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Stepwise intensification of human activities over the past two millennia in Southwest China

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ABSTRACT

As human activities accelerate landscape change, it is crucial to evaluate the potential impacts of natural climate fluctuations and anthropogenic disturbances. Accordingly, a continuous sediment record covering the past two millennia was collected from Beihai Wetland, Yunnan Province. The geochemical elemental compositions and organic material content were subsequently analyzed to evaluate the interactions between climate and human activities on the sedimentation process. The geochemical elements, such as K, Ti, Fe and Al, illustrate an overall increase in detrital inputs following catchment erosion. The total organic carbon content and C/N ratio suggest that organic matter deposition gradually decreased while terrestrial contribution increased. The geochemical indices mainly respond to regional moisture conditions before 1000 CE, and show a broadly consistent pattern with the intensity of Asian Summer Monsoon, suggesting that climate variation was a predominant factor in the catchment erosion and deposition process. Accordingly, the collapse of Nanzhao Kingdom in southwest China in 902 CE is supposed to be closely associated with an exceptionally weak monsoon phase between 900 and 1000 CE. During the Medieval Warm Period and the Little Ice Age, the terrestrial contributions (indicated by compositions of Ti, Fe, K, Al, and C/N ratio) increased significantly, which cannot be solely attributed to the gradual decline in monsoonal precipitation. The substantial population growth and implementation of production policies in southwest China provide a plausible explanation for such phenomenon. Since the Ming Dynasty, the impact of human activities on the landscape evolution and subsequent sedimentation process gradually increased and overcame the impact of natural climate fluctuations. In addition, various sediment records and historical documents have also supported the gradual intensification of human activity in southwest China over the past two millennia. The results revealed the interactive influence of climate change and human activities on the sedimentation process, providing a scientific basis for understanding the mechanisms of environmental changes during historical periods.

1. Introduction

Human activities have exerted a certain impact on regional environment variations during the Holocene, and have emerged as a significant driving force behind landscape changes (Guo et al., 2018; Hillman et al., 2014, 2019; Roberts, 2019). In recent years, as the impact of human activities on the earth system intensified progressively, the concept of Anthropocene was put forward to describe the environmental changes dominated by human activities in the current geological era (Crutzen, 2002; Dirzo et al., 2014; Lewis and Maslin, 2015). Human activities, such as constructions, agriculture and deforestation, have significantly altered the landscape of watersheds (Bucala, 2014; Jia et al., 2012; Liu et al., 2019; Njagi et al., 2022; Szymczyk and Nita, 2021). Accordingly, it is necessary to investigate the long-term human activity related records to improve our current understanding, particularly about the spatial-temporal patterns, to better depict the future relationships between climate variations and human society (Branch and Marini, 2014; Holmes et al., 2009; Sun et al., 2023).

The Yunnan Plateau (YP) is located on the southeast margin of Qinghai-Tibetan Plateau, responding sensitively to the Asian Summer Monsoon based on both modern meteorological data and various paleoclimate records (Hillman et al., 2020; Wang et al., 2020a, 2020b; Xiao

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et al., 2015). Meanwhile, human habitation histories with numerous archaeological sites dating back to the Stone Age, Bronze Age have been reported from the YP as well (Li, 2004, Li et al., 2016; Ma, 2009; Yao and Jiang, 2012; Yuan et al., 2021). For instance, the ancient Nanzhao /Dali kingdoms once established and governed such region during the Tang and Song dynasties (You, 1994; Yuan, 2019). Therefore, the YP represents an ideal region for investigating potential interactions between climate changes and human activities. However, current studies on the YP focused mainly on long-term climate background during the Holocene (Hillman et al., 2022; Wang et al., 2020b; Xiao et al., 2015, 2020) and environmental issues in the recent past where human activities express strong influence (Yang et al., 2020; Zhang et al., 2010; Zhuo and Zeng, 2020). Accordingly, high-resolution records are essential for addressing the relative contributions of natural climatic events and the impact of human activities on regional environmental fluctuations (Yuan et al., 2021).

Lake sediment, with great application value in reconstructing past climate dynamics and potential human activities, has been regarded as an ideal archive to investigate the interaction between anthropogenic impacts and climatic variations (Chen et al., 2022; Dearing, 2013; Hillman et al., 2014; Wang et al., 2020a). For instance, the burial efficiency of nitrogen and phosphorus were quantified in Lake Dian, along with their potential responses to modern climate change and human activities (Chen et al., 2020). Based on the sediment record from Huguangyan Maar Lake, the red soil erosion process was evaluated and discussed, and it was believed that the reduction of vegetation coverage caused by the intensification of human activities was the cause of the red soil erosion process (Xue et al., 2023). Trace chemical elements in sediment cores recovered from Lake Blanc Huez revealed major Holocene climate changes in the French Alps, and also capture the medieval mining activities (Garçon et al., 2012). In addition, quantitative reconstruction of Holocene soil erosion rates based on sediment records from 35 lakes indicates that human activities have accelerated soil erosion through land use during the last millennium (Zhao et al., 2023). Besides, lake sediment records from southwestern China revealed the accumulation of heavy metals (e.g., Cd, As, and Hg) during the past century, which was closely associated with regional socioeconomic developments, such as urbanization and industrialization (Liang et al.,

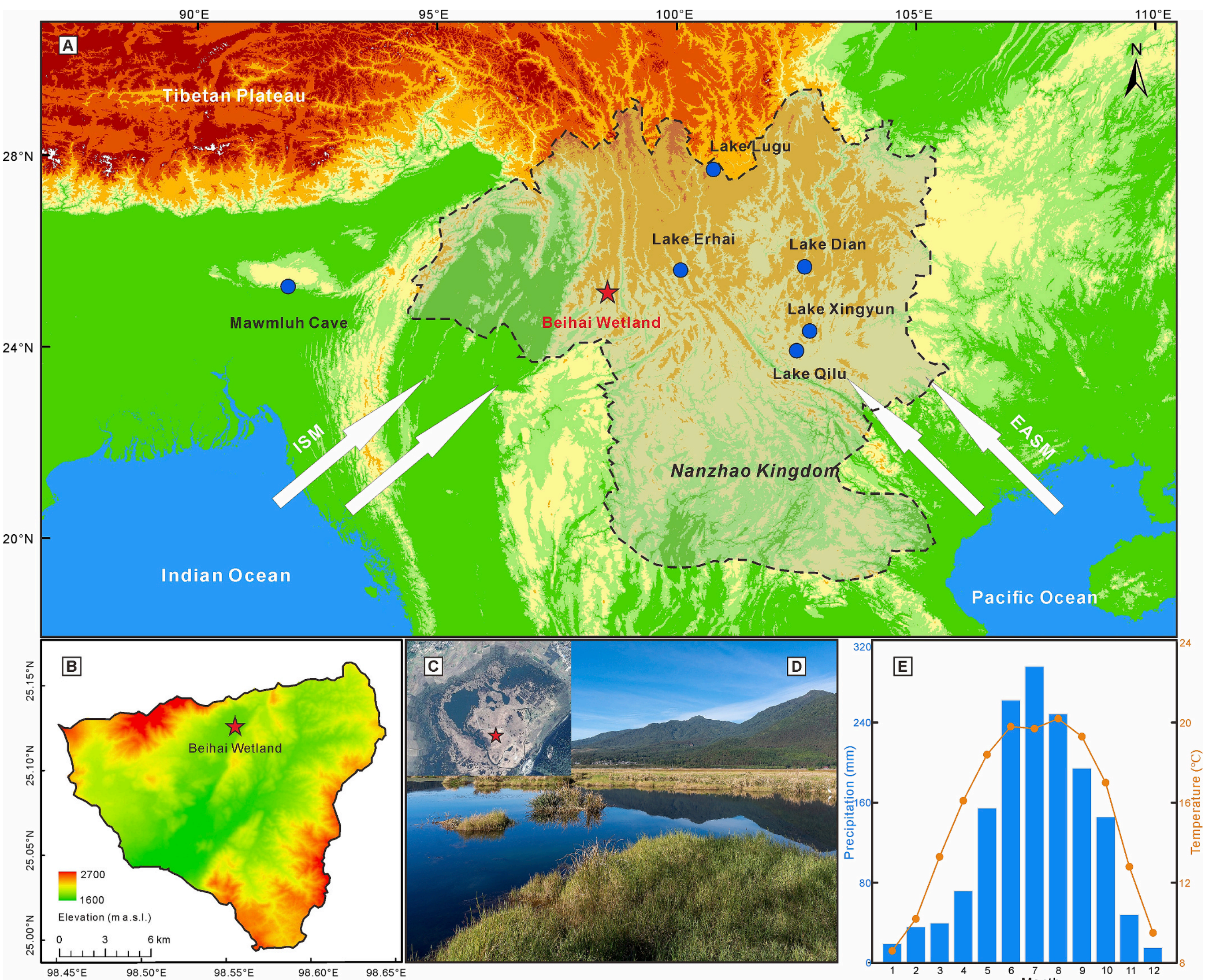

Fig. 1. (A) Location of Beihai Wetland and the paleoclimate records mentioned in the text, including Mawmluh Cave (Dutt et al., 2021), Lake Erhai (Xu et al., 2015), Lake Lugu (Wang et al., 2020a), Lake Qilu (Hillman et al., 2020), Lake Dian (Hillman et al., 2019) and Lake Xingyun (Chen et al., 2022). The dashed line defined territorial extent of Nanzhao Kingdom based on historical records (Daniels, 2021). (B) Catchment of Beihai Wetland and the sampling locations. (C) Satellite and (D) Field view of Beihai Wetland. (E) Monthly precipitation and temperature data from Tengchong meteorological station between 1981 and 2010 CE (https://data.cma.cn/).

2024; Li et al., 2025; Wang et al., 2024). Consequently, the sediment records could serve as a valuable archive to detect environmental variations, offering further insights into the interactions between climate fluctuations and human activities in both historical and contemporary contexts.

To better elucidate the impacts of natural climate and anthropogenic influences on sedimentary environment in southwest China, a continuous sediment record from Beihai Wetland was recovered and analyzed. Geochemical elements and organic proxies were evaluated and interpreted to determine: (1) temporal variations in the sedimentary environment over the past 2000 years, (2) the influences of human impacts and climate change on the sedimentation process, and (3) potential temporal pattern of human activities in southwest China.

2. Study area

Beihai Wetland (25°7′38″N, 98°33′10″E, 1740 m a.s.l.) is located in Tengchong County in western Yunnan Province, on the southeast margin of the Qinghai-Tibetan Plateau (Fig. 1). The wetland is a typical montane water body with a catchment area of 21.75 km^2. The water surface area within this catchment is 0.146 km^2, with an average depth of about 6 m. The wetland is subject to subtropical monsoon climate with warm and humid summers. Based on recent meteorological data, a backward trajectory analysis indicates that approximately 70 % of regional moisture originate from the Indian Ocean under predominant influences from the Indian Summer Monsoon (Cui et al., 2022). Instrumental data obtained from Tengchong Meteorological Station indicate that mean annual temperature and precipitation of the wetland are 14.1–15.1 °C and 1100–1870 mm, respectively, while 85 % of the annual precipitation is concentrated in summer from May to October (Fig. 1E; https://data.cma.cn/). The wetland is currently dominated by aquatic and swamp plants, including *Iris laevigala*, *Leersia hexandra*, *Menyanthes trifolia*, *Phragmites communis*, *Myriophyllum spicatum*, *Carex* spp. and *Cyperus* spp. (Shen and Liang, 2005). Vertical vegetation zones develop on the mountain slope surrounding the wetland, ranging from subhumid evergreen broad-leaved forest (dominated by *Castanopsis delavayi*, *Lithocarpus spp and Pinus yunnanensis*), mid-montane humid evergreen broadleaved forest of *Lithocarpus ethinotholus* and *Schina noronhae*, to subalpine shrub meadow such as *Rhododendron* following the altitude gradient (Fig. 1D; Shen and Duan, 2004).

3. Materials and methods

3.1. Field work and dating

In summer of 2011, a continuous sediment core with 2.7 m in length was collected from a depth of 1.5 m in the Beihai Wetland (Fig. 1B). Preliminary sub-sampling of sediment cores was carried out in the field at 1 cm intervals, and further sedimentary analyses were accomplished in the laboratory. The sediment core is mainly composed of grayish brown clay and silty sediments, and some pieces of plant remains were preserved. Five samples from different stratigraphic levels (including 3 plant remains and 2 bulk sediment samples) were selected for radiocarbon dating and measured at Beta Analytic Inc., USA and Rafter Radiocarbon Laboratory, New Zealand. The dated ^{14}C ages were then calibrated based on the IntCal13 dataset (Reimer et al., 2013), and interpolated using the Bayesian model (Bacon 2.2) in R 4.0.2 (Table 1; Blaauw and Christen, 2011; R Core Team, 2020). Accordingly, an age-depth model of the continuous sediment core from Beihai Wetland was constructed.

3.2. Geochemical element analysis

A total of 98 samples were selected for geochemical element compositions determination at intervals of 1–4 cm. The samples were frozen-dried and ground with an agate mortar before mounting on the slide.

Table 1
AMS ^{14}C dating results from Beihai Wetland.

No.	Lab ID	Depth (cm)	Dating material	^{14}C age (cal. yr BP)	δ^{13}C (‰)	Calendar age (AD)
1	Beta-491,888	14	Plant remains	290 ± 30	−20.2	1493–1601
2	Beta-493,799	56	Plant remains	750 ± 30	n.d.	1223–1286
3	Beta-496,017	119	Plant remains	980 ± 30	−12.4	1075–1154
4	NZA38015	183	TOC*	1508 ± 15	−19.6	539–601
5	NZA38016	233	TOC	1753 ± 20	−23.3	235–343

* TOC stands for total organic carbon.

The composition of major geochemical elements (including Ti, Al, Fe, Mn, Mg, Ca, Na, K, S, Rb, Sr, Zr, Si, Cu, Rh and Zn) was determined by the micro X-Ray Fluorescence spectrometer (TORNADO M4). The total organic carbon (TOC) and nitrogen (TN) content of 38 samples was measured at an interval of approximately 7 cm following standard experimental procedure. Selected samples were frozen-dried, ground and treated with 10 % hydrochloric acid (HCl) to remove potential inorganic carbon, which was subsequently measured by Euro EA3000 Elemental Analyzer. Accordingly, the total inorganic carbon content (TIC) was determined by the difference in the carbon content before and after acid treatment.

3.3. Numerical analysis

Principal component analysis (PCA), which can represent the principal similarities and dissimilarities among individual variables and reveal the dominant patterns within datasets (Wold et al., 1987), was applied to the lithogenic elements in order to determine potential correlations and temporal patterns. Subsequently, the major elements (including Ti, Al, Fe, Mn, Ca, K, Rb, Sr, Zr, Si, Cu and Zn) detected in the sediment samples were logarithmic transformed and submitted for PCA analysis, which was accomplished by the CANOCO v5.0 program (ter Braak and Smilauer, 2012).

4. Results

4.1. Chronology

The radiocarbon dates from three plant remain samples and two total organic carbon samples were distributed in stratigraphic order with a good linear relationship (Fig. 2; Table 1), indicating an overall stable sedimentation process with little influence by the carbon reservoir effect. The Bacon age-depth model associated with IntCal13 dataset was then applied to five AMS ^{14}C dates for calibration and interpolation, while the results indicate that the retrieved 270 cm long sediment core covered the past 2000 years with an average sediment accumulation rate (SAR) of approximately 0.14 cm/yr (Fig. 2). The SAR was approximately 0.15 cm/yr during the period before 1000 CE, followed a significant increase between 1000 and 1300 CE (up to 0.25 cm/yr), which decreased dramatically to around 0.09 cm/yr during the past 700 years (Fig. 3C).

4.2. Geochemical element composition

The intensity of major geochemical elements preserved in sediment samples was captured by the XRF scanning method, it was found that the detrital elements (such as Ti, K and Fe) show consistent temporal patterns, illustrating progressive increasing trends (Fig. 3I-L). The composition of Ca and K/Ti ratio exhibit opposite patterns to that of the dominant detrital elements (Fig. 3G, H). In addition, the first two PCA

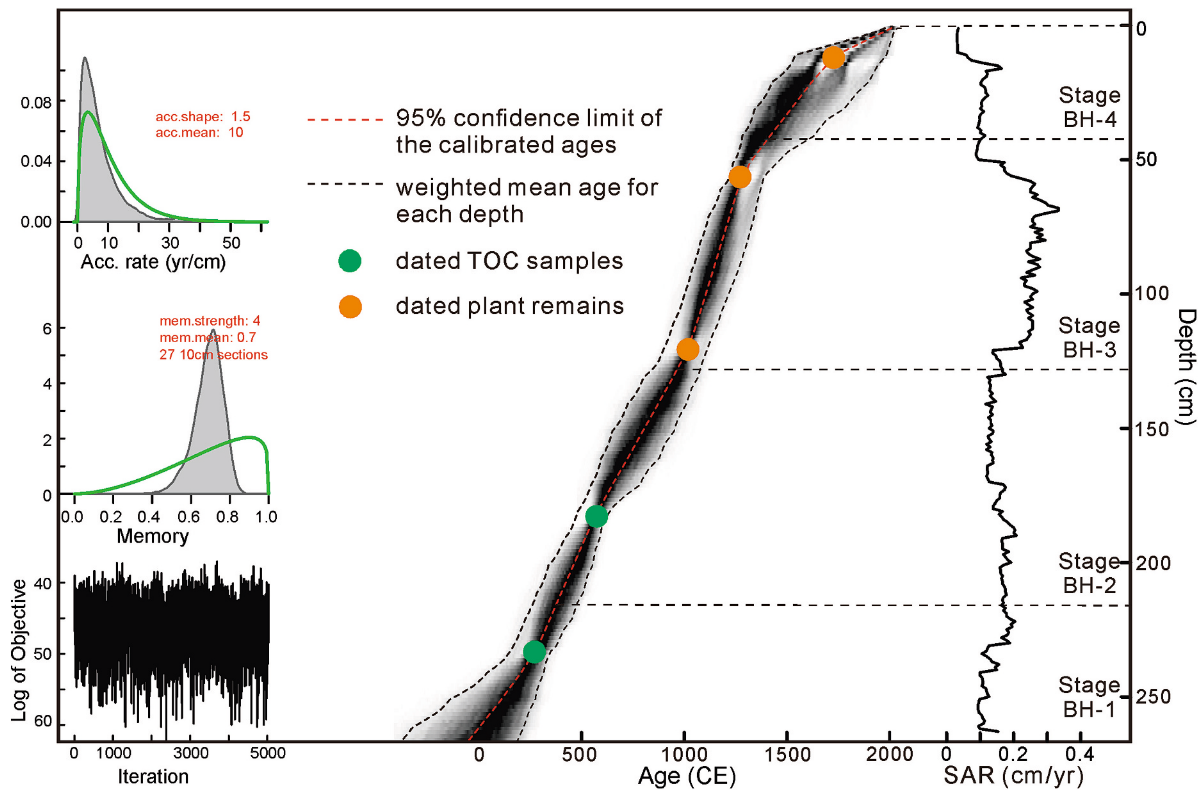

Fig. 2. Radiocarbon dates and sediment accumulation rate (SAR) in the sediment core from Beihai Wetland. The black dashed lines represent the 95 % confidence intervals of calibrated ^{14}C age, while the red dashed line stands for the weighted average of the calibrated ^{14}C age based on the Bayesian age-depth model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

axes based on the element data capture 75.2 % of the total variance, of which the first axis (PC1) accounts for 63.6 %, representing the dominant temporal variations of detrital elements (Fig. 4). Accordingly, the sediment sequence from Beihai Wetland was divided into four distinct zones based on the variations in element compositions and PCA axis score (Fig. 3M).

Zone BH-1 (0–350 CE): The signals of detrital elements, including Al, Fe, K and Ti, as well as the PC1 score, are at the lowest level throughout the entire record (Fig. 3I-M). For instance, the intensity of Ti declined gradually from approximately 120 cps to below 80 cps at 350 CE (Fig. 3L). Meanwhile, it is worth noting that the authigenic element Ca exhibited relatively high values in this zone, while the ratio of K/Ti displayed an increasing trend with fluctuations (Fig. 3G, H).

Zone BH-2 (350–1000 CE): The content of lithogenic elements is slightly higher than that of the previous period, and the determined PC1 scores expressed a slight increase from the previous stage as well (Fig. I-M). On the other hand, both the K/Ti ratio and Ca content experienced a gradual decline in this zone (Fig. 3G, H). During the 9th century, the geochemical indices of the entire sedimentary sequence exhibited a notable deviation. For instance, the content of diagenetic elements and PC1 score were at a low level, while the K/Ti ratio and Ca content increased slightly (Fig. 3G-M).

Zone BH-3 (1000–1400 CE): The geochemical elements changed significantly during this stage, and the content of detrital elements exhibited remarkable increases, reaching the maximal values at around 1400 CE, such as Ti, Al and K (Fig. 3J-L). As a consequence, the PC1 scores increased progressively during this period (Fig. 3M). On the other hand, large fluctuations were detected from the compositions of Fe and Ca, as well as element ratio of K/Ti (Fig. 3G-I). The element Ca displayed an opposite pattern with the detrital elements as indicated by a substantial decline in content (Fig. 3H). In addition, a significant decrease in the K/Ti ratio was observed, along with substantial fluctuations throughout this stage (Fig. 3G).

Zone BH-4 (after 1400 CE): The stage is characterized by continued high and stable intensities of clastic elements (including Ti, Al and K) and PC1 scores (Fig. 3I-M), while the K/Ti ratio and Ca content reached their lowest levels in the entire record (Fig. 3G, H).

4.3. Organic geochemistry

The total organic carbon (TOC) content in the sediment samples shows variations between 4 % and 20 % (Fig. 3F). Generally, the TOC values were relatively high (approximately 17 %) before 1075 CE, which experienced a rapid decline to 5 % after 1450 CE (Fig. 3F). Meanwhile, the temporal variation of total inorganic carbon (TIC) content expressed consistent pattern with that of TOC (Fig. 3E). In addition, the variations in C/N ratio could be divided into three stages, experiencing relatively low values before 1075 CE, high values up to 17 from 1075 to 1450 CE and a notable decline afterwards (Fig. 3D).

5. Discussions

5.1. Environmental information implied by sedimentary proxies

Analysis of element abundance in sediments has been widely employed to elucidate sediment source and potential responses to catchment erosion and sedimentation processes (Davies et al., 2015; Ding et al., 2019; He et al., 2023; García-Rodríguez et al., 2021; Metcalfe et al., 2010). The PCA results of the element compositions from Beihai Wetland represent a comprehensive correlation-cluster distribution (Fig. 4). The lithogenic elements, e.g., K, Ti, Al and Fe, are usually derived from terrestrial inputs because they are chemically stable, which are conserved and carried by resistant minerals (Aufgebauer et al., 2012; Lauterbach et al., 2011; Shen et al., 2013). Accordingly, the PC1 scores are interpreted to represent terrestrial inputs as a result of enhanced erosion process within the catchment. For instance, the hydroclimatic

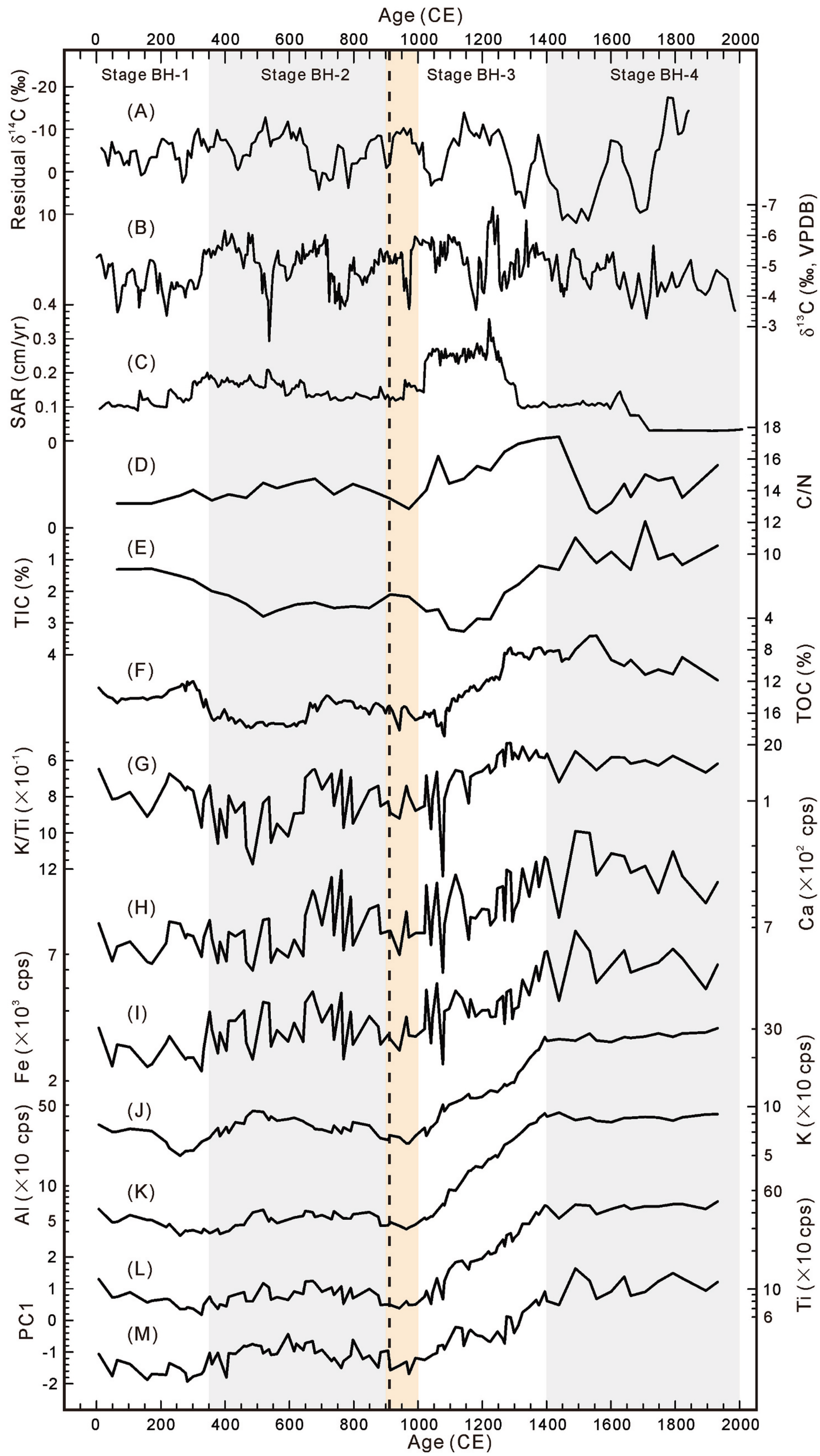

Fig. 3. Comparison of SAR (C) and geochemical indices (D-M) from Beihai Wetland with (A) detrended atmospheric δ14C record (Stuiver et al., 1998) and (B) stable carbon isotope record from Mawmluh Cave (Dutt et al., 2021). The yellow-shaded area denotes the period of rapid decline in Asian Summer Monsoon, whereas the dashed line indicates the collapse of Nanzhao Kingdom. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

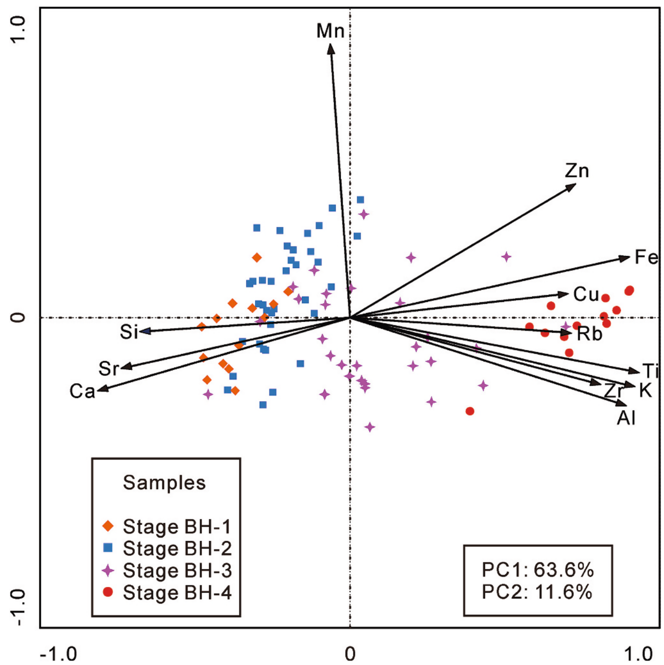

Fig. 4. PCA bi-plot of the geochemical elements in sediment samples from the Beihai Wetland, while the samples were grouped based on the distribution on the bi-plot.

variations of Lake Xiaolongchi in the central Tianshan Mountains during the Holocene have been reconstructed based on variations in lithogenic elements such as Ti and Fe (He et al., 2023). During the mid to late Holocene, high precipitation conditions in Lakes Hogsback were reconstructed by geochemical indicators such as Ti and K, representing the watershed erosion process (Gushulak et al., 2021). In the record from Lake Holzmaar, high Ti values were interpreted to represent increasing catchment erosion following regional humidity and intensification of anthropogenic disturbances (García et al., 2022). On the other hand, the elements of Ca and Sr could also be produced in lake system along with carbonate precipitation, responding to regional climate variations and water level fluctuations (Brown, 2011; Heymann et al., 2013). Particularly, Ca and Sr are distributed in the negative part of the first PCA axis, expressing negative correlations with the lithogenic elements mentioned above (Fig. 4). Besides, the consistent temporal patterns between Ca and TIC content in the sediment samples further confirmed such autogenic origin within the water system (Fig. 3E, H). In summary, the first PCA component accounts for most of the variance (up to 63.6 %) in the element composition of sediments from Beihai Wetland (Fig. 4), that higher PC1 scores indicate increase in detrital inputs following intensified erosion and transportation within the catchment.

To acquire more accurate information on climate and environmental variations, element ratios have been widely employed (García-Rodríguez et al., 2021; He et al., 2023; Weltje and Tjallingii, 2008), by eliminating factors unrelated to geochemical process, such as changes in organic matter and water content (Davies et al., 2015; Elbert et al., 2012; Tjallingii et al., 2007). Generally, the element Ti in lake sediments is considered to be chemically conservative compared to K, that K/Ti ratio is used as an indicator of the intensity between chemical and physical weathering (Arnaud et al., 2012; Brown, 2011). Enhanced regional physical/chemical weathering is usually accompanied by more watershed runoff, resulting in increased detrital elements into the lake while relatively more K is dissolved. Therefore, lower K/Ti ratio can be used to indicate the enhancement of weathering in Beihai Wetland (Fig. 3G).

In addition, organic geochemistry results provide important information for reconstructing past environmental variations in lake and wetland systems (Bertrand et al., 2010; Contreras et al., 2018; Meyers, 2003). The total organic carbon content (TOC) serves as an important index to represent organic matter preserved in sediments (Shen et al., 2010). Accordingly, determining the source of TOC (terrigenous or aquatic) is necessary for paleoenvironment interpretation. The C/N ratio is commonly used to identify the source of organic matters in lake sediments (Meyers and Teranes, 2001; Talbot and Johannessen, 1992). Studies have shown that the C/N ratio of aquatic organisms (algae and cyanobacteria) ranges from 4 to 10, while that of terrestrial organic matter exceeds 20 (Contreras et al., 2018; Meyers, 1994; Jasper and Gagosian, 1990). The C/N ratio of sediments from Beihai Wetland varies between 12 and 18, illustrating a mixture source of organic materials and the relative contributions of terrestrial and aquatic origins could be inferred accordingly (Fig. 3D).

5.2. Climate variations and human activities during the past 2000 years

The environmental evolution history of Beihai Wetland during the past 2000 years was divided into four stages based on variations in sedimentary proxies, and potential human impacts were yielded in combination with historical documents in southwest China.

5.2.1. Stage BH-1 (0–350 CE)

During this period, negative PC1 scores indicate relatively low detrital inputs owing to limited surface runoff and corresponding basin erosion (Fig. 3M). Reconstructed mean annual precipitation based on fossil pollen assemblage confirmed such regional moisture condition (Wang et al., 2020b). Meanwhile, the generally increasing trend of K/Ti ratio suggests that chemical weathering in the basin was gradually constrained under a relatively cool and dry environment (Fig. 3G), corresponding to the weakening of the Asian summer monsoon (ASM) intensity and the decrease in regional moisture (Wang et al., 2021). Our results were supported by the sediment record from Lake Dian. The grain size composition and geochemical proxies indicated that relatively low lake water level persisted until the 3rd century, which was mainly controlled by declined ISM rainfall (Wünnemann et al., 2024). Such decline in monsoon precipitation was further inferred from the stable carbon isotope record in Mawmluh Cave (Fig. 3B; Dutt et al., 2021), following the gradual decline in solar radiation (Fig. 3A; Stuiver et al., 1998). Therefore, the Beihai Wetland area was dominated by limited monsoonal precipitation supply during this stage, resulting in a progressive shrinkage in the water level.

5.2.2. Stage BH-2 (350–1000 CE)

Between 350 and 900 CE, the PC1 value exhibited a gradual increasing trend, accompanied by increased inputs of detrital materials into the water system (Fig. 3I-M). The declining K/Ti value revealed intensified erosions within the catchment (Fig. 3G; Davies et al., 2015; Piva et al., 2008), while the decrease in Ca and TIC contents indicated relatively high-water level during this period (Fig. 3E, H; Brown, 2011; Foerster et al., 2012). In addition, higher C/N ratio and TOC level indicated increased inputs of terrigenous organic matter, which could be attributed to enhanced catchment erosion under intensified surface runoff (Fig. 3D, F; Douglas et al., 2022; Meyers and Teranes, 2001; Selvaraj et al., 2012). The results suggest that the basin experienced a relatively humid condition during this period, corresponding to the intensification of summer monsoon recorded in stable carbon isotope from Mawmluh Cave (Fig. 3B; Dutt et al., 2021). Based on $\delta^{13}C$ and fossil pollen data, high monsoon rainfall was also reconstructed from Dzukou profile in northeastern India during this period (Misra et al., 2020). Furthermore, there was a significant decrease in terrestrial clastic input and the C/N ratio between 900 and 1000 CE, which is closely related to the widely reported medieval monsoon decline (Fig. 3D, I-M; Chen et al., 2021; Dykoski et al., 2005; Sheng et al., 2015). Such arid condition led to reduced erosion in the watershed as well as declined water level, resulting in gradual increase in the productivity of wetland plants

(Contreras et al., 2018; Gushulak et al., 2021). The isotope record of stalagmite from northeastern India shows strong ISM conditions prevailed from 640 to 1060 CE, which was terminated by a weak monsoon event between 940 and 980 CE (Fig. 3B; Dutt et al., 2021). According to historical records, the Nanzhao Kingdom, an ancient ethnic regime in southwest China, collapsed in this period and initiated a long period of conflict (Fang, 2003; Zhu, 2016). Extreme climate events act as the important contributing factors for culture evolution. At the end of the 9th century, a three-year-long severe drought was reported in the area of Nanzhao, which has possibly exacerbated the political crisis and social instability (Zhan, 2002). Previous studies have demonstrated that climate variations exert significant influences on cultural and political evolutions during historical epochs (Tan et al., 2018). For instance, the oxygen isotope record of retrieved from Wanxiang Cave stalagmite revealed that the monsoon was relatively weaker in the late Tang, Song, and Ming dynasties (Zhang et al., 2008). It is plausible to infer that the rapid decline of ASM in the 9th century might have played a key role in the collapse of Nanzhao Kingdom.

5.2.3. Stage BH-3 (1000–1400 CE)

The hydrological variations in southwest China over the past millennium have been extensively investigated (e.g., Chen et al., 2022; Wu et al., 2015; Yuan et al., 2021), revealing a generally dry period under decreased ASM during the MWP (Wang et al., 2020a; Xu et al., 2015). For the period between 1000 and 1300 CE, the decrease of *Tsuga* pollen abundance in southwest China indicated reductions in regional moisture availability (Jarvis, 1993; Xiao et al., 2014). At the same time, diatom assemblages and geochemical indices from Lake Lugu revealed that climate warming was accompanied by decreases in monsoon precipitation and subsequent catchment runoff (Wang et al., 2020a). According to the multi-proxy sediment record from Lake Erhai, a severe drought was reported during the Middle Ages (Xu et al., 2015). In addition, the dry condition between 1100 and 1300 CE was also captured by the stable isotope compositions in stalagmite from Mawmluh Cave (Fig. 3B; Dutt et al., 2021). However, a significant increase in clastic inputs was detected in the Beihai Wetland record after 1000 CE, as indicated by the detrital element contents (Fig. 3I-M). During this period, the establishment of the Dali Kingdom was accompanied by a remarkable population increase from less than 0.2 million to over 5.7 million between the 10th and 14th centuries (Fig. 5A; He, 2011; Zou and Miao, 1989). Accordingly, a complete land ownership system was implemented and economic productivity increased significantly compared with the Nanzhao period (Zhu, 2016). Furthermore, the construction of water conservancy infrastructures has led to the continuous expansion of arable land in Yunnan (Song, 1976). The increased in lake detrital inputs and the corresponding decline in TOC levels could be attributed to intensified deforestation and agricultural activities resulting from population growth (Hillman et al., 2014; Wang, 1994). The high SAR values was mainly attributed to increase in terrestrial organic matter inputs caused by deforestation, which is indicated by relatively high C/N ratios (Dong et al., 2012). The sedimentary record of Lake Xingyun demonstrated that soil erosion increased significantly during the late Holocene, which was attributed to regional population growth (Wu et al., 2015). In addition, the eutrophication of water body within Lake Dian is primarily induced by intensified human activities after 900 CE, particularly the substantial impact of land use changes (Hillman et al., 2019). In general, the increase in human activities, coupled with climate fluctuations, has had a significant impact on catchment erosions.

5.2.4. Stage BH-4 (after 1400 CE)

Beihai Wetland was characterized by extremely high clastic inputs indicated by detrital element contents and PC1 scores in this stage (Fig. I-M), suggesting that the impacts of human activities on catchment environment have increased. Higher compositions of coniferous and herbaceous pollen species were reported previously, suggesting a more open landscape surrounding Beihai Wetland (Xie et al., 2021). During

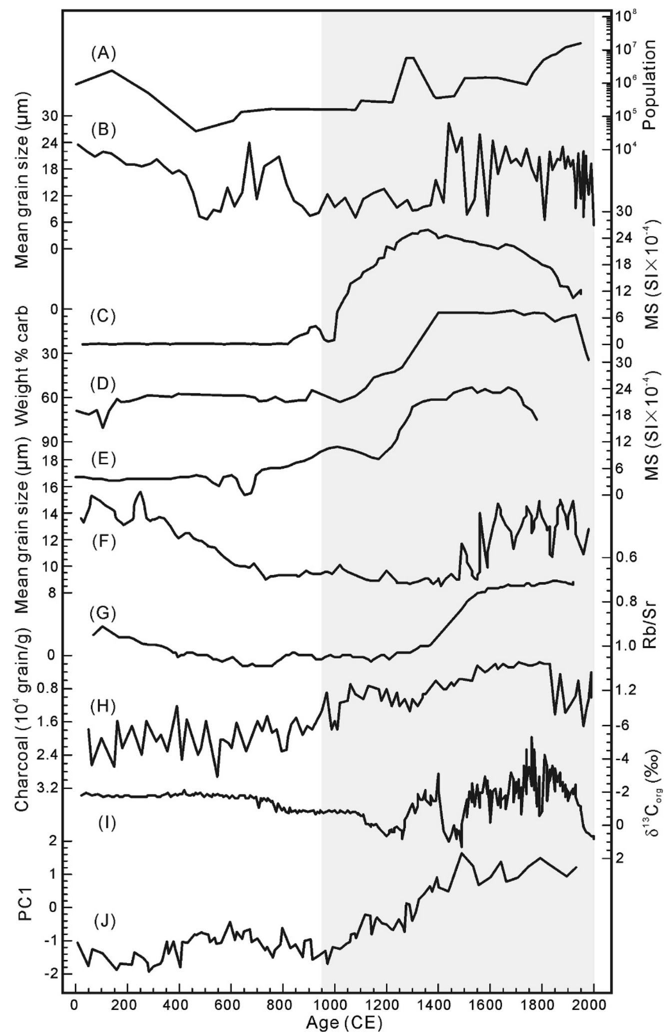

Fig. 5. Comparison the geochemical elements PC1 (J) from the Beihai Wetland with (A) historical population of Yunnan (Zou and Miao, 1989); (B) mean grain size from Lake Lugu (Wang et al., 2020a); (C) loss-on-ignition (LOI) and (D) Magnetic susceptibility (MS) from Lake Qilu (Hillman et al., 2020); (E) MS from Lake Dian (Hillman et al., 2019); (F) mean grain size and (G) Rb/Sr ratios from Lake Erhai (Xu et al., 2015); (H) charcoal concentration and (I) carbon isotopic composition from Lake Xingyun (Chen et al., 2022; Hillman et al., 2014).

the Ming Dynasty, immigrants from the Yangtze River catchment brought improved techniques that greatly increased agricultural productivity (Ding, 2019; Lu, 2005). According to historical records from the Qing Dynasty, “the cultivated land near the river had been reclaimed”, and “there is no uncultivated place in the mountains and ravines” (You, 1994). Therefore, large proportions natural vegetation were replaced by cultivated land, which is reflected by high inputs of terrigenous clastic elements and low organic matter contents (Fig. 3D-M). The extremely low SAR values are closely related to the low terrestrial plant residues supplies to the lake (Fig. 3C; Dong et al., 2012). Since Ming and Qing Dynasties, intensified human activities in Yunnan have been widely reported, including geochemical records from Lake Qilu (Fig. 5D; Hillman et al., 2020), Lake Erhai (Fig. 5G; Xu et al., 2015) and Lake Xingyun (Fig. 5H, I; Chen et al., 2022), as well as sedimentary records from Lake Lugu (Fig. 5B; Wang et al., 2020a), Lake Erhai (Fig. 5F; Xu et al., 2015) and Lake Dian (Fig. 5E; Hillman et al., 2019). In summary, the sedimentation condition in Beihai Wetland has been predominantly influenced by anthropogenic activities rather than natural processes during this period.

5.3. Stepwise intensification of human activities in Yunnan over the past millennium

The geochemical proxies of sediment record in Beihai Wetland show a significant increase in detrital element inputs, indicating a progressive intensification of human impacts on catchment erosion and subsequent sedimentation process (Fig. 5J). According to historical documents and paleoclimate archives, human activities in Yunnan have been investigated in terms of agriculture development, mineral exploitation, hydraulic engineering, and potential anthropogenic activities (Chen et al., 2022; Hillman et al., 2014, 2019; Wu et al., 2015; Yuan et al., 2021). During the last millennium, the progressive transition from natural- to anthropogenic-dominant landscape changes in southwest China has been widely reported (Hillman et al., 2016, 2020; Wang et al., 2020a; Xie et al., 2021). The fossil pollen assemblage from Beihai wetland revealed a gradual replacement of arboreal species by herbaceous taxa (especially Poaceae pollen), suggesting that potential deforestations and agricultural developments may have occurred over the past 2000 years due to regional population growth (Wang et al., 2020b; Xie et al., 2021). The multi-proxy sediment records from Lake Xingyun and Lake Dian both indicated that land use held significant impacts on regional vegetation and landscape changes, as well as human-induced eutrophication of water bodies during the Middle Ages (Fig. 5E, H, I; Chen et al., 2022; Hillman et al., 2014, 2019). Meanwhile, long-term anthropogenic activities, such as deforestation and farming have significantly reduced ecological stability, leading to the ecosystem fluctuations in Lake Qilu (Fig. 5C, D; Hillman et al., 2020) and Lake Yilong (Yuan et al., 2021). In addition, human impacts on ecosystems are supposed to be much more severe than climate variations in the earlier stages during the Holocene (Yuan et al., 2021). The significant fluctuations in the geochemical proxies and fossil pollen assemblage from Lake Xingyun indicated an abrupt increase in catchment erosion caused by human activities, which is closely correlated to dynastical replacement (Fig. 5 H, I; Chen et al., 2022; Hillman et al., 2014; Wu et al., 2015). Organic matter content and metal concentrations in Lake Chenghai revealed early signals of human-induced land use changes at around 1150 CE, along with potential evidences concerning dam construction during the Ming Dynasty (Hillman et al., 2016). The variations in mean grain size of Lugu Lake indicated that the ecosystem was dominated by natural climate before 1300 CE, while the agriculture-climate interactions have played significant roles in ecological transformation over the past 700 years (Fig. 5B; Wang et al., 2020a). In addition, according to historical documents, the governments of Song and Yuan Dynasties prioritized the development of China's southwest border and implemented a series of regional policies (Li and Liu, 2019; Song, 1976). The promoted policies, such as the improvement of transportation infrastructure, expansion of military and civilian farmland, construction of water conservancy systems, mining and metallurgy operations, as well as significant immigration into Yunnan, all significantly contributed to the changes in regional landscape (Ding, 2019; Holdren and Ehrlich, 1974; Lu, 2005; You, 1994). Then, human activities have step-wisely extended the impacts on regional landscape changes in Yunnan over the past two millennia, becoming the dominant factor progressively instead of natural climate variations.

6. Conclusions

Based on the geochemical indices derived from sediments in Beihai Wetland, the environmental evolution history of southwest China over the past 2000 years was reconstructed and discussed, revealing the potential influences caused by human activities. The compositions of typical detrital elements (e.g., Fe, Ti, Al) and the first principal component (PC1) were used to represent the terrestrial inputs and related catchment erosion process. Over the past 2000 years, the depositional condition of Beihai Wetland has undergone significant changes characterized by a progressive increase in detrital inputs since 350 CE. The variations of detrital elements and organic matter content mainly responded to regional humidity before 1000 CE, experiencing relatively dry (0–350 CE) and wet (350–900 CE) conditions, respectively. Particularly, a rapid decline of the Asian Summer Monsoon between 900 and 1000 CE is suggested to have accelerated the collapse of Nanzhao Kingdom. In the Middle Ages, significant increases in detrital elements and C/N ratio were attributed to the implementation of policies, along with significant increases in regional human activities due to the population growth. After 1400 CE, the influences of climate changes on regional landscape changes and subsequent sedimentary process were predominantly replaced by intensified human activities. The results of the Beihai Wetland study are largely consistent with previously published results from sediment sequences and historical literature records in southwest China. Generally, human activities have significantly increased over the past two millennia, and expressed serious impacts on the landscape evolutions in southwest China, especially after the Middle Ages.

CRediT authorship contribution statement

Yongbo Wang: Funding acquisition, Writing – review & editing. **Xingqi Liu:** Resources. **Ji Shen:** Resources. **Yong Wang:** Resources. **Kai Cui:** Writing – original draft.

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.

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Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

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