The Spatiotemporal Evolution And Driving Factors Of Chinese Cliff Stone Carvings: A Case Study Of 146 National Heritage Sites In Mainland China

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Cliff stone carvings are a valuable form of material cultural heritage that integrates stone carving art with writing, calligraphy, historical records, and religious beliefs, serving as tangible evidence of the continuity of Chinese civilisation. This study investigates 146 nationally designated cliff stone carving heritage sites in mainland China. Using geospatial analytical methods-including Kernel Density Estimation (KDE), Geographical Concentration Index (GCI), and Standard Deviation Ellipse (SDE)-combined with ArcGIS spatial analysis, the spatiotemporal distribution patterns and driving factors are systematically examined. The results show that cliff stone carving activities span from the pre-Qin period to the Republic of China, peaking during the Song and Yuan dynasties. Spatially, sites display significant clustering, with core concentrations in Sichuan and Zhejiang and secondary clusters in Hunan, Shandong, and Fujian. Their distribution evolved from early dispersion to later concentration and convergence. Topography, waterways, socio-political development, and religious diffusion jointly influenced this pattern, offering insights for heritage conservation and sustainable regional development.

Keywords: Cliff stone carvings; Spatiotemporal evolution; Geographic analysis methods; Driving factors

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1. Introduction

Cliff carvings are a significant type of traditional Chinese stone carving art [1]. Cliff carvings reflect historical events and culture of literature [2] and can be of high historical, cultural and artistic value [3]. Spatiotemporal patterns have been driven by natural and socio-cultural factors [4]. Gao and Li analyze cultural landscapes spatiotemporal evolution [5], Liu studies Tang craftsmen and process production of carving [6], Ma et al. locate clustered spatial evolution [7]. Spatial and digital technologies enhance analysis [8, 9], risk surveillance platforms assist in protecting heritage, spatiotemporal patterns and underlying environmental human driving forces [10]. GIS and remote sensing provide tools to analyze and cluster cultural heritage spatiotemporally, leading to enhanced insights into human-environment relations, but research is still scattered and incomplete on scales of dynastic extent [11, 12].

Absence of national level studies inhibits knowledge building; GIS studies spatial distribution, development, and natural and socio- cultural driving forces of cliff stone carvings. The study establishes a dataset involving 146 sites and utilizes GIS techniques (KDE, GCI, SDE) to examine spatial patterns and evolution, with the assistance of maps, clustering graphs, directional ellipses, Fig. 1 for conceptual clarity.

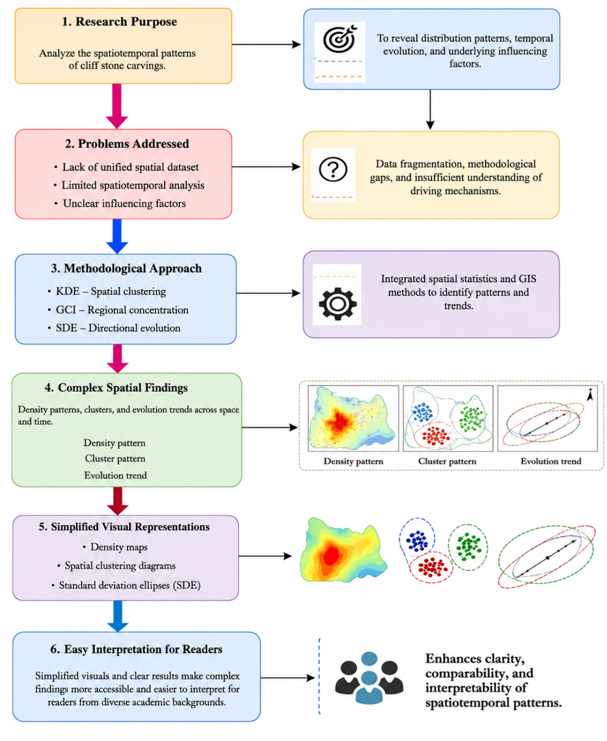


Fig. 1. Conceptual Framework of Purpose Problems Methods Visualization

2. Data sources and methodology

2.1. Study region

The research encompasses the area of mainland China ($73°33' - 135°05'E, 3°51' - 53°33'$ N) which has west-high, east-low topography, and the official boundary and the NKCRPU cliff carvings are classified as cave temples and stone carvings. The overview of the study area and the spatial distribution of cliff carvings are shown in Fig. 2.

2.2. Data sources

The research makes use of official NKCRPU lists published by the State Council of China for the years 1961 to 2019, and systematically analyzes data as "cave temples and stone carvings" for 2021. It chooses cliff carvings, sculptures and rock paintings as the objects of this study with the data sourced from the National Cultural Heritage Administration platform (http://gl.ncha.gov.cn/#/Home). The research employs 146 NKCRPU cliff stone carvings (1961-2019) from 25 provinces to ensure a national-scale representation with a comprehensive of diverse and dependable spatiotemporal and regional distribution perspectives. The screening yielded 146 provincial-level national key cultural heritage sites for cliff carvings across 14 administrative regions, as shown in Table 1. The data consist of 146 cliff

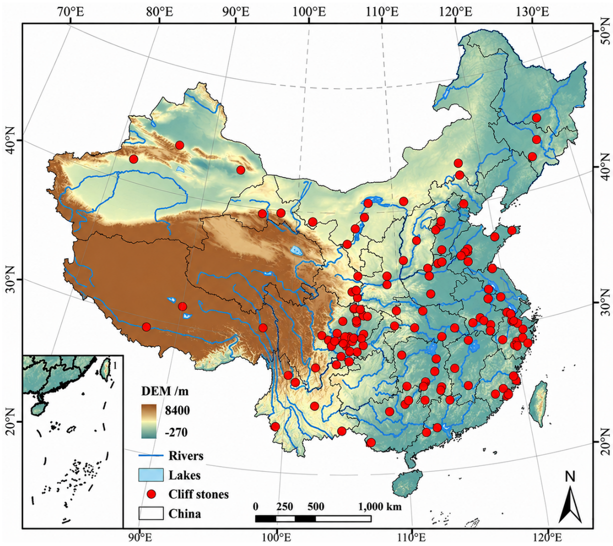


Fig. 2. The study area and spatial distribution of the cliff stone carvings

stone carving sites listed in the NKCRPU that were chosen on the basis of the strict inclusion criteria so that only those records that were officially recognized, geocoded, unique and with a complete set of attributes were included.

In this study, multi-source spatial data such as DEM acquired through Google Earth Engine and hydrological data from National Earth System Science Data Center (https://www.geodata.cn/) are utilized. DEM and hydrological data are converted to WGS 84 and resampled to allow for spatial integration and analysis in GIS.

2.3. Methodology

This study investigates spatiotemporal evolution characteristics and influencing factors of cliff stone carvings in China using GIS method. GIS tools analyze spatiotemporal clustering and patterns of cliff stone carvings. Coordinates were extracted and processed in ArcGIS with KDE, GCI, SDE, for spatiotemporal patterns. "Cliff stone carvings", "rock carvings" and "stone inscriptions" are distinguished as separate heritage categories, while KDE, GCI and SDE together describe multi-scale spatial patterns with the analysis of hotspots, regional concentration, and directional trend. Finally, quantitatively and qualitatively examine the influence and interactions of natural environmental, socio-political, and historical factors on the spatial distribution of cliff stone carvings. Fig. 3 illustrates the GIS workflow based on KDE, GCI, and SDE with the structured spatial analysis.

Table 1. The Count of Cliff Stone Carvings in the Provincial Administrative Regions of China

Province	Counts	Province	Counts	Province	Counts	Province	Counts	Province	Counts
Sichuan	27	Zhejiang	15	Hunan	11	Shandong	9	Fujian	9
Hubei	6	Anhui	6	Yunnan	6	Jiangsu	5	Gansu	5
Hebei	5	Henan	5	Chongqing	5	Inner Mongolia	5	Guangxi	4
Shaanxi	3	Guangdong	3	Jiangxi	3	Xizang	3	Xinjiang	3
Shanxi	2	Jilin	2	Ningxia	2	Heilongjiang	1	Tianjin	1

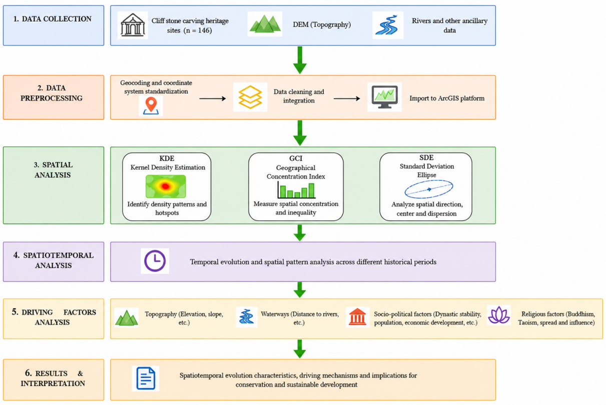


Fig. 3. GIS workflow for cliff stone carvings analysis

2.3.1. *Data Preprocessing for Missing and Coordinate Consistency*

Data are cleaned, validated, and standardized to the WGS 84 for spatial uniformity.

$$X' = f(X, Y), Y' = g(X, Y) \tag{1}$$

2.3.2. *Kernel Density Estimation, KDE*

In this study, kernel density estimation is employed to conduct spatial clustering analysis to visualize distribution, density, and patterns of cliff stone carving .

$$f(x) = \frac{1}{n\,\mathrm{h}} \sum_{i=1}^{n} k\left(\frac{x - x_i}{\mathrm{h}}\right) \tag{2}$$

KDE measures the intensity of clustering and detects hotspots; the bandwidth selected by sensitivity analysis allows for a robust detection balanced by scale.

2.3.3. *Geographical concentration index*

Humanities geoinformatics Anisotropy measures spatial clustering and is used to examine the long-term distribution and province-level clustering of cliff carvings.

$$GCI = 100 \times \sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\frac{x_i}{T}\right)^2} \tag{3}$$

2.3.4. *Standard Deviation Ellipse*

Standard deviation ellipse detects spatial concentration, directional trend, and center shift of cliff stone carving, allowing to quantify the pattern of distribution and the spatial coverage while it can be used for supporting the assessment of spatiotemporal evolution and the underlying driving force. The formula for the standard deviation ellipse is as follows:

$$\mathrm{SDE_x} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} (x_i - \bar{X})^2}{\mathrm{n}}} \tag{4}$$

$$\mathrm{SDE_y} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} (y_i - \bar{Y})^2}{\mathrm{n}}} \tag{5}$$

The x-axis and y-axis of the standard deviation ellipse are represented as follows:

$$\tan\theta = \frac{\left(\sum_{i=1}^{n} \tilde{x}_i^2 - \sum_{i=1}^{n} \tilde{y}_i^2\right) + \sqrt{\left(\sum_{i=1}^{n} \tilde{x}_i^2 - \sum_{i=1}^{n} \tilde{y}_i^2\right)^2 + 4\left(\sum_{i=1}^{n} \tilde{x}_i \tilde{y}_i\right)^2}}{2\sum_{i=1}^{n} \tilde{x}_i \tilde{y}_i} \tag{6}$$

2.3.5. *Geostatistical analysis*

ArcGIS processes cliff stone carvings by utilizing buffer, statistical, and intersect methods. ArcGIS allows for an efficient spatial analysis through KDE, SDE, and buffer tools to handle voluminous geospatial data. Overlay, buffer, and cross-tabulation reveal spatial relations but lack quantitative analysis of cliff stone carving patterns. GIS considers scale ensuring KDE, SDE, GCI stable and comparable.

2.3.6. *Geodetector-Based Quantitative Analysis of Environmental and Socio-Cultural Influencing Factors*

Geodetector measures factor influence on spatial heterogeneity using q-statistic for cliff stone carving distribution analysis. The model is expressed as:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \tag{7}$$

Environmental and socio-cultural characteristics are studied to determine the extent to which they influence spatial variability of cliff stone carvings.

3. Result

3.1. Temporal distribution characteristics

This study analyzes temporal characteristics of cliff stone carvings. Time analysis documents cliff-hanger engravings in six dynastic units for systematic spatiotemporal parallelism. Cliff stone carvings are analyzed across six Chinese historical periods, reflecting temporal variation in quantity and distribution from Pre-Qin to the modern era. Six dynastic periods allow for a systematic spatiotemporal study of cliffstone carvings throughout China. Fig. 4 shows cliff stone carvings rising from 13 Pre-Qin to 34 modern sites.

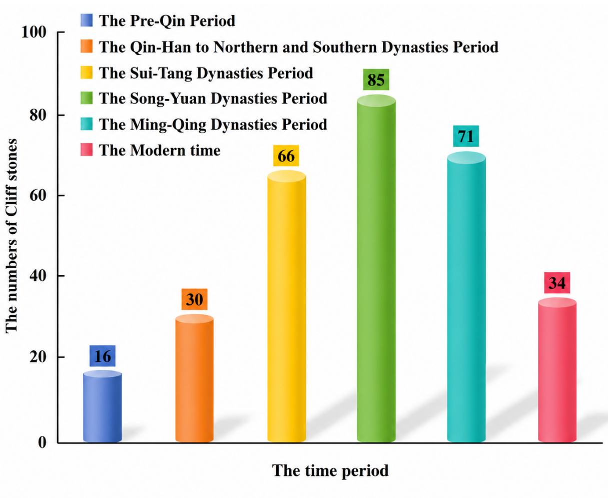


Fig. 4. Number of cliff stone carvings in Pre-Qin and Modern periods

3.2. Spatial distribution characteristics

3.2.1. Spatial distribution density

NNI indicate that there is a significant clustering of cliff stone carvings ($p < 0.01$, $NNI = 0.68$, $Z = -7.37$), Fig. 5 shows Sichuan, Zhejiang cores; Hunan, Shandong, Fujian clusters.

ArcGIS confirms KDE, GCI and SDE outputs are validated by NNI, Z-score and p-value. KDE present clusters stability in Sichuan and Zhejiang provinces; NNI suggests the pattern is clustered (0.68) with a significant Z -score (-7.37) at $p < 0.01$; GCI indicates ($G = 27.14 > G_0 = 20$).

3.2.2. Geographical concentration

G analysis ($G = 27.14, G_0 = 20$) of 146 cliff stone carvings across 25 provinces shows strong clustering. The density

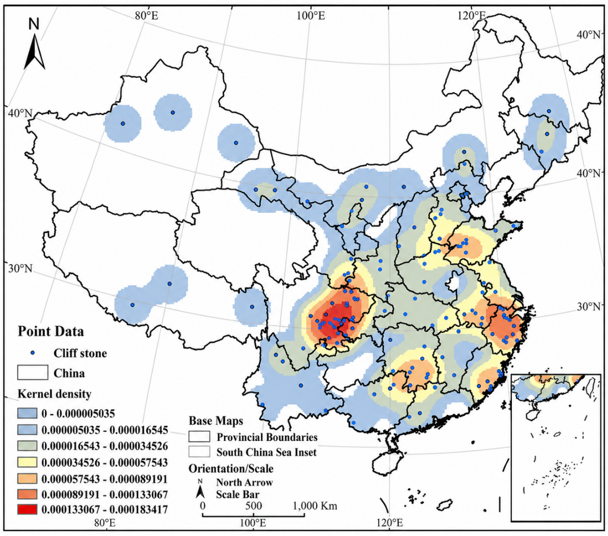


Fig. 5. Kernel density of cliff stone carvings during the study period

of cliff carvings reveals hierarchical core-periphery spatial patterns.

3.2.3. Spatial Autocorrelation Analysis (Moran's I)

Moran's I test shows a significant positive spatial autocorrelation and clustering of cliff stone carvings among provinces. The results of the Global Moran's I are shown in Table 2.

3.3. Spatiotemporal analysis of SDE

Fig. 6 (a-g) presents spatiotemporal development of cliff stone carving on SDE with a centroid in Hubei & exhibiting varying directional, clustered, and regional pattern distributions.

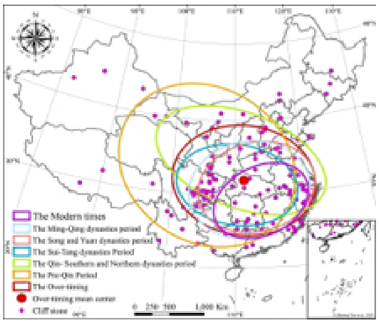
Fig. 7 shows centroid migration from Gansu to Hubei, then southeast to Hunan.

3.4. Geodetector Analysis Results of Influencing Factors

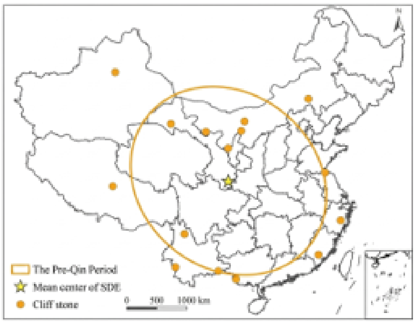
Geodetector results indicate that environmental and socio-cultural factors vary in their ability. Elevation ($q = 0.63$, rank 1, strong influence), river proximity ($q = 0.58$, rank 2, strong influence), terrain slope ($q = 0.49$, rank 3, moderate influence), historical transportation routes ($q = 0.45$, rank 4, moderate influence), political stability ($q = 0.42$, rank 5, moderate influence), religious diffusion ($q = 0.38$, rank 6, moderate influence), and population density ($q = 0.35$, rank 7 , relatively weaker influence).

4. Discussion of influencing factors

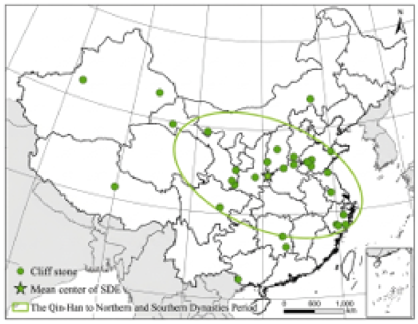
The spatio-temporal distribution characteristics of cliff stone carvings are shaped by the combined influence of



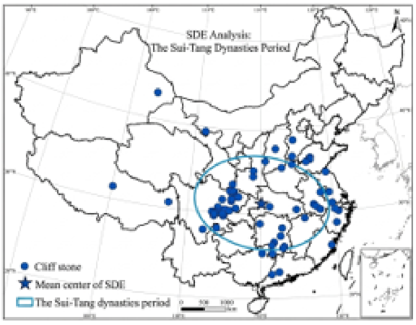
(a) General distribution map for different periods.



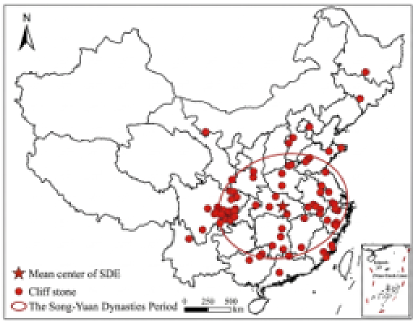
(b) The Pre-Qin Period, including the Stone Age.



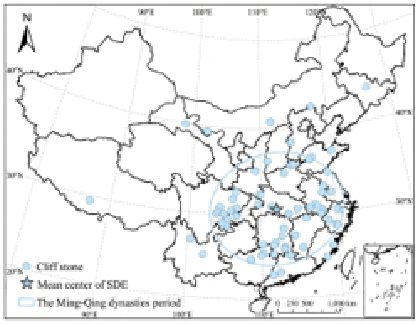
(c) The Qin–Han to Northern and Southern Dynasties Period.



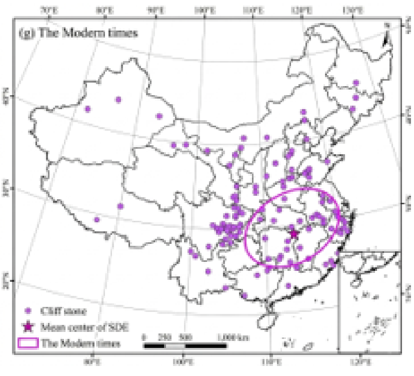
(d) The Sui–Tang Dynasties Period.



(e) The Song–Yuan Dynasties Period.



(f) The Ming–Qing Dynasties Period.



(g) The Modern Period.

Fig. 6. SDE distribution across different historical periods.

Table 2. Global Moran's I spatial autocorrelation analysis of cliff stone carvings

Metric	Value
Provinces	25
Moran's I	0.612
Expected I	-0.041
Variance	0.018
Z-score	5.87
p-value	< 0.001
95% CI	0.428-0.796
Pattern	Significant positive clustering

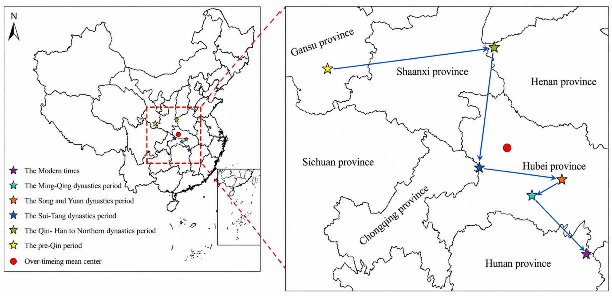


Fig. 7. Centroid trajectory of cliff stone carvings spatiotemporal distribution

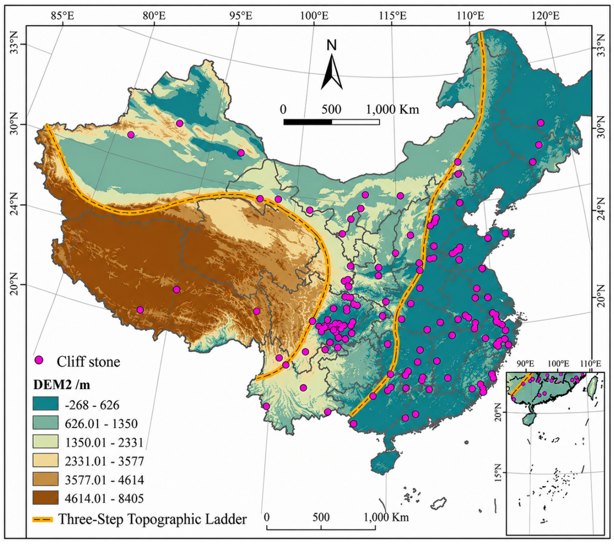


Fig. 8. Topography and cliff carvings distribution

multiple factors. The distribution of cliff stone carving is result of natural conditions and socio-cultural influences that determine clustering, intensity, and regional dispersion. This paper examines these relevant factors, categorising them into natural elements and cultural elements. Based on the above analysis, the spatial clustering explained by environmental, historical, and cultural factors.

4.1. Natural factors

4.1.1. Topography factor

Cliff reliefs are found at altitudes of -268 to 626 m , mainly on 2nd and 3rd terraces, Fig. 8 illustrates the distribution patterns.

4.1.2. River system factors.

Rivers encourage settlement and culture diffusion; buffer zones (1 km, 2 km, 4 km, 8 km, 10 km) evaluate their effect on the distribution of cliff carvings. Along rivers, buffers of 1-10 km capture human-river interactions, with later stages of cliff carving highest immediately adjacent rivers and strong settlement and cultural reliance. The distribution of the cliff carving sites as: 1 km, 36 sites (24.65%), 2 km, 54 sites (36.99%), 4 km, 64 sites (43.84%), 8 km, 91 sites (62.33%), 10 km, 91 sites (62.33%), and > 10 km, 55 sites (37.67%).

4.2. Social and political factors

Rock carvings are a reflection of socio-political reality and flourished during periods of stable prosperous dynasties.

4.3. Religious belief factors

Buddhism arrived through the Silk Road and adapted to Chinese culture, influencing cliff carvings ; Taoism played a part and Tang-Song religious dissemination and region expansion.

5. Discussion

GIS-based analysis of cliff stone carvings' patterns in time and space and its driving factors at the national scale; Limitations and Research Prospects. Based on fragmented information and qualitative approaches, and lacking quantitative spatial investigations.

6. Conclusion

Based on GIS, this paper reveals the distribution feature and the influencing factors of 146 nationally gazetted cliff carving sites by exploring their spatial and temporal distribution. Result indicates that spatial clustering is significant with Sichuan and Zhejiang as the density cores and a concentration index of $G = 27.14$. Evolution develops from the Pre-Qin scattered pattern to the Sui-Tang peak clustering and to the multi-centered and convergent pattern. An outline of shifts in distribution from Gansu to Hunan is sketched.

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8. Declarations

Funding: The authors did not receive any funding for this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Data Availability Statement: All data generated or analyzed during this study are included in this manuscript.

Code Availability: Not applicable.

Authors' Contributions: Ji Zhou and Zhuting Tan contributed to the study design, data analysis, validation, and manuscript preparation. Jiaxing Hu and Chao Xie contributed to data curation, software development, manuscript review, and project administration.

Ethical Approval: This study did not involve human participants or animal subjects; therefore, ethical approval was not required.

Consent to Participate: Not applicable.

Consent to Publication: All authors have provided consent for the publication of this manuscript.

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

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