was implemented using the program CANOCO 5 for Windows (ter Braak and Šmilauer, 2012). In DCCA, species data were square-root transformed, and nonlinear rescaling and detrending by segments was applied. We not only analyzed data from Gongzhu Co, but also pollen records from elsewhere on the Tibetan Plateau. We collected ten high-resolution (about 1–20 years) fossil pollen records with $^{210}Pb/^{137}Cs$ dating covering the last thousand years: for further information see Table 1.

4 Results

4.1 Chronology

The age-depth model for the short core from Gongzhu Co was constructed using ^{210}Pb and ^{137}Cs activities in the upper 22.25 cm, while quadratic polynomial extrapolation for depths from 22.5 to 30.5 cm (Fig. 2(a)). Peak ^{137}Cs activity occurred at depth of ~9 cm (regarded as the 1963 CE) (Fig. 2(c)), and plum results indicate an age of −24 ± 11 year BP (before present; equal to 1974 CE) for the same depth (Fig. 2(b)), and therefore, we regard the dating results as reliable generally (Appendix). We choose the quadratic polynomial to estimate ages for depths from 22.5 to 30.5 cm (R^2 = 0.9995). Thereby, the short core covers a age range from 1766 to 2016 CE and pollen analysis has a high temporal resolution (ca. 4 years per sample).

4.2 Fossil pollen assemblages

Fifty-two pollen taxa were identified from the 54 samples. The pollen spectra are strongly dominated by herbaceous pollen taxa, such as *Artemisia* (26.8%–41.7%;

Table 1 Site details and detrended canonical correspondence analysis (DCCA) axis 1 scores (in standard deviation (SD) units) as estimates of compositional species turnover for Gongzhu Co (our study) and ten other lakes from the Tibetan Plateau

No.	Lake	Latitude/ °N	Longitude/ °E	Elevation/ (m.a.s.l.)	Lake Area/ km^2	Time span/ yr	Temporal resolution/ yr	SD units	Reference
	Gongzhu Co	30.39	82.15	4786	56.00	240	4	0.41	Our study
1	Tian’E Lake	39.24	97.92	3012	0.05	300	7	0.53	Wang et al. (2020)
2	Hurleg Lake	37.28	96.90	2818	52.00	1700	18	0.17	Zhao et al. (2010)
3	Toson Lake	37.15	97.00	2808	150.00	994	10−20	0.15	Zhao et al. (2010)
4	Gahai Lake	37.13	97.52	2853	37.00	50	1	0.30	Zhao et al. (2008)
5	Flower Swamp	33.91	102.81	3440	–	600	15	0.43	Sun et al. (2020)
6	Xing Co	33.86	102.36	3437	3.00	1439	5−20	0.51	Zhang et al. (2022)
7	Dongerwuka	33.22	101.12	4307	0.24	600	18	0.38	Wischnewski et al. (2014)
8	Wuxu Lake	29.15	101.40	3705	0.50	200	7−20	0.36	Wischnewski et al. (2011)
9	LC6 Lake	29.82	94.45	4132	0.60	200	5−12	0.81	Wischnewski et al. (2011)
10	Basomtso	30.00	93.91	3479	26.50	1143	7	0.76	Li et al. (2017)

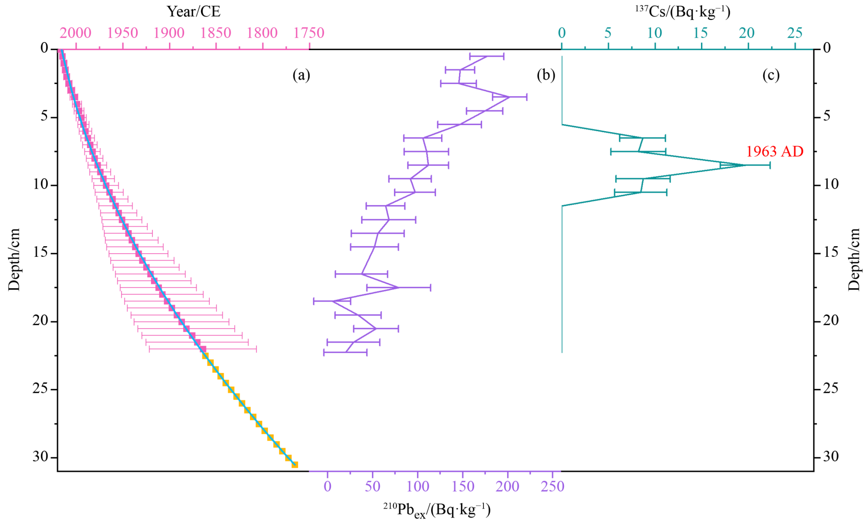

Fig. 2 (a) Age-depth model for the sediment core from Gongzhu Co. $^{210}Pb_{ex}$ (b) and ^{137}Cs (c) activity concentrations (Bq/kg) in Gongzhu Co.

mean 34.4%), Cyperaceae (8.0%–15.9%; mean 11.7%), Ranunculaceae (9.5%–22.2%; mean 16.4%), and Poaceae (2.7%–8.5%; mean 4.8%). The percentage of tree and shrub pollen ranges from 15.7% to 36.9%, with a mean of 24.1%: tree pollen taxa mainly include *Pinus*, *Alnus*, and *Betula*. The percentages of these pollen taxa and pollen diversity (richness and evenness) show little change. Based on the CONISS analysis of all terrestrial pollen data, the fossil pollen record was divided into two zones (Fig. 3).

Pollen Zone I (30.5–18 cm, 1766–1907 CE). The mean pollen concentration of this zone is 62342 grains·g^{-1}. Pollen assemblages are dominated by herbaceous taxa and the main pollen taxa are *Artemisia* (34.4%), Ranunculaceae (17.7%), and Cyperaceae (12%). There are low arboreal pollen percentages (21.3%), including *Pinus* (7.3%), *Alnus* (4.7%), and the *Betula* (4.1%).

Pollen zone II (18–0 cm, 1907–2016 CE). Mean pollen concentration is 68121 grains·g^{-1} which is slightly higher than that of Zone I. This zone is also characterized by herbaceous taxa, including *Artemisia* (34.3%), Ranunculaceae (15.4%), and Cyperaceae (11.4%), which are very similar to those in Zone I. Arboreal pollen percentages are higher than in Zone I with the percentage of *Pinus* reaching to 11.7%.

4.3 Principal component analysis (PCA)

The PCA of 17 terrestrial pollen taxa from the 54 samples reflects the main features of the pollen diagram and the pattern of vegetation development. The results show that the first two axes capture 40.5% (axis 1: 25.3%, axis 2: 15.2%) of the total variance in the data. As shown in Fig. 4, herbaceous taxa such as *Artemisia*, Ranunculaceae, Cyperaceae, and Poaceae are located on the positive side of the first axis and arboreal taxa (*Pinus*, *Picea*, *Quercus* evergreen (E)) are located on the negative side. Pollen samples for the different zones are clustered in the biplot (Fig. 4) and pollen samples of Zones I and II are scattered across the two axes and hard to separate.

4.4 Detrended canonical correspondence analysis (DCCA)

In this study, we used pollen records from 11 lakes on the Tibetan Plateau to analyze turnover. From DCCA, Gongzhu Co and other lakes have a low and non-significant compositional species turnover (0.15–0.81 SD) (Table 1). The pollen records during the past 300 years show that the average turnover is 0.48 SD; although there is a slight but non-significant increase in the last millennium to 0.60 SD.

5 Discussion

5.1 Interpretation of vegetation changes around Gongzhu Co

The depositional environment of Gongzhu Co, with its continuous sedimentation, makes it a good site for high-resolution pollen analysis, especially when combined with a reliable age-depth model. Pollen assemblages in the lake sediment mainly contain two components, pollen grains carried by inflowing rivers and surface wash from catchment, and grains transport by wind (Pennington, 1979; Luly, 1997; Wilmshurst and McGlone, 2005; Zhao

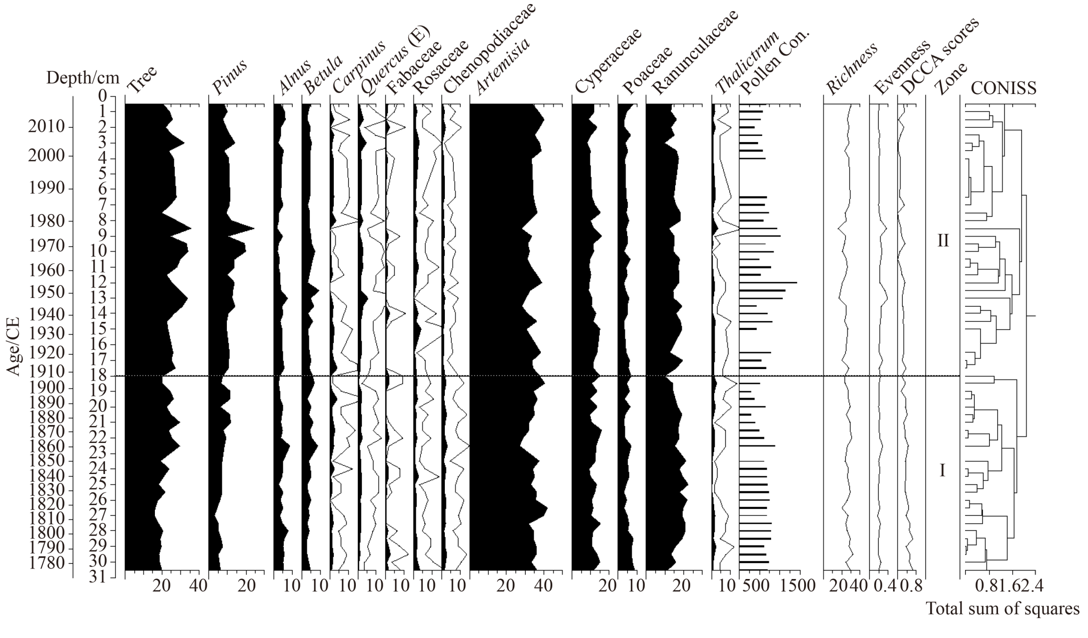

Fig. 3 Diagram of selected pollen taxa (percentage) and pollen concentration (con.) together with pollen diversity and detrended canonical correspondence analysis (DCCA). Open curves for taxa are five times exaggerated.

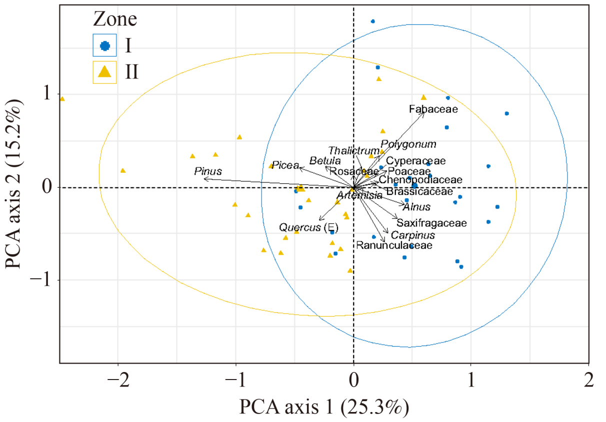

Fig. 4 Biplot of the principal component analysis (PCA) of the fossil pollen data (17 common taxa) from Gongzhu Co.

and Herzschuh, 2009; Xu and Zhang, 2013). Previous research revealed that waterborne pollen grains are the main pollen origan for lake with inflowing rivers (Xu et al., 2012). The windborne pollen source area has been estimated by model (Sugita, 1993) quantitively, and windborne pollen grains beyond the source area should have slighter contribution for the pollen assemblages obtained from lake sediment (Xu et al., 2012; Wang et al., 2014).

We argue that the pollen grains transport by inflowing rivers and surface wash should be the main component for the pollen assemblage from Gongzhu Co. Based on previous researches (Xu et al., 2012; Wang et al., 2014), the radius of pollen source area of Gongzhu Co (with water area of 66.2 km^2) should range from 50 to70 km. However, there is no arborvitae occurred within this radius and lake catchment, indicating that arboreal pollen grains extracted from Gongzhu Co should be exogenous pollen transported by wind from south margin of the plateau (beyond the windborne pollen source area), hence its high percentage should indicate low vegetation cover and low pollen production around lakes (Zhu et al., 2015; Ma et al., 2019; Han et al., 2020). Although herbaceous pollen may also be imported from exogenous sources, this is more difficult to distinguish from endogenous pollen herbaceous pollen. The pollen assemblages that form are influenced by both climate and human activities around the catchment and so can be used to reflect the environmental information.

Pollen spectra of Gongzhu Co are dominated by *Artemisia*, Ranunculaceae, Cyperaceae, and Poaceae and show little variation in pollen concentration and percentages, suggesting a vegetation type of alpine steppe in the catchment during the past 250 years (Fig. 3). In Zone 2 – the more recent part of the core – the percentage of arboreal pollen increases by 5%, mainly driven by an increase in *Pinus* (from 7.3% to 11.7%). However, around pollen source area and lake catchment, there are no trees so the arboreal pollen must be long-distance transported by the wind probably from the forest zones on the southern slopes of the Himalayan Mountains (Herzschuh, 2007; Ma et al., 2017, 2019). The increase in arboreal pollen suggests that the vegetation has become sparser than before around the lake (Herzschuh et al., 2006; Zhu et al., 2015; Lü et al., 2020), which could indicate that the climate is drying out. In addition, tree-ring records from the surrounding Himalayan Mountains show that precipitation has decreased over the past 250 years (Sano et al., 2012). Therefore, this climate change may have caused the reduction in vegetation coverage around Gongzhu Co.

5.2 Stability of the terrestrial ecosystem on the Tibetan Plateau during recent centuries

Ecosystem stability is key to studying the future ecological development on the Tibetan Plateau (Miehe et al., 2011b). In this study, we collected 11 pollen records which have ^{210}Pb/^{137}Cs dating at a high temporal resolution and used DCCA to assess ecological stability around the Tibetan Plateau (Table 1).

Results of the PCA and DCCA of Gongzhu Co show that there is little variation in the pollen assemblages from the different sites (Fig. 4; Table 1). The PCA results for Gongzhu Co suggest that the vegetation composition of the lake basin has been relatively stable over the past 250 years. DCCA scores show that turnover is lower than 1 SD, which could also indicate that the ecology was stable. Reasons for this inferred stability of vegetation include the intensity of climate change and human activities not exceeding the threshold for vegetation change, or that the large lake area reduces the sensitivity of pollen to capture signals of climate and human activities (Sugita, 1993, 1994; Xu and Zhang, 2013; Tian et al., 2014).

The general characteristic of these pollen records is a very stable species composition throughout their entire profiles. The low compositional turnover (0.14–0.81 SD) suggests insignificant ecological changes throughout these records, with only minor compositional shifts identified (Smol et al., 2005; Hobbs et al., 2010; Wischnewski et al., 2011). Despite these records having time scales ranging from 50 to 1700 years, the DCCA scores are insignificantly different. For example, the DCCA score of Gahai Lake with 50-year time scale is 0.30 SD, yet the pollen record from Hurleg Lake covering the past 1700 years has an even lower score (0.17 SD). However, lake size could affect the response to ecological change. Small lake could more sensitive to ecological change than large lake and it could have relatively higher turnover values. For example, the DCCA score of Toson Lake with an area of 150 km^2 is 0.15 SD, but the result of Lake LC6 with an area of 0.6 km^2 is 0.81 SD, implying pollen spectra from a small lake are more sensitive to ecological changes. In this study, no matter how large the lake is, the DCCA score is less than 1, indicating that during the recent centuries, the terrestrial ecosystem of the Tibetan Plateau has been stable.

6 Conclusions

Our pollen record from Gongzhu Co revealed the history of vegetation change over the past 250 years. The analysis reveals that the vegetation composition was alpine steppe dominated by *Artemisia*, Ranunculaceae, and Cyperaceae with no significant changes in vegetation composition. This suggests the vegetation around this area is not sensitive to recent climate changes or the historic intensity of human activities. In addition, our assessment of ten other high-resolution pollen records from across the Tibetan Plateau suggests that the Plateau's terrestrial ecosystem has been in a stable condition for the past few centuries.

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Competing interests The authors declare that they have no competing interests.

Appendix

Table A1 Results of ^{210}Pb/^{137}Cs dating for the top 22.25 cm of the Gongzhu Co sediment core

Depth/cm	Sample weight/g	^{137}Cs / (Bq·kg^{-1})	^{210}Pb / (Bq·kg^{-1})	^{226}Ra / (Bq·kg^{-1})	^{210}Pb$_{ex}$ / (Bq·kg^{-1})	Date
0.5	2.49	0.00	227.64	50.73	176.92	2014.9
1.5	2.97	0.00	188.97	41.82	147.15	2011.6
2.5	3.02	0.00	201.81	56.36	145.45	2007.7
3.5	3.10	0.00	257.47	55.29	202.19	2002.3
4.5	2.71	0.00	223.09	48.60	174.49	1996.9
5.5	2.39	0.00	201.49	54.81	146.68	1992.3
6.5	2.67	8.67	159.68	53.99	105.69	1987.6
7.5	2.29	8.21	159.32	49.62	109.70	1982.7
8.5	2.51	19.65	158.16	46.39	111.77	1977.3
9.5	2.54	8.72	144.46	52.87	91.59	1971.2
10.5	2.34	7.46	143.07	46.05	97.02	1964.7
11.5	2.66	0.00	110.09	45.81	64.29	1958
12.5	1.89	0.00	116.49	48.57	67.92	1951.3
13.5	1.83	0.00	111.52	55.94	55.59	1944.2
14.5	1.97	0.00	96.86	44.81	52.05	1936.8
16.5	1.96	0.00	82.02	44.44	37.58	1929.1
17.5	2.02	0.00	125.60	46.72	78.88	1920.8
18.5	2.46	0.00	62.22	57.07	5.15	1912.2
19.5	2.35	0.00	88.93	55.15	33.78	1903.2
20.5	2.13	0.00	110.25	56.54	53.71	1893.4
21.5	1.83	0.00	85.55	56.83	28.72	1882.6
22.25	1.90	0.00	71.73	51.90	19.83	1871.1

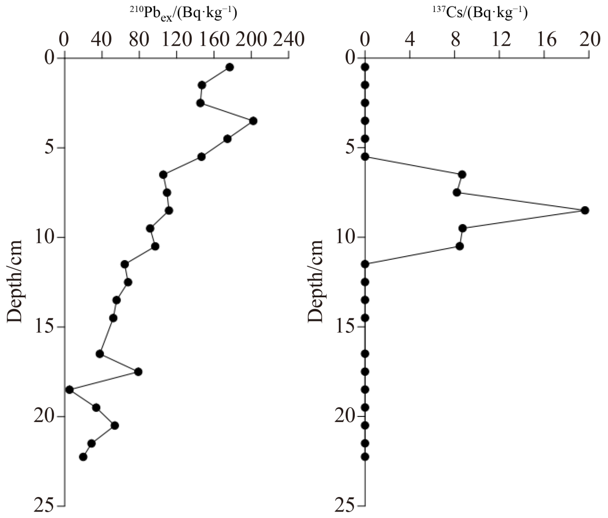

Fig. A1 Fallout radionuclides in the core from Gongzhu Co showing ^{210}Pb and ^{137}Cs concentrations.

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