Agriculture, Ecosystems and Environment 294 (2020) 106862

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Fragility of karst ecosystem and environment: Long-term evidence from lake sediments

Jingan Chen[a,*], Jia Yu[a,b], Xiaoyong Bai[a], Yan Zeng[a], Jingfu Wang[a]

[a] State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, 550081, China
[b] University of Chinese Academy of Sciences, Beijing, 100049, China

ARTICLE INFO

Keywords:
Karst
Ecosystem
Environment
Fragility
Agricultural activities
Lake sediment

ABSTRACT

Southwest China is the largest continuous karst area in the world, which has suffered from serious ecological degradation. Many researchers have discussed the fragility of karst ecosystem and environment (KEE). However, these studies focused mainly on the particular karst geologic setting and short-term (annual) eco-environmental changes. At longer timescales, knowledge of how KEE responds to external disturbances such as climate changes and human activities is very limited. Based on geochemical analysis of lake sediments in the karst region of Southwest China (KRSC), this paper probes into the evolutionary characteristics of KEE at decadal-centurial timescales. Organic C/N ratios, Sr/Rb ratios and pollen assemblage in Baixian Lake indicate that striking eco-environmental deterioration occurred as a result of the drought event between 3.6 ka B.P. and 2.2 ka B.P. The regional vegetation degraded with dwindling herbs, increasing ferns and decreasing terrestrial productivity. Furthermore, the karst ecosystem had not restored to the earlier level even after a long time. Once degradation happens, the karst ecosystem would be unlikely to recover in the short term. Poor water-soil conservation capacity and weak drought resistance of karst soil should be the inherent mechanism of the fragility of terrestrial KEE. Hongfeng Lake has suffered from rapid eutrophication in the last three decades. Reservoirs respond more sensitively to agricultural N and P addition because of abundant dissolved inorganic carbon (DIC) supply from the carbonate catchment in karst region than in non-karst region. A positive feedback loop may develop among elevated primary productivity, higher deposition fluxes of organic matter, anoxia in hypolimnion and enhanced internal P release in aquatic ecosystem. This positive feedback, together with the DIC fertilization effect and sensitivity to agricultural N and P addition, may explain the fragility of aquatic KEE. This paper for the first time presents a long-term evidence for the fragility of both terrestrial and aquatic ecosystem in the KRSC, and provides new insights into the sensitivity and resilience of KEE to climate change and agricultural activities, highlighting the extreme importance of eco-environment protection in karst region.

1. Introduction

Globally, karst rocks are abundant on the Earth's surface and approximately 15 % of land comprises karst region, where as much as 20 % of the global population live (Brandt et al., 2017; Ford and Williams, 2013; Jiang et al., 2014; Tong et al., 2018; Zhang et al., 2017). China has approximately 3.44 million km^2 karst region, accounting for 15.6 % of the total global karst area. The karst region of Southwest China (KRSC) is the largest continuous karst area in the world, with a total karst area of 540, 000 km^2 (Fig. 1). There are about 0.1 billion people living in the KRSC which provides a variety of ecosystem services, such as water supply, agricultural production, soil erosion prevention, regulation of nutrient cycles and hydrologic functions, and carbon sequestration. However, the KRSC has suffered from serious ecological degradation driven by climate change, population growth, agricultural activities, land use change and pollutant discharge, and is regarded as one of the most arduous areas for poverty alleviation in China. It was reported that 22 % of the KRSC had suffered from mild-severe rocky desertification, resulting in a series of ecological and environmental issues, such as vegetation cover loss, soil erosion, productivity decrease, biodiversity loss, and water eutrophication (Bai et al., 2019; Dai et al., 2017; Mellander et al., 2012; Song et al., 2010; Yan et al., 2018). The livelihoods of the local people living in the KRSC are directly impacted by the rocky desertification. Even more, the health and well being of the people downstream are also affected indirectly from socioeconomic and ecological dimensions. This situation has challenged us to think critically about the running regularities of karst ecosystem and environment (KEE), and sustainable development strategies in the KRSC.

* Corresponding author.
E-mail address: chenjingan@vip.skleg.cn (J. Chen).

https://doi.org/10.1016/j.agee.2020.106862
Received 6 November 2019; Received in revised form 1 February 2020; Accepted 9 February 2020
Available online 14 February 2020

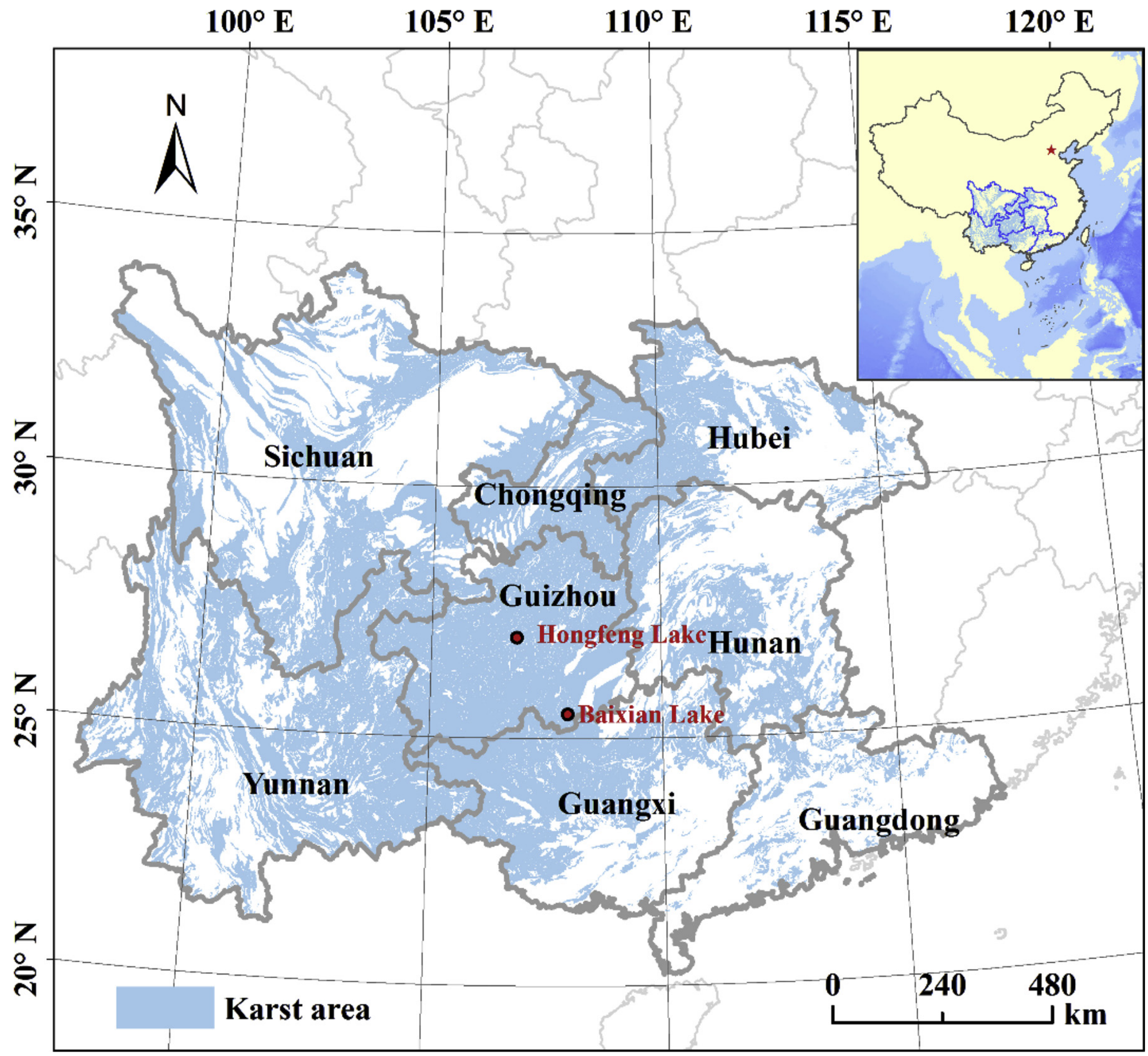

Fig. 1. The karst distribution area in Southwest China and location of Baixian Lake and Hongfeng Lake.

Karst region is strongly constrained by the geological background and characterized by relatively high degree of heterogeneity, porosity and connectivity (Ford and Williams, 2013; Wang et al., 2004; Yuan and Liu, 1998). A comprehensive understanding of the characteristics and evolution processes of KEE impacted by natural disturbances and human activities will provide scientific foundation for formulating regional sustainable development strategies. Many researchers have discussed the fragility of KEE, such as high ecological sensibility, low environmental capacity, weak resilience and poor stability, and realized that intensive human activities easily lead to karst rocky desertification (Ford and Williams, 2013; Liao et al., 2018; Wan, 2000; Wang et al., 2004; Zhang et al., 2002). However, most of these studies have been focusing on the particular karst geologic setting and short-term (annual) changes of terrestrial ecosystem and environment. At longer decadal-centurial timescales, knowledge of how KEE responds to external disturbances such as climate changes and human activities is very limited, and little is known about the resilience of KEE because of the absence of long-term observation data. As a main lodging of surface substances, lake sediment consists of a variety of biological, physical and chemical components, and can thus provide abundant information on atmosphere (precipitation, temperature, acid rain), terrestrial ecosystem/environment (vegetation types, productivity, physical erosion, chemical weathering) and aquatic ecosystem/environment (primary productivity, plankton assemblage, water quality) over thousands of years, which is very useful for understanding fully the evolutionary characteristics of KEE at long timescales. Here, based on geochemical analysis of lake sediments in the KRSC, we probe into the fragility of KEE and how KEE responds to external disturbances such as climate changes and human activities at decadal-centurial timescales. Furthermore, the inherent mechanisms of the fragility of both terrestrial and aquatic KEE are explored.

2. Study sites and methods

2.1. Study sites

Baixian Lake is located in the virgin forest area of Maolan State-level Karst Forest Nature Reserve in Libo County, Guizhou Province, which is the center of the karst distribution area in Southwest China (Fig. 1). The Maolan nature reserve has an area of 20,000 ha (25°09′20″ ~ 25°20′50″N, 107°52′10″ ~ 108°05′40″E). The regional climate is strongly influenced by the southeast monsoon and the southwest monsoon. Thus it is obviously seasonal. More than 85 % of the mean annual precipitation of 1700 mm falls between April and October, when warm-humid air from the southeast and southwest predominates. From November to March, there is less precipitation. The mean annual temperature is 18°C. Baixian Lake is a small typical karst lake at an altitude of 700 m a.s.l., with a surface area of 5000 m^2, a mean water depth of 2 m and a watershed area of 2.5 km^2. There is neither inflow stream nor outflow stream. The lake water mainly comes from surface

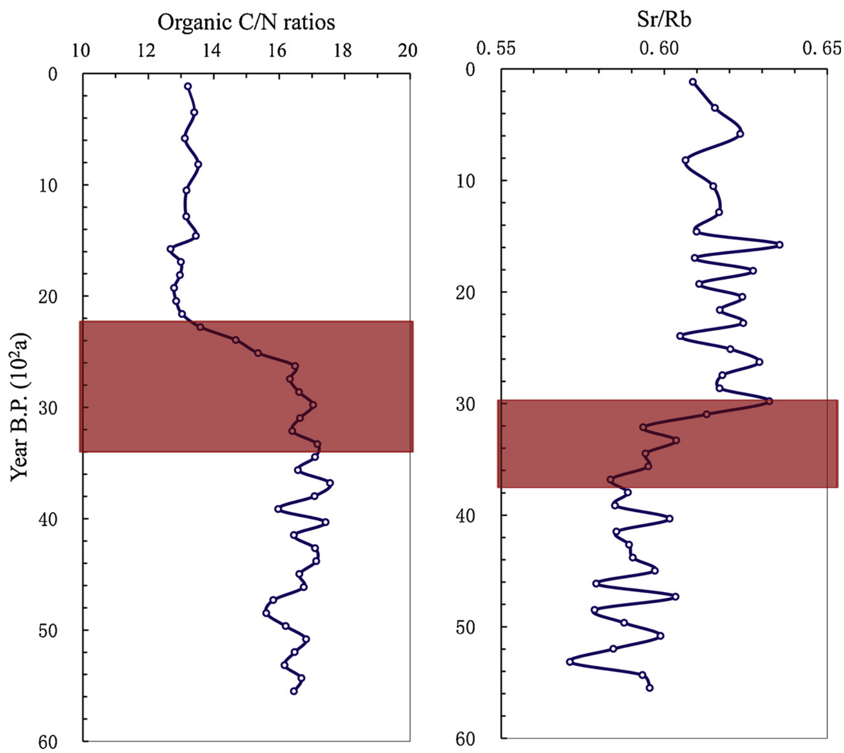

Fig. 2. Variations in organic C/N and Sr/Rb ratios in the sediment core of Baixian Lake.

runoff and underground water. The bedrock is dominated by carbonate in the catchment.

Hongfeng Lake (26°26′ ~ 26°36′N, 106°19′ ~ 106°28′E), located in central Guizhou province (Fig. 1), has a surface area of 57.2 km^2, a mean water depth of 10.5 m. The bedrock consists mainly of carbonate and clastic rock in the catchment. The mean annual temperature is 14.1℃, and the mean annual precipitation is 1200 mm. Hongfeng Lake supplies drinking water to Guiyang City with a population over three million. However, it has suffered from remarkable water quality deterioration, especially eutrophication in the last three decades.

2.2. Sampling and analysis

Sediment cores were retrieved from lake center using a gravity sampler. The sediment cores were perfectly preserved, with a length of 56 cm in Baixian Lake and 38 cm in Hongfeng Lake, respectively. They were immediately divided into 1.0–1.5 cm sections and put into plastic bags in the field. Wet sediment samples were freeze-dried and then ground to homogeneous powders (smaller than 0.15 mm) for geochemical analysis.

Terrestrial plant macrofossils were picked out from sediments to carry out radiocarbon dating on the accelerator mass spectrometry (AMS) at the Scottish Universities Environmental Research Centre AMS Facility. The calibrated age was determined from the University of Oxford Radiocarbon Accelerator Unit calibration program (OxCal3).

Contents of Rb and Sr in sediments were measured by X-ray Fluorescence Analysis using Synchrotron Radiation (SRXFA) technique at a VEPP-3 storage ring at the "Baikal" SRXFA station in the Budker Institute of Nuclear Physics, Novosibirsk (Zolotarev et al., 2001). The reproducibility of Rb and Sr measurements has been tested by repetitive analyses with a relative standard deviation of less than 2 %.

Contents of total carbon and total nitrogen (TN) in sediments were measured by the Element Analyzer (PE2400 SERIES II) and chemical volumetric method was used to measure inorganic carbon (Chen and Wan, 2002). Replicate analysis of samples has a precision of 0.2 % (2σ). Organic carbon (TOC) was calculated from the difference between total carbon and inorganic carbon. Contents of total phosphorus (TP) in sediments were determined by the method harmonized and validated in the frame of standards, measurements and testing programme (Ruban et al., 1999).

Pollen analysis was completed at the Institute of Hydrogeology & Environmental Geology, Chinese Academy of Geological Sciences. Standard preparation techniques were used to prepare the pollen samples. A minimum of 500 pollen grains were counted for each sample to ensure statistical significance. A total of 23,287 pollen grains were identified and counted.

3. Results

3.1. Sediment dating

The cored sediments in Baixian Lake consist of homogeneous greenish-grey gyttja and silty clay without clear lamination. The average sedimentation rate is calculated to be about 0.1 mm a^{-1} according to the terrestrial plant macrofossil ^{14}C age of 4943 ± 30a B.P. at depth of 49 cm in the sediment core. The sediment accumulation rate is expected to be relatively stable as a result of good preservation conditions and less human influence in the virgin forest area. In Hongfeng Lake, a clear boundary between soil and sediment exists at the depth of 38 cm in the sediment core, corresponding to 1960 when the reservoir just formed. Thus, the average sedimentation rate can be calculated to be 6.5 mm a^{-1} in Hongfeng Lake. Sediment age can be estimated according to the average sedimentation rate and sediment depth. Although the sediment age may not be precise, it provides a sediment age scale with sufficient resolution for our discussion of major eco-environment changes.

3.2. C/N ratios of organic matter

The C/N ratios of sedimentary organic matter (OM) have been widely used to indicate OM sources (Chen and Wan, 2002; Dean, 1999; Meyers and Ishiwatari, 1993). Our sampled aquatic macrophytes in

Baixian Lake were determined to have low C/N ratio of about 10 while terrestrial plants collected from the catchment have relatively high C/N ratio of about 22. This proves that the organic C/N ratios can be used to identify OM sources. Variations of the organic C/N ratios displayed three distinct stages in Baixian Lake over the last 6, 000 years (Fig. 2).

Stage 1 (before 3.3 ka B.P.): The C/N ratios were relatively high and stable, with an average value of about 17. This reflects the sedimentary OM was derived from both aquatic and terrestrial plants. The contribution of terrestrial OM to the sediment should be a little more than that of aquatic plants, because the average value of the C/N ratios is closer to terrestrial plants. This stable state had remained for a long time until 3.0 ka B.P.

Stage 2 (3.3 ~ 2.2 ka B.P.): The C/N ratios decreased dramatically from around 16.5 to around 13. This indicates a persistent trend towards decreasing terrestrial OM supply from the catchment into the lake, and may thus imply that terrestrial productivity decreased remarkably.

Stage 3 (from 2.2 ka B.P. to present): The C/N ratios were relatively low and stable, with only small fluctuations around the average value of 13. This suggests a relatively larger contribution of aquatic plants to sedimentary OM than that of terrestrial plants. The terrestrial productivity is supposed to be low at that time.

3.3. Sr/Rb ratios in sediment

As a result of significant differences in geochemical behavior of Rubidium (Rb) and Strontium (Sr) in surface environment, Rb and Sr are easily fractionated in the weathering process (Chen et al., 1999; Dasch, 1969; Goldstein, 1988). Rb tends to retain in weathering residue while Sr is easily leached from the source rocks, resulting in a relative enrichment of Rb over Sr in relicts. Rb/Sr ratios have been successfully used to reconstruct the history of chemical weathering and climate changes over the past tens of thousands of years (Chen et al., 1999; Gallet et al., 1996). Baixian Lake is a small fresh lake. Dissolved components are hardly precipitated because of short residence time and low salinity. Sediments should come mainly from weathering residue in the catchment. Thus, the Sr/Rb ratios could be expected to reflect chemical weathering. As shown in Fig. 2, variations of the Sr/Rb ratios can be divided into three stages in Baixian Lake.

Stage 1 (before 3.6 ka B.P.): The Sr/Rb ratios were relatively low and fluctuated around an average value of 0.59. This reflects Sr was apparently leached, indicating intensive chemical weathering at that time.

Stage 2 (3.6 ~ 3.0 ka B.P.): The Sr/Rb ratios increased rapidly from around 0.59 to around 0.63. This suggests weakening chemical weathering. It is well known that chemical weathering is dominated by precipitation in tropical and sub-tropical regions. Thus, the increase of the Sr/Rb ratios may indicate that chemical weathering gradually weakened.

Stage 3 (from 3.0 ka B.P. to present): The Sr/Rb ratios were relatively high, with small fluctuations around the average value of 0.62. This reflects the chemical weathering was generally weak in this period.

3.4. Pollen assemblage

Pollen, derived from plants surrounding a sedimentary basin, provides the most straightforward evidence for past ecological variability. As shown in Fig. 3, an extraordinary ecological change occurred in Baixian Lake between 3.6 ka B.P. and 2.2 ka B.P. The fern populations increased rapidly from < 10 % to more than 30 % while herb decreased sharply from 60 % to less than 40 %. This indicates remarkable deterioration of terrestrial vegetation at that time.

4. Discussions

4.1. Fragility of terrestrial ecosystem and environment in karst region

In summary, all the proxies (organic C/N ratios, Sr/Rb ratios and pollen assemblage) show coincidental remarkable ecological and environmental changes within the lake-catchment system between 3.6 ka B.P. and 2.2 ka B.P. (Figs. 2 and 3). The sudden increase of the Sr/Rb ratios occurred between 3.6 ka B.P. and 3.0 ka B.P., a little earlier than when the organic C/N ratios started to decline rapidly. This may reflect that the input of terrestrial OM was not reduced at the earlier stage of the dryness and suggests a delayed response of sedimentary C/N ratios to vegetation degradation in the catchment. As a whole, the information inferred from these proxies is quite accordant, especially considering they are absolutely different in nature: The C/N ratios depend on the sources of sedimentary OM; The Rb/Sr ratios represent chemical weathering intensity; The pollen assemblage reflects the changes in plant types. What have caused such large and synchronous changes within the catchment?

Baixian Lake is located in the virgin forest area with little human influence, so the striking eco-environment changes could not result from human activities. Climate change is thus supposed to be the main cause. Fortunately, paleoclimate over the past 10,000 years has been reconstructed using stalagmite samples in Dongge Cave, 10 km to the north of Baixian Lake (Yuan et al., 2004; Zhang et al., 2004; Wang et al., 2005). The oxygen isotope composition of the stalagmite ($\delta^{18}O_{sta}$) has been proved to reflect precipitation changes (Yuan et al., 2004; Zhang et al., 2004). The $\delta^{18}O_{sta}$ values were more negative before 3.6 ka B.P., suggesting wetter climate at that time. From 3.6 ka B.P. to 2.2 ka B.P., the $\delta^{18}O_{sta}$ values tended to be more and more positive, indicating persistent drying (Zhang et al., 2004). In fact, the pollen assemblage also recorded this drying event. Among herbaceous plants, the hygrophilous *Cyperaceae* populations decreased dramatically from more than 30 % to about 10 % while *Artemisia*, adapted to dry habitat, increased rapidly from less than 0.5 % to 4 % between 3.6 ka B.P. and 2.2 ka B.P. (Fig. 3), indicating striking vegetation deterioration resulted from drying conditions at that time. Many evidences have shown that a widespread drought possibly occurred in most of China during 4 ~ 2 ka B.P. (Wang et al., 2008) and the precipitation is weakening steadily in Southwest China (Xu et al., 2019).

The above discussions demonstrate that climate changes could greatly affect the agroecosystem such as forest ecosystem in karst region. From 3.6 ka B.P. to 2.2 ka B.P., climate was drying persistently, resulting in remarkable deterioration of forest ecosystem which was reflected by dwindling herbs, increasing ferns and decreasing terrestrial primary productivity in the catchment. The organic C/N ratios stabilized at a low level for a long time after the drought event (Fig. 2), suggesting the establishment of a new equilibrium state in the ecosystem within the catchment. This is supported by the pollen records. The arbor and herb populations never returned to the earlier level while the fern populations persisted at a high level after the drought event (Fig. 3). This shows that abrupt climate changes have a big and long lasting impact on karst ecosystem. Once degradation happens, the karst ecosystem would be unlikely to recover in the short term by itself. This provides a long-term solid evidence for the fragility of terrestrial KEE. Generally, soils developed in the karst context are very thin, and there exists a distinct interface between soil and carbonate bedrock (Wang et al., 2004). Especially, characterized by relatively high degrees of heterogeneity, porosity and rapid water flow through the conduit structure into groundwater, soils in karst region have poor water retention and weak drought resistance (Wang et al., 2004; Ford and Williams, 2013; Yang et al., 2016a; Oliver et al., 2020), which makes the soil and vegetation highly susceptible to drought event and anthropogenic disturbance. This should be the inherent mechanism of the fragility of terrestrial KEE.

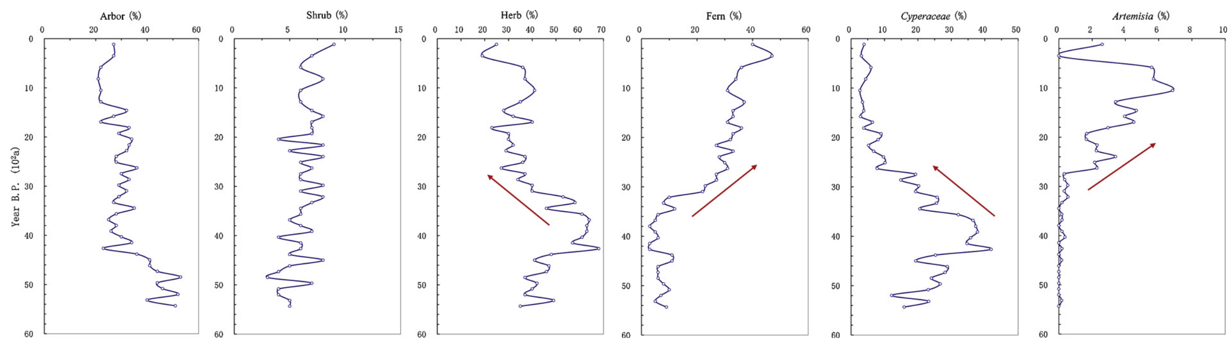

Fig. 3. Variations in pollen assemblage in the sediment core of Baixian Lake.

4.2. Fragility of aquatic ecosystem and environment in karst region

As the largest continuous karst region in the world, Southwest China provides abundant fresh water resources for several major rivers, such as Yangzte and Pearl River, and is referred to as 'Water Tower in South China'. Reservoir is the main form of surface water resource utilization because of the scarcity of natural lakes in the KRSC. However, a variety of eco-environmental problems such as algae blooms and water quality deterioration have occurred in many reservoirs in the last three decades (Chen et al., 2018; Wang et al., 2016).

TOC, TN, TP and organic C/N ratios reflect rapid water eutrophication in Hongfeng Lake (Fig. 4). TOC, TN and TP stabilized at lower values when the reservoir just formed. Higher organic C/N ratios indicate that OM was dominated by terrestrial plant debris at this initial stage. A significant increase in TOC, TN and TP, along with decreasing organic C/N ratios, occurred around 1990 (Fig. 4), indicating higher in-lake primary production which is supposed to result from excessive N and P addition from agricultural activities. The intensification of agricultural land use has been proved to accelerate water eutrophication because of widespread application of fertilizers (Gruber and Galloway, 2008; Smith and Siciliano, 2015; Vitousek et al., 2009). Globally, the synthetic nitrogen fertilizer use has grown from 12 Tg N y^{-1} in 1960 to 110 Tg N y^{-1} in 2013 (Battye et al., 2017). A significant fraction N and P applied to cropland as fertilizer enters the surrounding freshwater (Carpenter, 2005; Galloway and Cowling, 2002; Huang et al., 2017; Liang et al., 2019). The contribution percentage of fertilizer use to nitrates may reach up to 60 % in aquatic systems (Hundey et al., 2016). According to Bulletin of National Environmental Statistics 2009 issued by China's Ministry of Environmental Protection, 57 % of N and 69 % of P entering watercourses are from agriculture in China. The percentages could be higher in karst agricultural region, considering serious soil erosion and nutrient loss due to thin soil, sloping land and rapid water flow (Liu et al., 2020; Oliver et al., 2020; Wang et al., 2004). Extensive use of chemical fertilizer, as well as livestock and poultry breeding, have been demonstrated to have important contribution to N and P pollution in Hongfeng Lake (Yang et al., 2016c). In addition, the burgeoning in-lake cage culture activity discharged large amounts of nutrients directly into the water body from mid-1980s to 1990s (Zhong et al., 2004).

In short, increasing agricultural activities such as extensive use of chemical fertilizer, livestock and poultry breeding, and in-lake cage culture, are supposed to result in rapid water eutrophication and algae blooms in Hongfeng Lake around 1990. This suggests that Hongfeng Lake responds very sensitively to agricultural N and P addition. Since 2000, the cage culture has been prohibited, steeply sloping croplands have been abandoned to reduce soil erosion and nutrient loss under the Grain for Green Project (Wang et al., 2017), and nutrient use efficiency has been improved through optimized fertilization and irrigation management. However, TOC, TN and TP still maintained at a high level (Fig. 4), implying that Hongfeng Lake remained in a state of eutrophication even after controlling external N and P input. The in-lake nutrient cycling may contribute a lot to sustain high primary production.

It is well known that surface and underground water is rich in dissolved inorganic carbon (DIC) as a result of extensive carbonate weathering in karst region. Yang et al. (2016b) found that phytoplankton biomass was positively correlated with DIC concentration in the Pearl River, indicating the DIC fertilization effect on aquatic

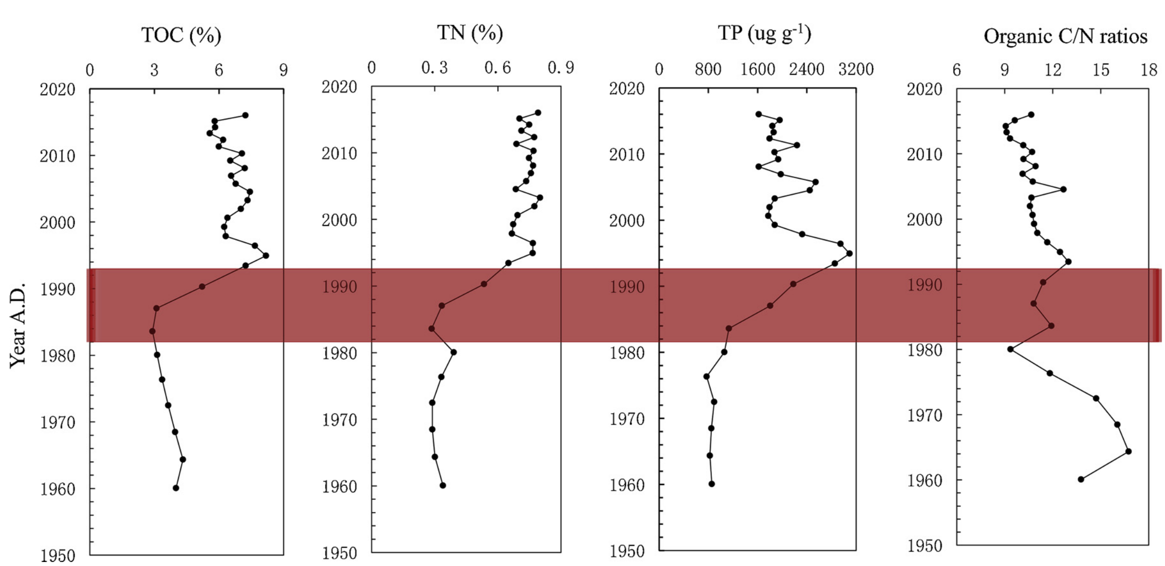

Fig. 4. Variations in TOC, TN, TP and organic C/N ratios in the sediment core of Hongfeng Lake.

photosynthesis. Thus, reservoirs are expected to respond more sensitively to N and P addition from agricultural activities in karst region than in non-karst region. Abundant DIC supply from the carbonate catchment will promote aquatic primary productivity once N and P are adequate, resulting in higher deposition fluxes of endogenous OM and accelerating hypoxia in hypolimnion. As a result of DIC fertilization effect and high OM burial efficiency, reservoirs are usually abundant in sedimentary OM in the KRSC. For example, the average contents of TOC, TP and TN in Hongfeng sediments are 3.2 %, 0.12 % and 0.31 %, respectively, which are two to four times higher than those in Taihu Lake (Chen et al., 2018). Endogenous OM is prone to degrade during early-diagenesis in sediment. Along with the degradation of OM, organic phosphorus and iron-bound phosphorus can be released into the water. This provides an endless supply of P for algae growth. Therefore, a positive feedback loop may develop among elevated primary productivity, higher deposition fluxes of OM, anoxia in hypolimnion and enhanced internal P release in aquatic ecosystem. This positive feedback, together with the DIC fertilization effect and sensitivity to agricultural N and P addition, may explain the fragility of aquatic KEE. Once eutrophication happens as a result of increasing agricultural activities in karst region, it would be very difficult to restore clear water ecosystem in the short term. This highlights the importance of controlling agricultural N and P pollution for maintaining good water quality in karst region. To minimize agricultural pollution, China has launched a campaign on zero growth of the fertilizer consumption by 2020. This campaign is very important for ecological improvement and environmental protection, and should be thoroughly implemented in karst region.

5. Conclusions

Organic C/N ratios, Sr/Rb ratios and pollen assemblage in Baixian Lake indicate that striking eco-environmental deterioration occurred as a result of the drought event between 3.6 ka B.P. and 2.2 ka B.P. The regional vegetation degraded with dwindling herbs, increasing ferns and decreasing terrestrial productivity. Furthermore, the karst ecosystem had not restored to the earlier level even after a long time. Once degradation happens, the karst ecosystem would be unlikely to recover in the short term. Poor water-soil conservation capacity and weak drought resistance of karst soil should be the inherent mechanism of the fragility of terrestrial KEE.

TOC, TN, TP and organic C/N ratios reflect rapid eutrophication in Hongfeng Lake. Reservoirs respond more sensitively to agricultural N and P addition because of abundant DIC supply from the carbonate catchment in karst region than in non-karst region. A positive feedback loop may develop among elevated primary productivity, higher deposition fluxes of OM, anoxia in hypolimnion and enhanced internal P release in aquatic ecosystem. This positive feedback, together with the DIC fertilization effect and sensitivity to agricultural N and P addition, may explain the fragility of aquatic KEE. Once eutrophication happens, it would be very difficult to restore clear water ecosystem.

The past is the key to understand the present and to predict the future. The fragility of both terrestrial and aquatic KEE, demonstrated by this study, highlights the extreme importance of eco-environment protection, and provides important references for formulating strategies on sustainable agriculture development and eco-environment protection in karst region.

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.

Acknowledgements

This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB40020300), and the Natural Science Foundation of China (Grant Nos. U1612441, 41573137).

References

Bai, K., Lv, S., Ning, S., Zeng, D., Guo, Y., Wang, B., 2019. Leaf nutrient concentrations associated with phylogeny, leaf habit and soil chemistry in tropical karst seasonal rainforest tree species. Plant Soil 434, 305–326.
Battye, W., Aneja, V.P., Schlesinger, W.H., 2017. Is Nitrogen the Next Carbon? Earths Future 5, 894–904.
Brandt, M., Rasmussen, K., Peñuelas, J., Tian, F., Schurgers, G., Verger, A., 2017. Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. Nat. Ecol. Evol. 1, 81.
Carpenter, S.R., 2005. Eutrophication of aquatic ecosystems: bistability and soil phosphorus. Proc. Natl. Acad. Sci. U.S.A. 102, 10002–10005.
Chen, J., Wan, G., 2002. Carbon environmental records in recent lake sediments. Sci. China (series D) 45, 875–884.
Chen, J., An, Z., Head, J., 1999. Variation of Rb/Sr ratios in the loess-paleosol sequences of central China during the last 130,000 years and their implications for monsoon paleoclimatology. Quat. Res. 51, 215–219.
Chen, J., Wang, J., Zeng, Y., Guo, J., 2018. Eco-environment of reservoirs in China: characteristics and research prospects. Prog. Phys. Geogr. 42, 185–201.
Dai, Q., Peng, X., Zhao, L., Shao, H., Yang, Z., 2017. Effects of underground pore fissures on soil erosion and sediment yield on karst slopes. Land Degrad. Dev. 28, 1922–1932.
Dasch, E.J., 1969. Strontium isotopes in weathering profiles, deep-sea sediments, and sedimentary rocks. Geochim. Cosmochim. Acta 33, 1521–1552.
Dean, W.E., 1999. The carbon cycle and biogeochemical dynamics in lake sediments. J. Paleolimnol. 21, 375–393.
Ford, D., Williams, P.D., 2013. Karst Hydrogeology and Geomorphology. John Wiley & Sons.
Gallet, S., John, B.M., Toril, M., 1996. Geochemical characterization of the Luochuan loess-paleosol sequence, China, and paleoclimatic implications. Chem. Geol. 133, 67–88.
Galloway, J.N., Cowling, E.B., 2002. Reactive nitrogen and the world: 200 years of change. Ambio 31, 64–71.
Goldstein, S.L., 1988. Decoupled evolution of Nd and Sr isotopes in the continental-crust and the mantle. Nature 336, 733–738.
Gruber, N., Galloway, J.N., 2008. An Earth-system perspective of the global nitrogen cycle. Nature 451, 293–296.
Huang, J., Xu, C.C., Ridoutt, B.G., Wang, X.C., Ren, P.A., 2017. Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. J. Clean. Prod. 159, 171–179.
Hundey, E.J., Longstaffe, F.J., Moser, K.A., 2016. Agriculture causes nitrate fertilization of remote alpine lakes. Nat. Commun. 7, 10571.
Jiang, Z., Lian, Y., Qin, X., 2014. Rocky desertification insouthwest China: impacts, causes, and restoration. Earth. Rev. 132, 1–12.
Liang, K., Zhong, X., Pan, J., Huang, N., Liu, Y., Peng, B., Fu, Y., Hu, X., 2019. Reducing nitrogen surplus and environmental losses by optimized nitrogen and water management in double rice cropping system of South China. Agric. Ecosyst. Environ. 286, 106680.
Liao, C., Yue, Y., Wang, K., Fensholt, R., Tong, X., Brandt, M., 2018. Ecological restoration enhances ecosystem health in the karst regions of southwest china. Ecol. Indic. 90, 416–425.
Liu, M., Han, G., Zhang, Q., 2020. Effects of agricultural abandonment on soil aggregation, soil organic carbon storage and stabilization: results from observation in a small karst catchment, Southwest China. Agric. Ecosyst. Environ. 288, 106719.
Mellander, P.E., Jordan, P., Wall, D.P., Melland, A.R., Meehan, R., Kelly, C., Shortle, G., 2012. Delivery and impact bypass in a karst aquifer with high phosphorus source and pathway potential. Water Res. 46, 2225–2236.
Meyers, P.A., Ishiwatari, R., 1993. Lacustrine organic geochemistry-an review of indicators of organic matter sources and diagenesis in lake sediments. Org. Geochem. 20, 867–900.
Oliver, D.M., Zheng, Y., Naylor, L.A., Murtagh, M., Waldron, S., Peng, T., 2020. How does smallholder farming practice and environmental awareness vary across village communities in the karst terrain of southwest China? Agric. Ecosyst. Environ. 288, 106715.
Ruban, V., Brigault, S., Demare, D., Philippe, A.M., 1999. An investigation of the origin and mobility of phosphorus in freshwater sediments from Bort-Les-Orgues Reservoir, France. J. Environ. Monit. 1, 403–407.
Smith, L.E.D., Siciliano, G., 2015. A comprehensive review of constraints to improved management of fertilizers in China and mitigation of diffuse water pollution from agriculture. Agric. Ecosyst. Environ. 209, 15–25.
Song, T., Peng, W., Zeng, F., Wang, K., Cao, H., Li, X., Qin, W., Tan, W., Liu, L., 2010. Community composition and biodiversity characteristics of forests in karst cluster-peak-depression region. Biodivers. Sci. 18, 355–364.
Tong, X., Brandt, M., Yue, Y., Horion, S., Wang, K., Keersmaecker, W.D., 2018. Increased vegetation growth and carbon stock in china karst via ecological engineering. Nat. Sustain. 1, 44–50.
Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwater, L.E., Holland, E., Johnes,

P.J., Katzenberger, J., Martinelli, L.A., Matson, P.A., Nziguheba, G., Ojima, D., Palm, C.A., Robertson, G.P., Sanchez, P.A., Townsend, A.R., Zhang, F.S., 2009. Nutrient imbalances in agricultural development. Science 324, 519–1520.
Wan, G., 2000. Carbonates and Environment Vol 2. Earthquake Press, Beijing, pp. 1–6.
Wang, S., Li, R., Sun, C., Zhang, D., Li, F., Zhou, D., Xiong, K., Zhou, Z., 2004. How types of carbonate rock assemblages constrain the distribution of karst rocky desertified land in Guizhou Province, PR China: phenomena and mechanisms. Land Degrad. Dev. 15, 123–131.
Wang, Y., Cheng, H., Edwards, R., He, Y., Kong, X., An, Z., Wu, J., Kelly, M., Dykoski, C., Li, X., 2005. The Holocene Asian monsoon: links to solar changes and North Atlantic climate. Science 308, 854–857.
Wang, S., Huang, J., Wen, X., 2008. Evidence and modeling study of droughts in China during 4 ~ 2kaBP. Chinese Sci. Bull. 53, 2215–2221.
Wang, J., Chen, J., Ding, S., Guo, J., Christopher, D., Dai, Z., Yang, H., 2016. Effects of seasonal hypoxia on the release of phosphorus from sediments in deep-water ecosystem: a case study in Hongfeng Reservoir, Southwest China. Environ. Pollut. 219, 858–865.
Wang, B., Gao, P., Niu, X., Sun, J., 2017. Policy-driven China's grain to green program: implications for ecosystem services. Ecosyst. Serv. 27, 38–47.
Xu, H., Song, Y.P., Goldsmith, Y., Lang, Y.C., 2019. Meridional ITCZ shifts modulate tropical/subtropical Asian monsoon rainfall. Sci. Bull. (Beijing) 64, 1737–1739.
Yan, Y., Dai, Q., Yuan, Y., Peng, X., Zhao, L., Jing, Y., 2018. Effects of rainfall intensity on runoff and sediment yields on bare slopes in a karst area, SW China. Geoderma 330, 30–40.
Yang, J., Nie, Y.P., Chen, H.S., Wang, S., Wang, K.L., 2016a. Hydraulic properties of karst fractures filled with soils and regolith materials: implication for their ecohydrological functions. Geoderma 276, 93–101.
Yang, M., Liu, Z., Sun, H., Yang, R., Chen, B., 2016b. Organic carbon source tracing and DIC fertilization effect in the Pearl River: insights from lipid biomarker and geochemical analysis. Appl. Geochem. 73, 132–141.
Yang, T., Liu, H., Yu, Y., Chen, Z., Rao, C., Jiang, C., 2016c. Agricultural non-point source pollution in drinking water conservation area of the Hongfeng Lake in Guiyang City. Journal of Landscape Research 8, 100–104.
Yuan, D., Liu, Z., 1998. Global Karst Correlation. Science Press, Beijing.
Yuan, D., Cheng, H., Edwards, R., Dykoski, C., Kelly, M., Zhang, M., Qing, J., Lin, Y., Wang, Y., Wu, J., Dorale, J., An, Z., Cai, Y., 2004. Timing, duration and transition of the last interglacial Asian Monsoon. Science 304, 575–578.
Zhang, D., Wang, S., Li, R., 2002. Study on the eco -Environmental vulnerability in Guizhou Karst Mountains. Geography and Territorial Research 18, 77–79.
Zhang, M., Cheng, H., Lin, Y., Qing, J., Zhang, H., Tu, L., Wang, H., Feng, Y., 2004. High resolution paleoclimatic environment records form a stalagmite of Dongge Cave since 15000a in Libo, Guizhou Province, China. Geochimica 33, 65–74.
Zhang, C., Qi, X., Wang, K., Zhang, M., Yue, Y., 2017. The application of geospatial techniques in monitoring karst vegetation recovery in southwest China: a review. Prog. Phys. Geogr. 41, 450–477.
Zhong, X., Liao, G., Sun, W., 2004. Effect of cage-culture fishing on the water quality of lakes and reseroirs and protection for water source. Journal of Guizhou Normal University (Natural Sciences) 22, 34–38.
Zolotarev, K.V., Goldberg, E.L., Kondratyev, V.I., 2001. Scanning SR-XRF beamline for analysis of bottom sediments. Nucl. Instrum. Methods Phys. Res. A 470, 376–379.