INTERNATIONAL JOURNAL OF DIGITAL EARTH
2024, VOL. 17, NO. 1, 2356119
https://doi.org/10.1080/17538947.2024.2356119

OPEN ACCESS Check for updates

Monitoring spatio-temporal dynamics of multi-dimensional karst ecosystem quality in Southwest China by integrating multi-source data

Weiling Shen[a,b,c], Yuan Sun[c], Jiaguo Li[c], Hongsheng Zhang[d], Zhi Ding[b] and Xuguang Tang[a]

[a]Institute of Remote Sensing and Geosciences, Hangzhou Normal University, Hangzhou, People's Republic of China; [b]Chongqing Jinfo Mountain Karst Ecosystem National Observation and Research Station, School of Geographical Sciences, Southwest University, Chongqing, People's Republic of China; [c]Chinese Academy of Sciences, Aerospace Information Research Institute, Beijing, People's Republic of China; [d]Department of Geography, The University of Hong Kong, Hong Kong, People's Republic of China

ABSTRACT

A thorough assessment of the karst ecosystem quality plays an important role in regional sustainable development. In this study, based on multi-source remote sensing data, a comprehensive ecosystem quality index (EQI) was developed by integrating the ecosystem function index (EFI), the ecosystem stability index (ESI), and the ecosystem stress index (ESSI), to evaluate the spatio-temporal changes of ecosystem quality in the karst region of Southwest China during the past two decades. The results showed that the EFI exhibited a significant increasing trend in approximately 54.58% of the karst area from 2001 to 2020. The ESI experienced multiple stages from initially increasing around 2005, then decreasing around 2010, and finally increasing to the peak in 2020. The ESSI fluctuated at a high level since 2001. Overall, the comprehensive EQI experienced a gradual improvement in the initial period from 2001 to 2010, and then increased significantly from 2015 to 2020. The excellent EQI occupied by no more than 20% before 2005, but expanded sharply with about three times by 2020. Additionally, nearly 16.73% of the karst area experienced significant improvement in the EQI, whereas only 0.28% of the karst area exhibited severe degradation in the EQI during the past 20 years.

ARTICLE HISTORY
Received 17 January 2024
Accepted 11 May 2024

KEYWORDS
Karst ecosystem; ecosystem quality; ecosystem service; ecosystem stability; ecosystem stress

1. Introduction

Affected by climate change marked by global warming and substantial disturbances caused by human activities, the ecosystem quality in China is facing increasingly severe pressures. To alleviate ecological problems and improve ecosystem quality, the Chinese government has implemented a series of ecological projects, such as the planning of national key ecological functional zones (Sun et al. 2021), the delineation of ecological red lines (Tian et al. 2022; Xu et al. 2018), and the ecological protection and restoration project of mountain-river-forest-farmland-lake-grass (Zou

CONTACT Yuan Sun sunyuan@aircas.ac.cn Chinese Academy of Sciences, Aerospace Information Research Institute, Beijing 100094, People's Republic of China; Jiaguo Li jacoli@126.com Chinese Academy of Sciences, Aerospace Information Research Institute, Beijing 100094, People's Republic of China; Xuguang Tang xgtang@hznu.edu.cn Institute of Remote Sensing and Geosciences, Hangzhou Normal University, Hangzhou 311121, People's Republic of China

et al. 2018). Under the context of ecological civilization construction in China, promoting the quality and stability of the ecosystem has become one of the most important targets in China's 14th Five-Year Plan and Long-Range Objectives for 2035. Therefore, a deep understanding of the spatio-temporal variations in ecosystem quality is essential for evaluating the effects of climate change and eco-engineering, which can also provide theoretical support for the regional sustainable development of the karst ecosystem.

Although the scientific concept and the assessment method of ecosystem quality have not formed a broad consensus in current studies (Yu, Wang, and Yang 2022), the universal connotations of a good ecological environment are considered to encompass the inherent natural attributes of regional ecosystems and ecological products, along with their utility and the degree to which they fulfill the needs essential for the sustenance and progress of human society (Yu, Wang, and Yang 2023). Additionally, the quality of ecosystems is primarily influenced by ecological characteristics such as multifunctionality, authenticity, completeness, and stability, as well as external disruptions including global change, anthropogenic activities, and various surface natural processes (Yu, Wang, and Yang 2023). Thus, ecosystem quality generally involves three aspects, including the ability to provide various services to humans, ecosystem's stability and integrity, and the degree of resistance to external disturbances. In this study, it refers to the functional strength, stability, and stress of terrestrial ecosystems.

How to construct a scientific and rational assessment index system and select the key ecological indicators of ecosystem quality remains a challenge. Currently, based on the number of indicators utilized in the assessment framework, the ecosystem quality assessment system can be categorized into two main types: one that employs a comprehensive set of evaluation indicators, and another that focuses on a select few key performance indicators for evaluation (He, Xu, and He 2020). The former approach is typically designed to evaluate the overall quality of an ecosystem in a thorough and methodical manner, making it appropriate for assessing regions with a limited spatial extent and relatively comprehensive monitoring data. For example, Xia et al. (2023) constructed a pattern-service-stress ecosystem quality assessment model to evaluate ecosystem quality in Suide County and then combine the ecological network constructed by the minimum cumulative resistance model to identify the key areas for restoration. The latter aims to representatively assess the crucial aspects of the ecosystem quality, such as ecosystem service, ecosystem stress, vegetation status, etc. Besides, this method is commonly used for large-scale evaluation, such as urban regions (Xiao et al. 2016), countries (Ouyang et al. 2014), and transcontinental (Wei et al. 2023). It can also provide a critical understanding of the ecosystem quality and theoretical guidance for ecological conservation and restoration. Therefore, this study particularly used three key indicators including ecosystem function, stability, and stress to construct the assessment system, which is beneficial to identify the characteristics of the ecosystem quality from different perspectives.

Given to the advantages of rapid extraction of vegetation information, wide extent of coverage, long time series, and low cost, the satellite remote sensing-based method is now widely used for ecosystem quality assessment (Pan and Dong 2016; Tu et al. 2024; Wei et al. 2023). One typical example is the remote sensing-based ecological index (RESI) model proposed by Xu (2013), which uses the principal component analysis method to avoid the subjectivity of artificial weight determination. Through the RESI, plenty of studies provided insights into the long-term monitoring of ecological environment changes. However, this approach focuses only on the impacts of ecological environment, and does not comprehensively evaluate ecosystem quality. Thus, the index evaluation method based on multi-source remote sensing data is more advantageous because it reflects the characteristics of multiple aspects of the ecosystem. Generally, vegetation productivity is the most important ability to maintain ecosystem functions. Then the ecosystem stability refers to the fluctuation of vegetation production capacity, can represent the balance of the entire ecosystem. Lastly, the ecosystem stress needs to be considered under the context of human-induced disturbances. For example, Zhang et al. (2022) proposed a new index as ecosystem quality ratio (EQR) by integrating the status of landscape structure, ecosystem services, ecosystem stability, and human disturbance relative to their reference conditions, and assessed the EQR changes in China's National Key Ecological Function Zones (NKEFZs) from 1990 to 2015.

The karst region in southwestern China is one of the most typical, complex karst characteristics with diverse landscapes (Tang et al. 2022; Wang et al. 2023). The area is uniquely characterized by high ecological sensitivity, low environmental capacity, weak resistance to interference, and poor stability (Wang et al. 2021; Xiong and Chi 2015). Large-scale ecosystem restoration projects (e.g. the Grain for Green Program, Karst Rocky Desertification Restoration Project) have been implemented since the beginning of the new millennium to restore vegetation and improve the ecosystem quality in Southwest China (Ding et al. 2021; Tong et al. 2017). However, the previous work generally focused on ecosystem vulnerability (Guo, Zang, and Luo 2020),' ecosystem health (Zhao et al. 2021), and ecosystem restoration (Qiao, Jiang, and Zhang 2021). Therefore, in this study, we primarily aimed: (1) to propose an ecosystem quality assessment system by integrating multiple indicators of ecosystem service function, stability, and stress; (2) to explore the spatio-temporal variations characteristics of ecosystem service, ecosystem stability, and ecosystem stress; and (3) to figure out the long-term dynamics of ecosystem quality in the karst region of Southwest China during the past two decades. Our research can provide evidence and support for sustainable development in such ecologically-fragile areas.

2. Materials and methods

2.1. Study area

The study area is located at 97°35′∼112°06′E, 20°90′∼35°31′N with an area of 1.36 million km^2, which accounts for 14.33% of the land area of China, and includes Yunnan, Sichuan, Guizhou, and Guangxi provinces, and Chongqing city (Figure 1). As one of the three largest karst-distributed regions in the world, the karst area in Southwest China covers 0.42 million km^2. The region is characterized by diverse landscapes and complicated topography, including the West Sichuan Plateau, the Yunnan-Guizhou Plateau, the Hengduan Mountains, the Sichuan Basin, and the hills of Guangxi. The topography decreases along the northwest to southeast direction. Locating in low latitudes, it is mainly dominated by the subtropical monsoon climate with cold, dry winter and warm, wet summer. Multi-year mean annual precipitation is ranging from 1000 to 1300 mm and annual mean temperature (AMT) is approximately 17°C. The main vegetation types are comprised of coniferous forest, broad-leaved forest, shrubland, grassland, farmland, etc.

2.2. Data sets

2.2.1. Satellite remote sensing-based vegetation data

Leaf area index (LAI), fractional vegetation cover (FVC), and gross primary productivity (GPP) are used to represent terrestrial vegetation conditions. All data are derived from the global land surface satellite (GLASS) products at the University of Maryland GLASS Product Release Website (http://www.glass.umd.edu/). The latest version (V6) of the GLASS LAI product established the corresponding relationship between time series MODIS surface reflectance and LAI. The bidirectional long-term and short-term memory network (Bi-LSTM) model was used for model training and prediction (Ma and Liang 2022). Based on the machine learning method, the model between the preprocessed reflectance and the FVC value is trained to produce global surface vegetation coverage product (Jia et al. 2015). The GLASS GPP product is derived from the revised EC-LUE model, which can effectively generate reproduce the spatial, seasonal, and annual variations, especially improve the model performance in reproducing the interannual variations in GPP, by integrating the regulations of several important environmental variables such as atmospheric CO_2 concentration, radiation components, and atmospheric vapor pressure deficit (Yuan et al. 2010). This study used the GLASS product at the spatial resolution of 500 m for analysis.

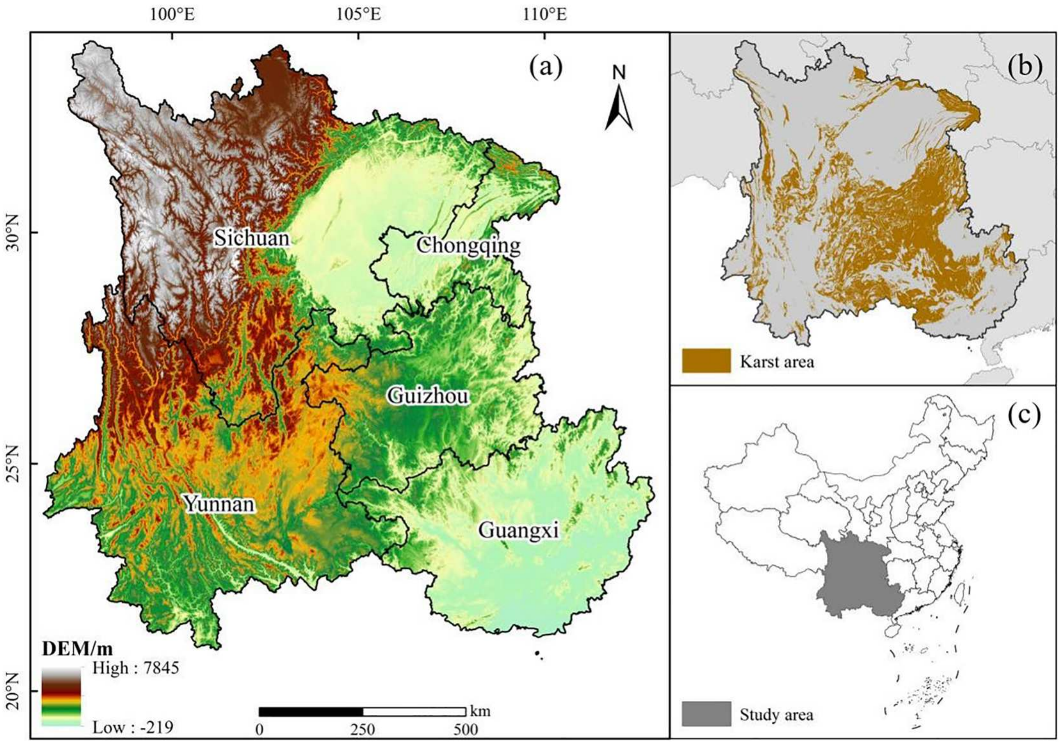

Figure 1. Spatial distribution of karst area in Southwest China and its digital elevation model.

2.2.2. Land cover data

In the study, we used the MCD12Q1 land cover data to characterize the ecosystem stress index (ESSI). The data are accessible from the MODIS data product distribution website of the National Aeronautics and Space Administration (NASA) of the United States (http://modis.gsfc.nasa.gov/). The MCD12Q1 (V6) product is derived from MODIS Terra and Aqua reflectance data using the supervised classifications, then undergoing additional post-processing that incorporates prior knowledge and ancillary information to further refine specific classes. Each MCD12Q1 Hierarchical Data Format 4 (HDF4) file provides layers for Land Cover Type 1–5, Land Cover Property 1–3, Land Cover Property Assessment 1–3, Land Cover Quality Control (QC), and a Land Water Mask. The study used the Land Cover Type 1 layer, which contains 17 main land cover types, according to the International Geosphere-Biosphere Program (IGBP). Based on our research framework, the land cover data were further divided into the following nine types including forest, woody savanna, savanna, grassland, cropland, cropland/natural vegetation mosaic, urban and built-up land, water body, and others.

2.2.3. Meteorological data

The study used the meteorological data including temperature and precipitation to reveal the underlying environmental effects. The temperature data are derived from the National Tibetan Plateau/Third Pole Environment Data Center (https://data.tpdc.ac.cn/), with a spatial resolution of approximately 1 km. The dataset is generated by downscaling through the Delta spatial downscaling scheme based on the global 0.5° climate dataset released by the Climatic Research Unit (CRU) and the global high-resolution climate dataset released by WorldClim. Moreover, the observation data from 496 independent meteorological observation stations are used for verification (Peng et al. 2018). The monthly precipitation data are derived from the China Science Data (http://www.csdata.

org/). The dataset is based on the precipitation data from more than 2400 meteorological stations in China from 1960 to 2020, and the national monthly precipitation interpolation dataset with 1 km spatial resolution is produced by using the spatial interpolation software ANUSPLIN4.4 (Qu et al. 2022). We completed the batch conversion and tailoring of meteorological data using Matlab 2018a. The monthly temperature was further averaged to AMT whereas the monthly precipitation was aggregated to annual total precipitation, respectively.

2.3. Methods

2.3.1. Ecosystem function index (EFI)

Ecosystem function refers to the material produced by natural ecosystems and ecological processes, as well as services that maintain a good environment for humanity (Christensen et al. 1996). The functions provided by terrestrial ecosystems can be summarized into 17 categories (Costanza et al. 1997), and ecosystem productivity is considered as the material basis for human production and livelihoods. Therefore, the study used the pivotal ecological indicators to form the comprehensive ecosystem quality evaluation system. The indicators used to reflect ecosystem productivity generally include vegetation index, net primary productivity, aboveground biomass, etc. LAI refers to the total area of green leaves per unit land area, mainly characterizing the vertical structure of vegetation. FVC refers to the percentage of the vertical projected area of vegetation (including leaves, stems, and branches) on the ground to the total area of the region, mainly characterizing the horizontal structure of vegetation. GPP refers to the total amount of organic carbon fixed by green plants through photosynthesis, mainly characterizing the photosynthetic capacity of vegetation. Therefore, the study uses a composite index of LAI, FVC, and GPP as a measure of ecosystem function in the karst region of Southwest China. The formula is as follows:

$$EFI_o = \frac{LAI_i + FVC_i + GPP_i}{3} \tag{1}$$

$$EFI_i = \begin{cases} 0.1 \\ 0.1 + (EFI_0 - EFI_{\min}) \times a \\ 1 \end{cases} \qquad a = (1 - 0.1)/(EFI_{\max} - EFI_{\min}) \tag{2}$$

where EFI_i is ecosystem function index of the pixel in year i; LAI_i , FVC_i , GPP_i are the normalized annual mean LAI, FVC, and GPP in year i, respectively. Given that even with very low EFI_o values, ecosystems still have a certain level of productivity, so the range of the EFI_o index is normalized to [0.1, 1]. Generally, the larger the EFI_i , the better the ecosystem quality. Using histogram analysis to study the distribution of EFI_0 during the period, the upper and lower limits of EFI_0 are determined. Then the linear stretching of EFI_0 was carried out to obtain the grades of EFI value, where a was the stretching constant. $EFI_{\max}$ and $EFI_{\min}$ are the upper and lower limits of the EFI_o, respectively.

2.3.2. Ecosystem stability index (ESI)

Ecosystem stability refers to the ability of ecosystem to maintain the original service by its self-stabilizing function when it is disturbed. The ecosystem is generally in a relatively stable state, with fewer fluctuations within a certain range. When disturbance occurs, the ecosystem deviates from its original equilibrium and undergoes a transition, ultimately reaching a new equilibrium through self-regulation. The stability of ecosystem can be characterized by quantitatively evaluating on the fluctuation of ecosystem functions. Therefore, the ESI is constructed by the variation coefficient of

Table 1. Disturbance assignment table for different land use types.

Type	Natural regeneration utilization	Artificial regeneration utilization	Artificial non-regeneration utilization
Land use type	Forest, grassland, water bodies, etc.	Cropland	Urban and built-up land
Disturbance gradient index	1	2	3

the EFI. The formula is as follows:

$$CV_i = \frac{S(EFI_i)}{D(EFI_i)} \tag{3}$$

$$ESI_i = \begin{cases} 0.1 \\ 0.1 + (CV_{\max} - CV_i) \times a \; CV_0 \geq CV_{\max} \\ 1 \end{cases}$$
$$a = (1 - 0.1)/(CV_{\max} - CV_{\min}) \tag{4}$$

where $S(EFI_i)$ and $D(EFI_i)$are the standard deviation and average of the EFI from the beginning i – 1 year to the i + 1 year, respectively. CV_i is the variation coefficient of the EFI in year i, with the larger the value the worse the stability. The ESI is limited to [0.1,1] by linear stretching and segmental processing. Generally, the larger the EFI_i , the better the ecosystem quality. a is the tensile constant; $CV_{\max}$ and $CV_{\min}$ are the upper and lower limits of the variation coefficient of the EFI, which is similar to the upper and lower limits of EFI_o.

2.3.3. Ecosystem stress index

The ESSI indicates the resistance of the ecosystem to external disturbances. Land use is a major anthropogenic change that has reshaped the earth's surface, thereby affecting all ecosystem functions (Steffen, Crutzen, and McNeill 2007). As a direct manifestation of external pressures, different land use types are typically associated with specific ecosystem states and functions. For instance, forest, grassland, and other natural regeneration utilizations yield more ecological benefits in terms of biodiversity, carbon storage, and water cycling, whereas urban and built-up land reflects adverse impact of human activities on the terrestrial ecosystem.

Besides, in the context of sustainable land management practices, land use types are typically categorized into the following three major categories based on the methods to manage or utilize natural resources, including natural regeneration utilization, artificial regeneration utilization, and artificial non-regeneration utilization. Natural regeneration utilization refers to the management or utilization of resources through allowing natural processes, such as seed dispersal and germination, to regenerate the ecosystem without human intervention. Artificial regeneration utilization involves deliberate human intervention to regenerate or replenish resources, often through techniques like planting seeds and saplings. Artificial non-regeneration utilization refers to the utilization of resources in a manner that does not promote the regeneration of natural resources.

The methods to manage or utilize natural resources reflect the degree of external disturbance on the ecosystem. Therefore, based on the degree of disturbance of different land use type, each land use is graded and assigned as Table 1:

Table 2. Weight table of each indicator.

Indicator	EFI	ESI	ESSI
Weight	0.45	0.35	0.2

Table 3. Grades of the ecosystem quality.

Level	Excellent	Good	Moderate	Low	Poor
Index	$EQI \geq 0.75$	$0.75 > EQI \geq 0.55$	$0.55 > EQI \geq 0.35$	$0.35 > EQI \geq 0.20$	$EQI < 0.20$

The larger the external pressure on the ecosystem, the larger possibility of ecosystem degradation, which leads to the worse ecosystem quality. Thus, the ESSI is negatively correlated with the disturbance gradient index (DGI) with the following formula:

$$ESSI_i = \begin{cases} 0.1 \\ 0.1 + (DGI_{\max} - DGI_0) \times a \\ 1 \end{cases} \tag{5}$$

$$DGI_i \geq DGI_{\max}$$

$$a = (1 - 0.1)/(DGI_{\max} - DGI_{\min})$$

where DGI_i is the disturbance gradient index in year i; $ESSI_i$ is the ecosystem stress index in year i. Given the possibility of ecosystems being disturbed by humans activities, the value of the ESI is limited to [0.1,1] by linear stretching and segmental processing. The method of $DGI_{\max}$ and $DGI_{\min}$ is as above. The degree of external disturbances is negatively correlated with ecosystem quality, that is, the larger the ESSI, the lower the degree of the ecosystem affected by external disturbances, and the better the ecosystem quality.

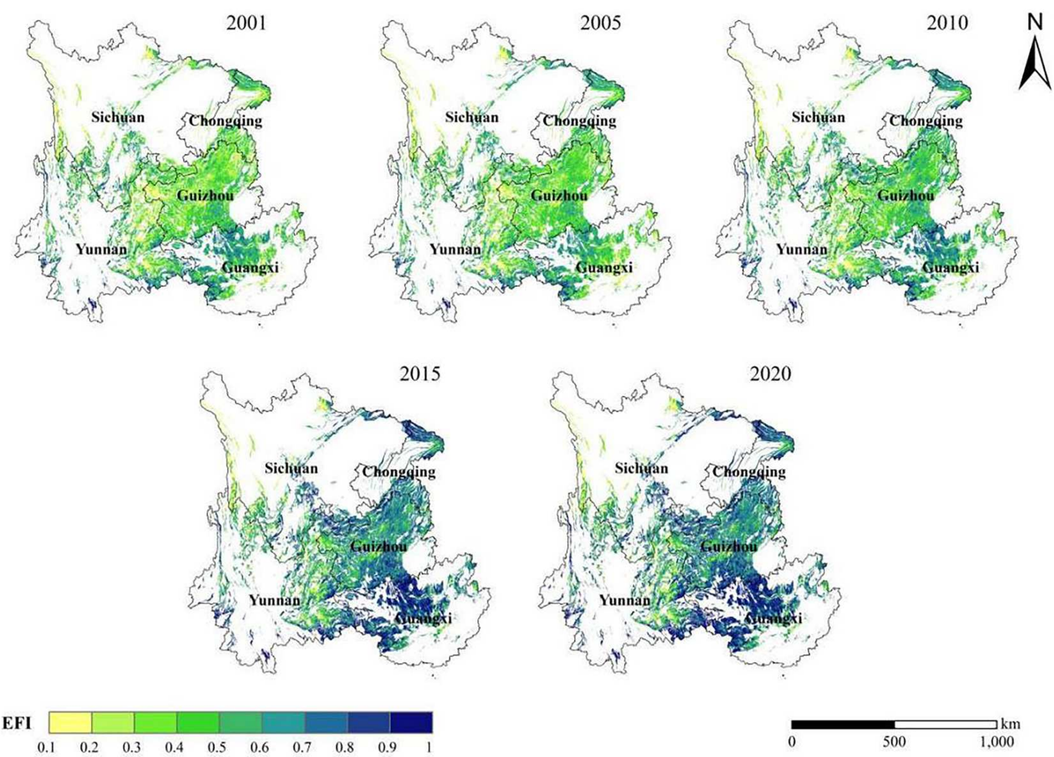

Figure 2. Spatial distribution of the EFI in the karst region of Southwest China from 2001 to 2020.

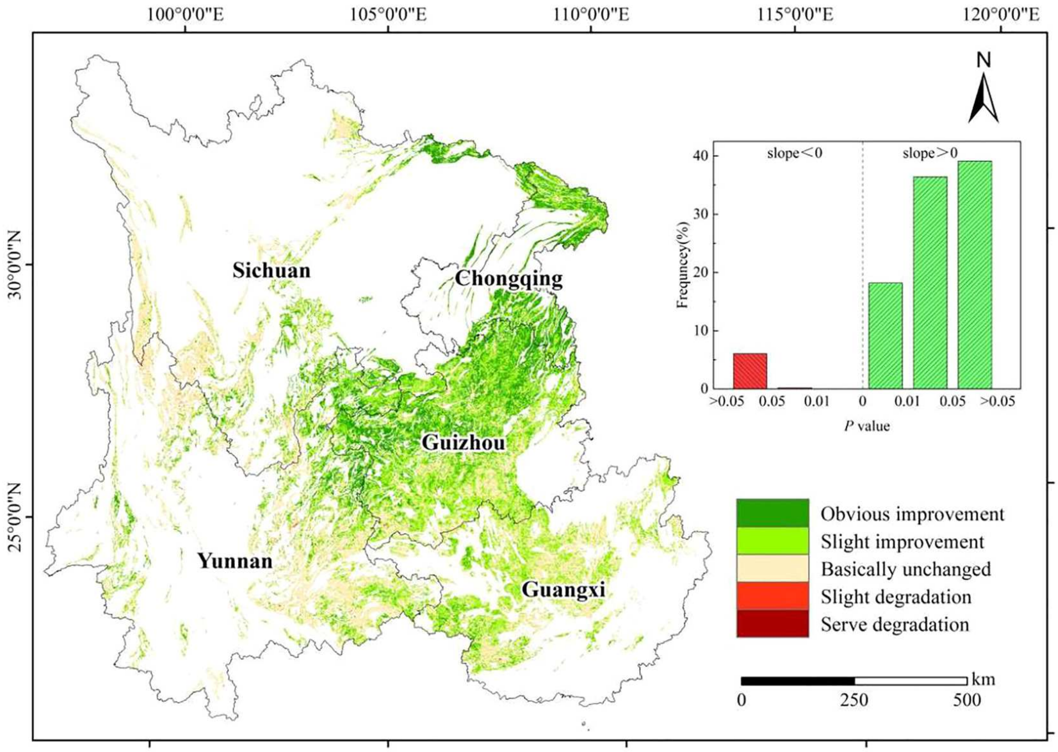

Figure 3. Trend analysis of the EFI in the karst region of Southwest China from 2001 to 2020. Frequency is the ratio of the EFI improved (green bars) and degraded (red bars) areas to the total study area, including significance levels of $p < 0.01$, $p < 0.05$, and $p > 0.05$.

2.3.4. Ecosystem quality index

The study established a the comprehensive index to reflect the overall status of regional ecosystem quality. The assessment system is comprised of EFI, ESI, and ESSI. The weighted sum of the three indices jointly constructs the EQI. The formula is as follows:

$$EQI = \sum_{i=1}^{n} W_i \times y_i \tag{6}$$

where *EQI* is the ecosystem quality index; y_i represents *EFI*, *ESI*, and *ESSI*, respectively; W_i is the weight of each index as shown in Table 2, which is derived from the expert scoring method (Tang et al. 2016).

After we calculated the EQI, the regional ecosystem was divided into five grades namely excellent, good, moderate, low, and poor, respectively, as shown in Table 3.

2.3.5. Trend analysis

The linear regression analysis is used to investigate the temporal variation trends of *EFI* and *EQI* from 2001 to 2020 on the pixel scale. The formula is as follows:

$$\theta_{\text{slope}} = \frac{n \times \sum_{i=1}^{n} i \times x_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} x_i}{n \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{7}$$

where θ_{slope} is the slope; n is the number of the study period, x_i means the value of the i year; if $\theta_{\text{slope}} > 0$, it indicates that the x indicator exhibits an increasing trend; otherwise, it shows a decreasing trend. Meanwhile, the trend is subjected to significant test and graded as follows: significantly decreased ($\theta_{\text{slope}} < 0$, $p \leq 0.01$), slightly decreased ($\theta_{\text{slope}} < 0$, $0.01 < p \leq 0.05$), basically unchanged

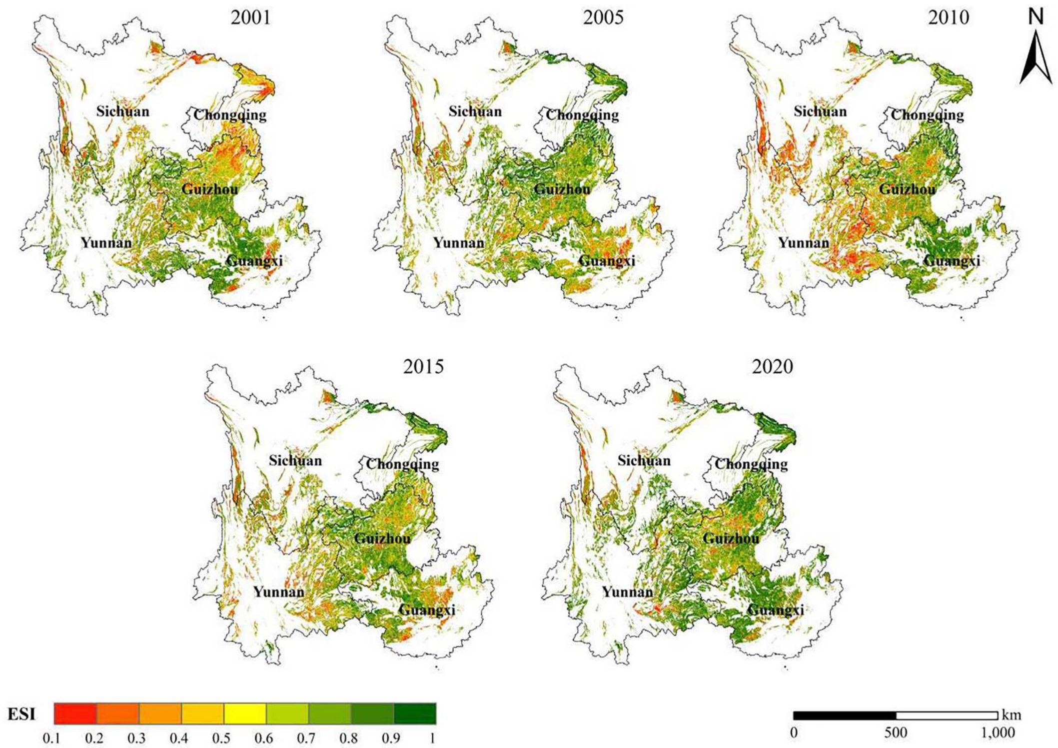

Figure 4. Spatial distribution of the ESI in the karst region of Southwest China from 2001 to 2020.

($\theta_{slope}< 0$ or $\theta_{slope}> 0$, $p > 0.05$), slightly increased ($\theta_{slope}> 0$, $0.01 < p \leq 0.05$), and significantly increased ($\theta_{slope}> 0$, $p \leq 0.01$), respectively.

3. Results

3.1. Evaluation of ecosystem function

Figure 2 illustrates the spatio-temporal patterns of the EFI in the karst region of Southwest China, which showed a continuously increasing trend during the past two decades. Through statistical analysis, the EFI in 2001 was about 0.45 ± 0.19, then it showed a slight improvement in 2005 with 0.46 ± 0.18, and further increased to 0.50 ± 0.19 in 2010. Then, the EFI reached 0.65 ± 0.18 in 2015, and peaked in 2020 with 0.68 ± 0.22. Meanwhile, the study indicated that the EFI exhibited a decreasing trend along with the southeast to the northwest direction from the spatial distribution.

As shown in Figure 3, this work also investigated the long-term trend of the EFI in the karst region of Southwest China from 2001 to 2020. Overall, the EFI of the karst ecosystem mainly exhibited an improving trend. During the past two decades, approximately 18.19% of the karst area showed an obvious improvement with $p < 0.01$ and 36.39% of the region improved slightly with $p < 0.05$. These areas were mainly concentrated in Chongqing and the northern Guizhou Province. However, the areas exhibited severe degradation and slight degradation were about 0.04% and 0.21%, respectively. In addition, 45.17% of the entire region seems relatively stable.

3.2. Evaluation of ecosystem stability

Through statistical analysis, it can be inferred that the ESI in the karst region of Southwest China experienced multiple stages of initially increasing, then decreasing, and then increasing again

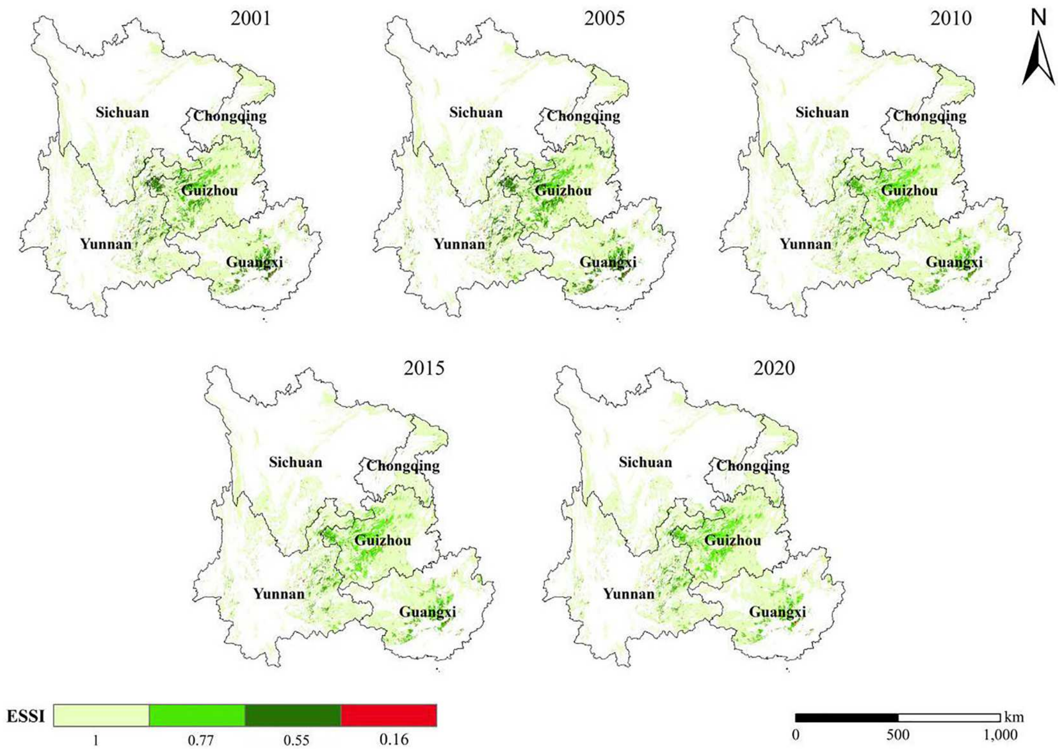

Figure 5. Spatial distribution of the ESSI in the karst region of Southwest China from 2001 to 2020.

during the past two decades (Figure 4). In the initial stage from 2001 to 2005, the ESI increased from 0.62 ± 0.26 to 0.66 ± 0.24. However, it decreased to 0.60 ± 0.27 in 2010. Fortunately, the ESI rose up again, which reached up to 0.65 ± 0.25 in 2010 and 0.72 ± 0.24 in 2020, respectively. Spatial dynamics of long-term ESI also revealed the troughs in ecosystem stability between 2001 and 2010. But the distributions with low ESI values were obviously different. In 2001, they were mainly located in Chongqing and the northern Guizhou and Sichuan provinces, whereas the severely low ESI were mainly concentrated in the Yunnan and Sichuan provinces in 2010.

3.3. Evaluation of ecosystem stress

The spatial and temporal patterns of the ESSI in the karst region of Southwest China from 2001 to 2020 were illustrated in Figure 5. It showed that the overall ESSI fluctuates around 0.95 during the past two decades. Additionally, the low ESSI values were mainly located in the western part of Guizhou province and the central part of Guangxi province.

Figure 6 further counts the main land use changes in the karst region of Southwest China during the past two decades, which indicated that the main land use types are forest, savanna, and cropland, accounting for about 99% of the total area. From 2001 to 2020, the most significant increase was in forest, which increased by 2.51×10^4 km^2, mainly from wood savanna, whereas the most significant reduction was in cropland, which reduced by nearly a half, mainly converted into cropland/natural vegetation mosaic.

3.4. Comprehensive evaluation of ecosystem quality

On the basis, this study comprehensively evaluated the EQI in the karst region of Southwest China during the past two decades (Figure 7). Overall, the EQI experienced a gradual improvement in the

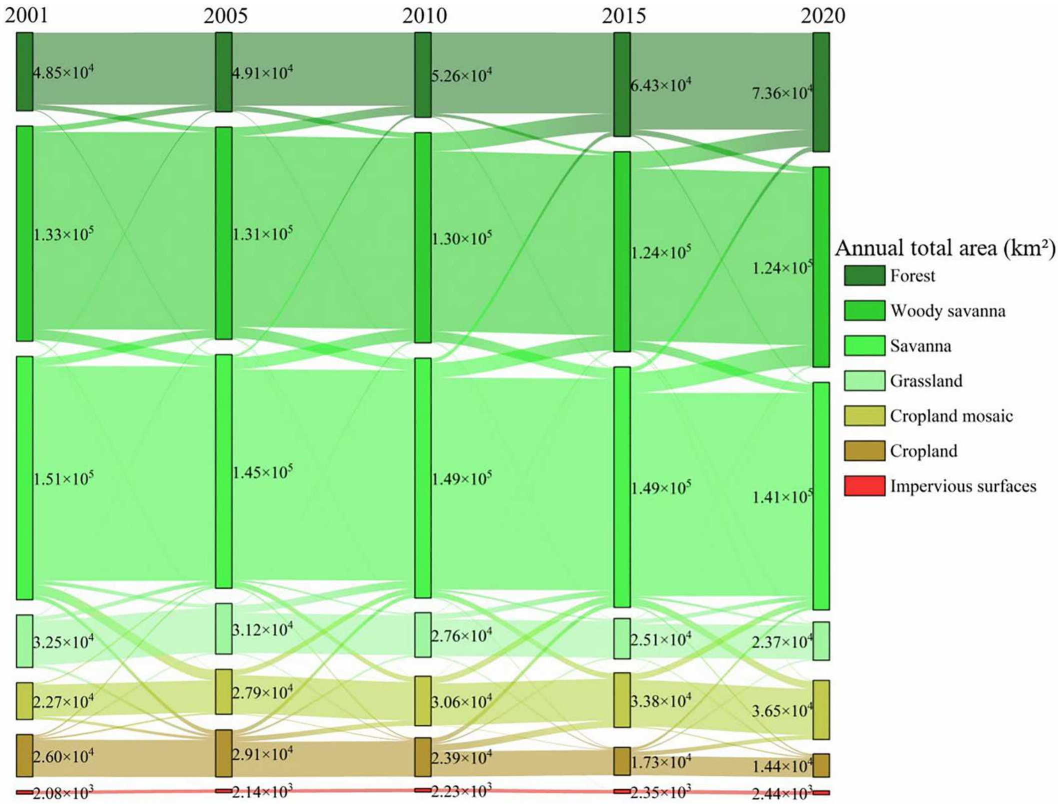

Figure 6. Transfer matrix of the main land use types in the karst region of Southwest China from 2001 and 2020. The bar charts represent the total area of different land use types annually.

initial period from 2001 to 2010, and then increased significantly in 2015 and 2020, with about 0.71 ± 0.15 and 0.75 ± 0.16, respectively. Figure 8 further counted the area proportions of the EQI grades in the karst ecosystem from 2001 to 2020, which indicated that the overall quality of the karst ecosystem has an obvious improvement. The excellent EQI occupied by no more than 20% of the entire region before 2005, but expanded sharply in the past decade, with about three times by 2020, reaching up to 58.26%.

Figure 9 shows the trend of ecosystem quality in the karst region of Southwest China from 2001 to 2020. Overall, the EQI exhibited strong spatial heterogeneity, but was mainly characterized by improvement. After the significance test of the trend, the areas exhibiting degradation were far less than those showing improvement. Approximately 16.73% of the karst areas showed an increasing trend, with 4.06% being obviously improved and 12.67% being slightly improved. These areas were mainly distributed in the northern parts of Chongqing and Guizhou provinces. In addition, about 0.65% of the karst areas indicated degradation trend, with 0.28% being severely degraded and 0.37% being slightly degraded, respectively.

4. Discussion

4.1. Effects of climate change

Recent work by Huang et al. (2022) illustrated that climate factors were the dominant environment drivers for the changes in vegetation greenness in globally karst regions. Amongst the complicated climate factors, precipitation and temperature are the most intuitive and prominent features, which

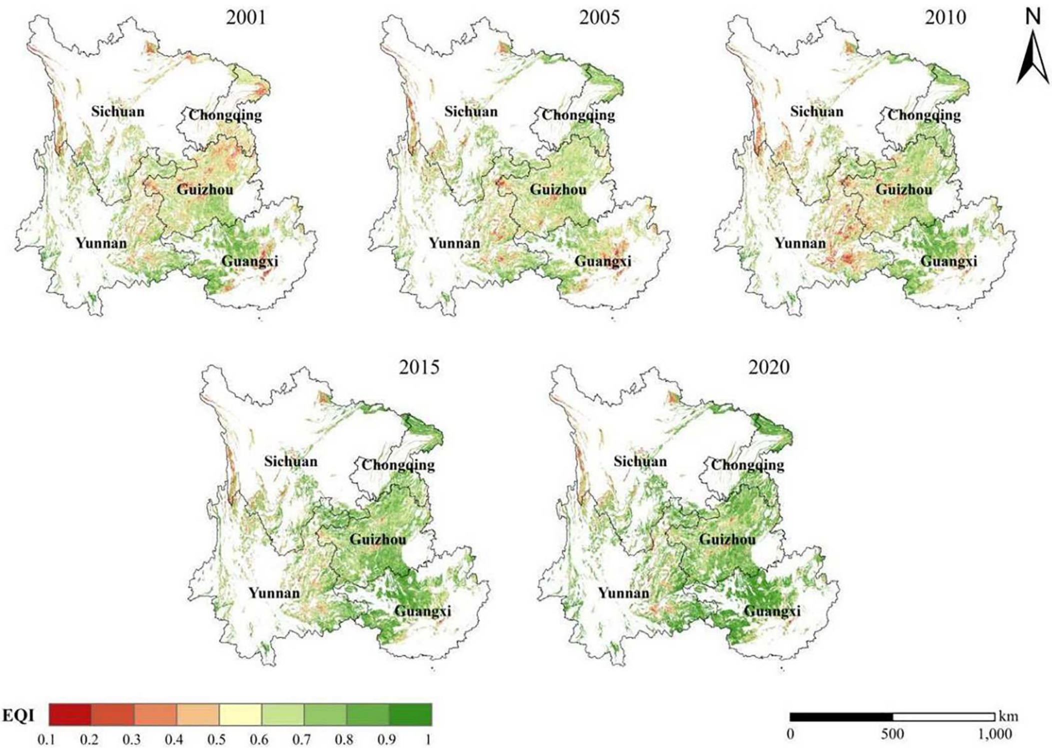

Figure 7. Spatial patterns of the EQI in the karst region of Southwest China from 2001 to 2020.

determine the spatial differentiation of terrestrial ecosystem status (Tang et al. 2022; Wang et al. 2021). Especially for the ecologically-fragile karst ecosystem, the climate dynamics strongly regional ecosystem quality.

As shown in Figure 10, we investigated the long-term trend of temperature and precipitation in the karst region of Southwest China from 2001 to 2020. Overall, the temperature mainly exhibited a rising trend across this region. Moreover, in terms of spatial patterns, precipitation showed increases in the eastern part but decreases in the western part. In order to further understand the effects of climate factors on the karst ecosystem quality in Southwest China, the partial correlation analysis was conducted as shown in Figure 11. The rising temperature positively impacted ecosystem quality in the eastern part of the region, while it negatively affected it in the western part. Meanwhile, increased rainfall in Chongqing and Guizhou provinces exerted a positive effect ecosystem quality, whereas decreased rainfall in the western part negatively impacted ecosystem quality, resulting in the improvement of ecosystem quality. Generally, the relatively higher temperature in the threshold range can lead to a longer growth period with enhanced vegetation GPP, and precipitation can provide sufficient water to help vegetation growth (Tu et al. 2024; Zhao et al. 2023), thus affects the productive capacity of vegetation and improve the ecosystem function. However, with the condition of high temperature and few rain, the severe drought in 2009 adversely affected the vegetation in Southwest China (Wang et al. 2021), resulting in ecosystem stability decreasing around 2010.

4.2. Implications from human-induced disturbance

Besides the climate conditions, the human-induced activities can also significantly affect the ecosystem quality positively or negatively. Large-scale ecological projects have been proved to be the main

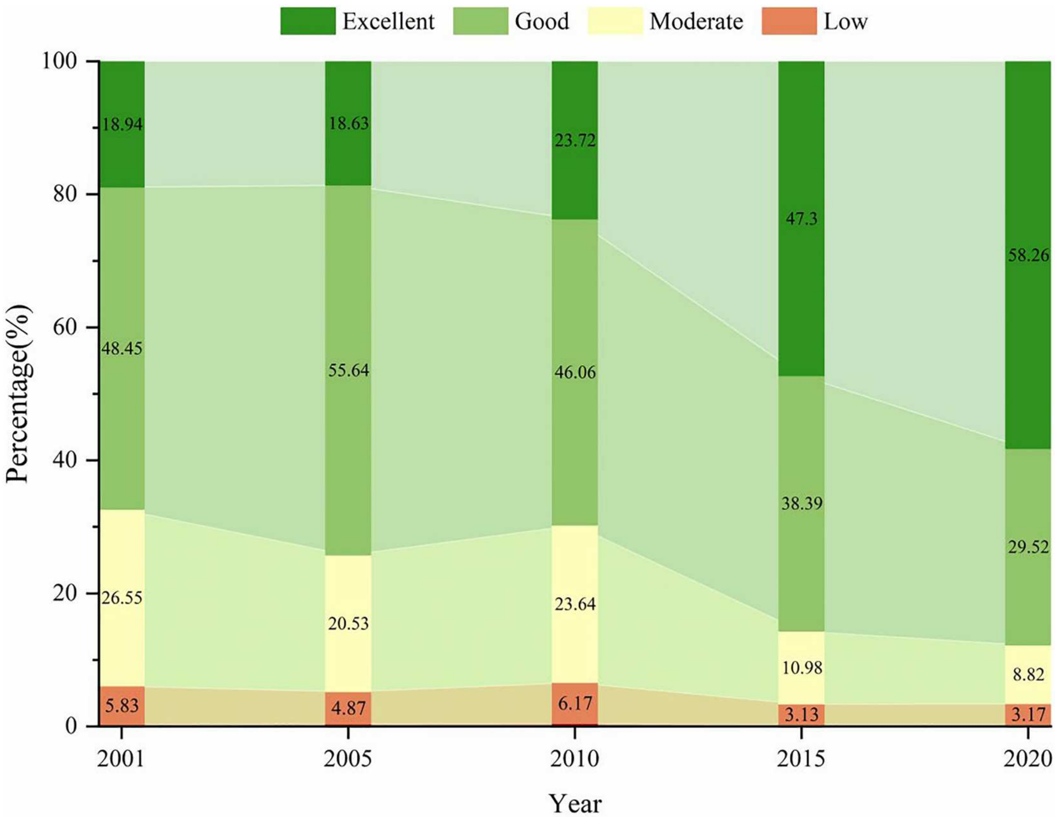

Figure 8. Statistics of the ecosystem quality grades in the karst region of Southwest China from 2001 to 2020. Percentage is the ratio of ecosystem quality areas at four grades to the total study area.

reason for the greening trend in China's karst region (Zhang et al. 2021). Additionally, during the process of rocky desertification control and restoration engineering, the annual afforestation area (forest plantation, closing hill for afforestation, and degraded forest restoration) increased by approximately 2.3×10^5 km^2 from 2006 to 2016, while the cumulative afforestation area reached nearly 3.4×10^6 km^2. Moreover, Ding et al. (2021) found that ecological projects positively affected water costs of terrestrial carbon sink and effectively improved the fragile karst ecosystem function. Nevertheless, human activities can also result to adverse consequences on the ecological environment, such as the swift transformations in land use and cover changes, including urban expansion and agricultural encroachment (Guan et al. 2019; Li et al. 2015; Zhao et al. 2021). Overall, as the external pressure on terrestrial ecosystems, human-induced activities have a crucial and tangible impact on ecosystem quality.

4.3. Limitations

This study proposed an objective method for ecosystem quality assessment and comprehensively analyzed the spatio-temporal characteristics of ecosystem quality in the karst region of Southwest China during the past two decades. However, there still existed some limitations. Firstly, our analysis only selected several key ecological indicators without considering multiple ecosystem functions such as water conservation and soil retention, which is also important to ecosystem quality (Green et al. 2019; Yuan et al. 2021). Secondly, the climate change drivers on ecosystem quality is

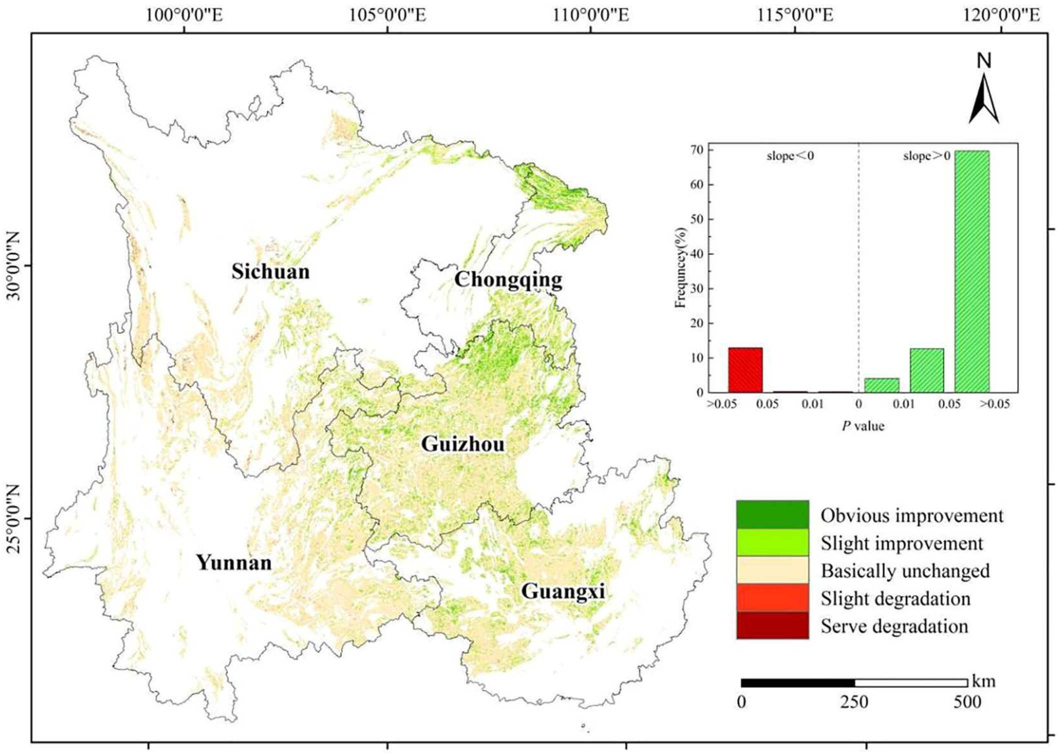

Figure 9. Trend analysis of the EQI in the karst region of Southwest China from 2001 to 2020. Frequency is the ratio of the EQI improved (green bars) and degraded (red bars) areas to the total study area, including significance levels of $p < 0.01$, $p < 0.05$, and $p > 0.05$.

insufficient. Temperature and precipitation are only two basic climate variables. Besides, the changes of solar radiation, atmospheric CO_2 concentration also exert substantial effects on the ecosystem functions as well as ecosystem quality (Cramer et al. 2001; Ito 2017). Recent work also revealed that the variations in rainfall intensity, frequency, and distribution (Lei et al. 2024; Xu et al. 2023), as well as alterations in temperature regimes (Chen et al. 2023), can not be neglected. Additionally, extreme weather events such as droughts and floods have become more frequent (Dai et al. 2023), posing challenges to ecosystem stability and the whole ecosystem quality. Therefore, a thorough investigation to the response mechanisms of ecosystem quality to climate change is crucial in future research.

5 Conclusions

In this study, we proposed an ecosystem quality assessment system by integrating ecosystem function, stability, and stress to comprehensively and objectively evaluate the spatio-temporal changes of ecosystem quality in the karst region of Southwest China during the past two decades. The results indicated that the spatio-temporal patterns of the EFI showed a continuously increasing trend across this area. Besides, approximately 18.19% of the karst area in the EFI showed an obvious improvement with $p < 0.01$ and 36.39% of the region improved slightly with $p < 0.05$, whereas the areas exhibited severe degradation and slight degradation only accounted for 0.04% and 0.21%, respectively. The ESI in the karst region of Southwest China experienced multiple stages of initially increasing, then decreasing, and then increasing again during the past two decades. The overall ESSI fluctuated around 0.95, because natural regeneration utilization accounted for

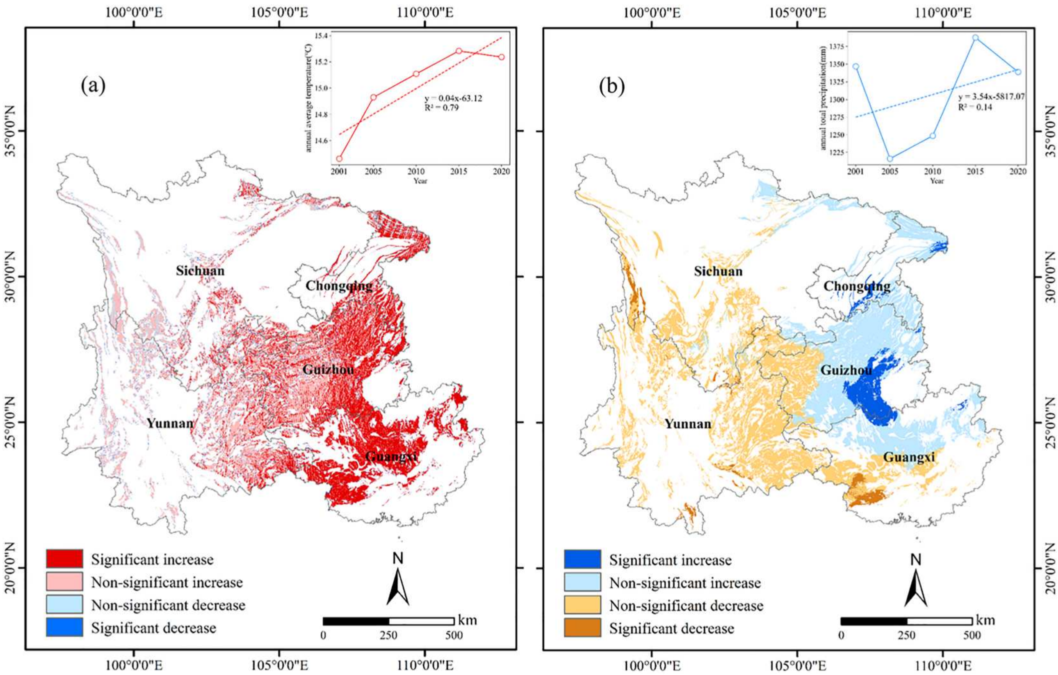

Figure 10. Trend analysis of meteorological factors including (a) temperature and (b) precipitation in the karst region of Southwest China from 2001 to 2020, with significance levels of $p < 0.05$ and $p > 0.05$.

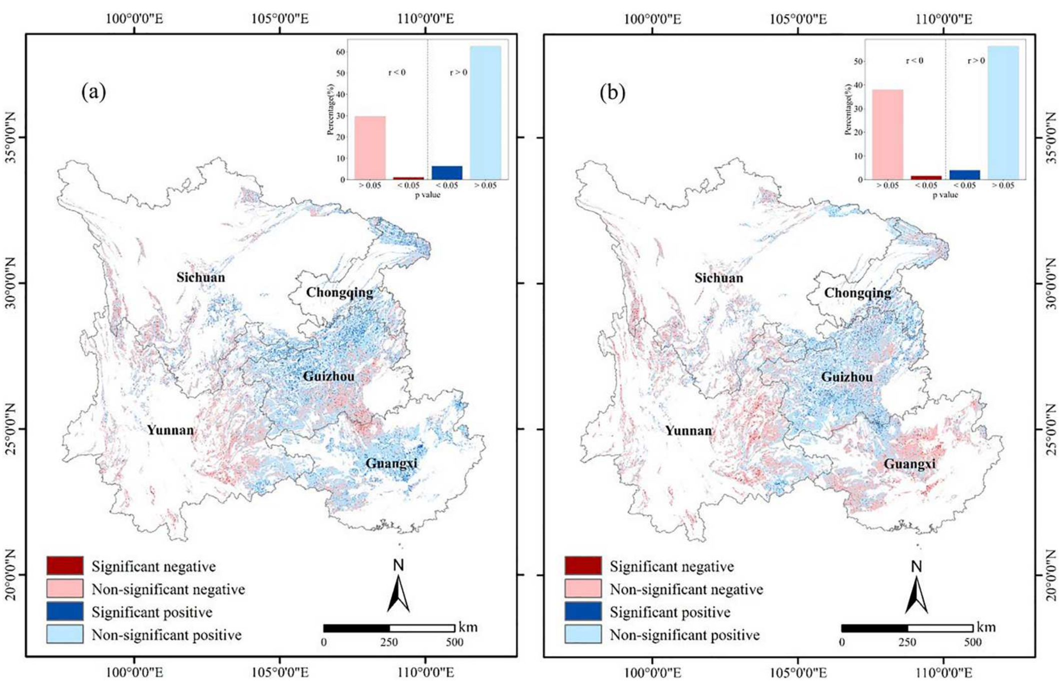

Figure 11. Spatial distribution of the partial correlation between ecosystem quality and meteorological factors including (a) temperature and (b) precipitation. Percentage is the ratio of areas positively (blue bars) and negatively (red bars) correlated with ecosystem quality to the total study area. The significance level is set as $p < 0.05$.

over 90%, mainly composed of savanna and forest. The EQI experienced a gradual improvement in the initial period from 2001 to 2010, and then increased significantly in 2015 and 2020. Areas of higher EQI were mainly concentrated in the eastern part, while areas of lower EQI were primarily located in the northwestern part of Sichuan province. The excellent EQI tripled and reached up to 58.26% during the past two decades. Moreover, the area proportions of obvious and slight improvement in ecosystem quality accounted for 4.06% and 12.67%, respectively, whereas obvious and slight degradation in ecosystem quality only appeared in a small area by 0.28% and 0.37%, respectively. All analyses are helpful in improving the karst ecosystem quality of Southwest China and beneficial for using our assessment system in other regions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by National Natural Science Foundation of China [grant number 41971391]; the Special Project on National Science and Technology Basic Resources Investigation of China [grant number 2021FY100701].

Data availability statement

All data can be accessed via the corresponding author upon request.

References

Chen, Yanli, Yue Zhang, Hui Zhang, and Jing Wang. 2023. “Extreme Temperatures Affect NDVI in Karst Ecological Fragile Area.” *Theoretical and Applied Climatology* 155:2017–2029. https://doi.org/10.1007/s00704-023-04737-1.

Christensen, N. L., A. M. Bartuska, J. H. Brown, S. Carpenter, C. Dantonio, R. Francis, J. F. Franklin, et al. 1996. “The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management.” *Ecological Applications* 6 (3): 665–691. https://doi.org/10.2307/2269460.

Costanza, R., R. dArge, R. deGroot, S. Farber, M. Grasso, B. Hannon, K. Limburg, et al. 1997. “The Value of the World’s Ecosystem Services and Natural Capital.” *Nature* 387 (6630): 253–260. https://doi.org/10.1038/387253a0.

Cramer, W., A. Bondeau, F. I. Woodward, I. C. Prentice, R. A. Betts, V. Brovkin, P. M. Cox, et al. 2001. “Global Response of Terrestrial Ecosystem Structure and Function to CO_2 and Climate Change: Results from Six Dynamic Global Vegetation Models.” *Global Change Biology* 7 (4): 357–373. https://doi.org/10.1046/j.1365-2486.2001.00383.x.

Dai, Li, Yuhan Zhao, Changying Yin, Chunyan Mao, Ping Zhang, Fang Zhou, and Xianyun Yu. 2023. “Spatial and Temporal Dynamics of Drought and Waterlogging in Karst Mountains in Southwest China.” *Sustainability* 15:5545. https://doi.org/10.3390/su15065545.

Ding, Zhi, Ying Liu, Lunche Wang, Yanan Chen, Pujia Yu, Mingguo Ma, and Xuguang Tang. 2021. “Effects and Implications of Ecological Restoration Projects on Ecosystem Water Use Efficiency in the Karst Region of Southwest China.” *Ecological Engineering* 170:106356. https://doi.org/10.1016/j.ecoleng.2021.106356.

Ding, Zhi, Hui Zheng, Ying Liu, Sidong Zeng, Pujia Yu, Wei Shi, and Xuguang Tang. 2021. “Spatiotemporal Patterns of Ecosystem Restoration Activities and Their Effects on Changes in Terrestrial Gross Primary Production in Southwest China.” *Remote Sensing* 13 (6): 1209. https://doi.org/10.3390/rs13061209.

Green, Sophie M., Jennifer A. J. Dungait, Chenglong Tu, Heather L. Buss, Nicole Sanderson, Simon J. Hawkes, Kaixiong Xing, et al. 2019. “Soil Functions and Ecosystem Services Research in the Chinese Karst Critical Zone.” *Chemical Geology* 527:119107. https://doi.org/10.1016/j.chemgeo.2019.03.018.

Guan, Xiaobin, Huanfeng Shen, Xinghua Li, Wenxia Gan, and Liangpei Zhang. 2019. “A Long-Term and Comprehensive Assessment of the Urbanization-Induced Impacts on Vegetation Net Primary Productivity.” *Science of the Total Environment* 669:342–352. https://doi.org/10.1016/j.scitotenv.2019.02.361.

Guo, Bing, Wenqian Zang, and Wei Luo. 2020. “Spatial-temporal Shifts of Ecological Vulnerability of Karst Mountain Ecosystem-Impacts of Global Change and Anthropogenic Interference.” *Science of the Total Environment* 741:140256. https://doi.org/10.1016/j.scitotenv.2020.140256.

He, Nianpeng, Li Xu, and Honglin He. 2020. “The Methods of Evaluation Ecosystem Quality: Ideal Reference and Key Parameters.” *Acta Ecologica Sinica* 40 (6): 1877–1886. https://doi.org/10.5846/stxb201903150488.

Huang, Jing, Zhongxi Ge, Yuqing Huang, Xuguang Tang, Zhan Shi, Peiyu Lai, Zengjing Song, Binfei Hao, Hong Yang, and Mingguo Ma. 2022. "Climate Change and Ecological Engineering Jointly Induced Vegetation Greening in Global Karst Regions from 2001 to 2020." *Plant and Soil* 475 (1-2): 193–212. https://doi.org/10.1007/s11104-021-05054-0.

Ito, Akihiko. 2017. "Solar Radiation Management and Ecosystem Functional Responses." *Climatic Change* 142 (1-2): 53–66. https://doi.org/10.1007/s10584-017-1930-3.

Jia, Kun, Shunlin Liang, Suhong Liu, Yuwei Li, Zhiqiang Xiao, Yunjun Yao, Bo Jiang, et al. 2015. "Global Land Surface Fractional Vegetation Cover Estimation Using General Regression Neural Networks from MODIS Surface Reflectance." *IEEE Transactions on Geoscience and Remote Sensing* 53 (9): 4787–4796. https://doi.org/10.1109/TGRS.2015.2409563.

Lei, Han, Yanan Chen, Ying Wang, Yuan Sun, Zhi Ding, Hongsheng Zhang, and Xuguang Tang. 2024. "Divergent Responses of Subtropical Evergreen and Deciduous Forest Carbon Cycles to the Summer 2022 Drought." *Environmental Research Letters* 19 (5): 054043. https://doi.org/10.1088/1748-9326/ad416e.

Li, Shuangshuang, Saini Yang, Xianfeng Liu, Yanxu Liu, and Mimi Shi. 2015. "NDVI-based Analysis on the Influence of Climate Change and Human Activities on Vegetation Restoration in the Shaanxi-Gansu-Ningxia Region, Central China." *Remote Sensing* 7 (9): 11163–11182. https://doi.org/10.3390/rs70911163.

Ma, Han, and Shunlin Liang. 2022. "Development of the GLASS 250-m Leaf Area Index Product (Version 6) from MODIS Data Using the Bidirectional LSTM Deep Learning Model." *Remote Sensing of Environment* 273:112985. https://doi.org/10.1016/j.rse.2022.112985.

Ouyang, Zhiyun, Qiao Wang, Hua Zheng, Feng Zhang, and Peng Hou. 2014. "National Ecosystem Survey and Assessment of China (2000-2010)." *Bulletin of the Chinese Academy of Sciences* 29 (4): 462–466. https://doi.org/10.3969/j.issn.1000-3045.2014.04.009.

Pan, Jing-hu, and Lei-lei Dong. 2016. "Comprehensive Evaluation of Ecosystem Quality in the Shule River Basin, Northwest China from 2001 to 2010." *Yingyong Shengtai Xuebao* 27 (9): 2907–2915. https://doi.org/10.13287/j.1001-9332.201609.015.

Peng, Shouzhang, Chengcheng Gang, Yang Cao, and Yunming Chen. 2018. "Assessment of Climate Change Trends Over the Loess Plateau in China from 1901 to 2100." *International Journal of Climatology* 38 (5): 2250–2264. https://doi.org/10.1002/joc.5331.

Qiao, Yina, Yongjun Jiang, and Caiyun Zhang. 2021. "Contribution of Karst Ecological Restoration Engineering to Vegetation Greening in Southwest China During Recent Decade." *Ecological Indicators* 121:107081. https://doi.org/10.1016/j.ecolind.2020.107081.

Qu, Lisha, Qiuan Zhu, Chaofan Zhu, and Jiang Zhang. 2022. "Monthly Precipitation Data Set with 1 km Resolution in China from 1960 to 2020." *Science Data Bank*. https://doi.org/10.11922/sciencedb.01607.

Steffen, Will, Paul J. Crutzen, and John R. McNeill. 2007. "The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature." *AMBIO: A Journal of the Human Environment* 36 (8): 614–621. https://doi.org/10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2.

Sun, Meiying, Rongjin Yang, Xiuhong Li, Le Zhang, and Qiang Liu. 2021. "Designing a Path for the Sustainable Development of key Ecological Function Zones: A Case Study of Southwest China." *Global Ecology and Conservation* 31:e01840. https://doi.org/10.1016/j.gecco.2021.e01840.

Tang, Xuguang, Hengpeng Li, Xibao Xu, Guishan Yang, Guihua Liu, Xinyan Li, and Dongqiang Chen. 2016. "Changing Land Use and Its Impact on the Habitat Suitability for Wintering Anseriformes in China's Poyang Lake Region." *Science of the Total Environment* 557-558:296–306. https://doi.org/10.1016/j.scitotenv.2016.03.108.

Tang, Xuguang, Jingfeng Xiao, Mingguo Ma, Hong Yang, Xing Li, Zhi Ding, Pujia Yu, et al. 2022. "Satellite Evidence for China's Leading Role in Restoring Vegetation Productivity Over Global Karst Ecosystems." *Forest Ecology and Management* 507:120000. https://doi.org/10.1016/j.foreco.2021.120000.

Tian, Meirong, Xiuli Chen, Jixi Gao, and Yuxin Tian. 2022. "Identifying Ecological Corridors for the Chinese Ecological Conservation Redline." *PLoS One* 17 (7): e0271076. https://doi.org/10.1371/journal.pone.0271076.

Tong, Xiaowei, Kelin Wang, Yuemin Yue, Martin Brandt, Bo Liu, Chunhua Zhang, Chujie Liao, and Rasmus Fensholt. 2017. "Quantifying the Effectiveness of Ecological Restoration Projects on Long-Term Vegetation Dynamics in the Karst Regions of Southwest China." *International Journal of Applied Earth Observation and Geoinformation* 54:105–113. https://doi.org/10.1016/j.jag.2016.09.013.

Tu, Zhiqin, Yuan Sun, Chaoyang Wu, Zhi Ding, and Xuguang Tang. 2024. "Long-term Dynamics of Peak Photosynthesis Timing and Environmental Controls in the Tibetan Plateau Monitored by Satellite Solar-Induced Chlorophyll Fluorescence." *International Journal of Digital Earth* 17 (1): 2300311. https://doi.org/10.1080/17538947.2023.2300311.

Wang, Min, Zhi Ding, Chaoyang Wu, Lisheng Song, Mingguo Ma, Pujia Yu, Bingqing Lu, and Xuguang Tang. 2021. "Divergent Responses of Ecosystem Water-Use Efficiency to Extreme Seasonal Droughts in Southwest China." *Science of the Total Environment* 760:143427. https://doi.org/10.1016/j.scitotenv.2020.143427.

Wang, Yanan, Yuan Sun, Yanan Chen, Chaoyang Wu, Changping Huang, Cheng Li, and Xuguang Tang. 2023. "Non-linear Correlations Exist Between Solar-Induced Chlorophyll Fluorescence and Canopy Photosynthesis in a

Subtropical Evergreen Forest in Southwest China." *Ecological Indicators* 157:111311. https://doi.org/10.1016/j.ecolind.2023.111311.
Wei, Xiangqin, Tianhai Cheng, Jian Yang, Shijiao Qiao, Li Li, Haidong Yu, Xiaofei Mi, et al. 2023. "Spatio-Temporal Changes in Ecosystem Quality Across the Belt and Road Region." *Sensors* 23 (18): 7752. https://doi.org/10.3390/s23187752.
Xia, Jiayu, Duyuzheng Ren, Xuhui Wang, Bo Xu, Xingyao Zhong, and Yajiang Fan. 2023. "Ecosystem Quality Assessment and Ecological Restoration in Fragile Zone of Loess Plateau: A Case Study of Suide County, China." *Land* 12:1131. https://doi.org/10.3390/land12061131.
Xiao, Yang, Zhiyun Ouyang, Liyan Wang, Enming Rao, Ling Jiang, and Lu Zhang. 2016. "Spatial Patterns of Ecosystem Quality in Inner Mongolia and its Driving Forces Analysis." *Acta Ecologica Sinica* 36 (19): 6019–6030. https://doi.org/10.5846/stxb201501290245.
Xiong, Kangning, and Yongkuan Chi. 2015. "The Problems in Southern China Karst Ecosystem in Southern of China and Its Countermeasures." *Ecological Economy* 31 (1): 23–30. https://doi.org/10.3969/j.issn.1671-4407.2015.01.006.
Xu, Hanqiu. 2013. "A Remote Sensing Urban Ecological Index and its Application." *Acta Ecologica Sinica* 33 (24): 7853–7862. https://doi.org/10.5846/stxb201208301223.
Xu, Xibao, Yan Tan, Guishan Yang, and Barnett Jon. 2018. "China's Ambitious Ecological red Lines." *Land Use Policy* 79:447–451. https://doi.org/10.1016/j.landusepol.2018.08.037.
Xu, Xiaojin, Youjin Yan, Quanhou Dai, Xingsong Yi, Zeyin Hu, and Longpei Cen. 2023. "Spatial and Temporal Dynamics of Rainfall Erosivity in the Karst Region of Southwest China: Interannual and Seasonal Changes." *Catena* 221:106763. https://doi.org/10.1016/j.catena.2022.106763.
Yu, Gui-rui, Yong-sheng Wang, and Meng Yang. 2022. "Discussion on the Ecological Theory and Assessment Methods of Ecosystem Quality and its Evolution." *Yingyong Shengtai Xuebao* 33 (4): 865–877. https://doi.org/10.13287/j.1001-9332.202204.026.
Yu, Gui-rui, Yong-sheng Wang, and Meng Yang. 2023. "Discussion on the Ecological Theory and Technological Approaches of Ecosystem Quality Improvement and Stability Enhancement." *Ying Yong Sheng tai xue bao = The Journal of Applied Ecology* 34 (1): 1–10. https://doi.org/10.13287/j.1001-9332.202301.025.
Yuan, Wenping, Shuguang Liu, Guirui Yu, Jean-Marc Bonnefond, Jiquan Chen, Ken Davis, Ankur R. Desai, et al. 2010. "Global Estimates of Evapotranspiration and Gross Primary Production Based on MODIS and Global Meteorology Data." *Remote Sensing of Environment* 114 (7): 1416–1431. https://doi.org/10.1016/j.rse.2010.01.022.
Yuan, Long, Kunqian Yue, Zaike Gu, Hu Chen, and Yongkuan Chi. 2021. "Analysis of Rainfall Factors and Soil Erosion in Different Soil and Water Conservation Measures in the Karst Plateau-Mountain." *Polish Journal of Environmental Studies* 30 (6): 5343–5349. https://doi.org/10.15244/pjoes/135824.
Zhang, Xuemei, Yuemin Yue, Xiaowei Tong, Kelin Wang, Xiangkun Qi, Chuxiong Deng, and Martin Brandt. 2021. "Eco-Engineering Controls Vegetation Trends in Southwest China Karst." *Science of the Total Environment* 770:145160. https://doi.org/10.1016/j.scitotenv.2021.145160.
Zhang, Mengyu, Li Zhang, Honglin He, Xiaoli Ren, Yan Lv, Zhong'en Niu, Qingqing Chang, Qian Xu, and Weihua Liu. 2022. "Improvement of Ecosystem Quality in National Key Ecological Function Zones in China During 2000-2015." *Journal of Environmental Management* 324:116406–116406. https://doi.org/10.1016/j.jenvman.2022.116406.
Zhao, Yan, Yanan Chen, Chaoyang Wu, Guo Li, Mingguo Ma, Lei Fan, Hui Zheng, Lisheng Song, and Xuguang Tang. 2023. "Exploring the Contribution of Environmental Factors to Evapotranspiration Dynamics in the Three-River-Source Region, China." *Journal of Hydrology* 626:130222. https://doi.org/10.1016/j.jhydrol.2023.130222.
Zhao, Yangling, Rui Han, Nan Cui, Jingbiao Yang, and Luo Guo. 2021. "The Impact of Urbanization on Ecosystem Health in Typical Karst Areas: A Case Study of Liupanshui City, China." *International Journal of Environmental Research and Public Health* 18 (1): 93. https://doi.org/10.3390/ijerph18010093.
Zou, Chang-xin, Yan Wang, Wen-lin Wang, De-lin Xu, Nai-feng Lin, and Wen-jing Li. 2018. "Theory of Mountain-River-Forest-Farmland-Lake-Grass System and Ecological Protection and Restoration Research." *Journal of Ecology and Rural Environment* 34 (11): 961–967. https://doi.org/10.11934/j.issn.1673-4831.2018.11.001.