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Research article

Promoting the sustainable development of traditional villages: Exploring the comprehensive assessment, spatial and temporal evolution, and internal and external impacts of traditional village human settlements in hunan province

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ABSTRACT

The protection and development of traditional villages are crucial for improving the human settlement suitability (HSS). The paper takes 703 traditional villages in Hunan Province as the research object and establishes the HSS evaluation system by using the pressure-state-response model. Then this paper introduces the vector autoregressive model to explore the interactions and contributions within the three major subsystems. Finally, this paper adopts Geodetector model and GTWR model to study the external driving effects and temporal-spatial influence mechanisms. The main findings of this paper are as follows. First, the overall trend of the composite index of traditional villages is upward. Its spatial pattern transitions from a low index in the northwest to a medium index in the central region and a high index in the southeast. Second, the state system becomes the main driver of the response system change and it is highly influenced by the pressure system. Distance from medical facilities, Distance from educational institutions, Distance from the intangible cultural heritage sites, and Degree of relief are the four most important driving factors affecting the HSS in Hunan Province. At the same time, Distance to medical facilities and Distance to intangible cultural heritage sites have a positive impact, while Distance to educational institutions and Degree of relief have a negative impact. Fourly, these four factors have a significant spatiotemporal impact on the HSS in the Xiangxi region. This paper provides a scientific basis for the sustainable development and conservation of traditional villages in Hunan from multiple perspectives.

1. Introduction

With the convening of the 2023 World Conference on Sustainable Urban Development and the ongoing implementation of the United Nations 2023 Agenda for Sustainable Development, there has been an increasing focus on the human settlement (HS) in rural areas. Although there is no unified definition of the rural human settlement (RHS) so far, it is commonly believed that the RHS is a

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phenomenon that involves the interaction of natural, economic, social, and cultural elements in the environment produced by the activities of farmers. This environment is formed by an organic combination of material and non-material elements [1].

In recent years, the relentless increase in environmental degradation due to global urbanization has adversely affected the RHS in various regions. Some European countries have seen their rural areas becoming increasingly marginalized in the context of urban development. Countries like the UK and Germany are facing issues such as dwindling rural populations, ecological damage, and inadequate infrastructure. In the United States, the concept of "large-scale farming" has led to a lack of diversity in rural landscapes and difficulties in sustaining village cultural landscapes. Moreover, China, as one of the largest developing countries, has seen some improvement in RHS under its "Rural Revitalization" policy in recent years. However, many villages still face worsening ecological conditions, loss of traditional culture, social disintegration, and hollowing out, with the challenges of regional development disparities becoming more prominent. To address these issues, different countries have formulated targeted policies based on their national conditions. For instance, Germany's Ministry of Agriculture aims to broaden farmers' income channels and enhance production management to improve RHS. The UK government has implemented rural production and construction models to ensure the regular supply of agricultural products and to reduce urban-rural disparities. In recent years, China has introduced a series of measures to improve RHS through its "Rural Revitalization" policy, including support for township industries, river management, ecological restoration, and comprehensive land consolidation. The improvement of RHS has a profound impact on the sustainable development of rural societies. It not only relates to the physical and mental health of rural residents but also serves as a crucial driving force for the economic advancement and cultural innovation of rural areas. A good RHS not only enhances the competitiveness of rural economies but also protects ecological environments and reduces pollution and destruction. Early studies of RHS were primarily from a geographical perspective, but as research has deepened, they have increasingly integrated urban-rural planning, sociology, and ecology. Therefore, expanding research on RHS can enhance interdisciplinary communication and cooperation, promoting the integration of complementary knowledge. Researching and constructing good HS has become a crucial task and challenge, and it is also a focal point of research and interest among scholars both domestically and internationally.

Currently, international scholars have explored the HS by considering various spatial scales and focusing on the conditions of HS in different regions. Cheng et al. (2024) have taken China as a spatial scale to study the development trajectory of RHS in China, established an evaluation system for the quality of HS, analyzed the spatial and temporal characteristics of the quality of RHS in China, and designed differentiated improvement strategies [2]. Zhang, T.T. et al. (2022) conducted field surveys of households in six nature reserves in China, proving that constructing a HS can significantly improve farmers' welfare [1]. Yu and Chen (2022) took the cities in the Yellow River basin as their research subject, analyzed the spatial and temporal differentiation characteristics of the coupling and coordination between the HS and the tourism industry in the Yellow River basin, and studied the interactive coupling relationship between the HS and tourism [3]. Panchang. (2019) took the city of Pimpri Chinchwad in Maharashtra, India as a spatial scale to study the impact of basic sanitation facilities on the urban architectural environment [4]. Overall, the research on HS currently mainly focuses on large spatial scales such as nations, regions, and cities, while studies based on smaller spatial scales like village areas are still rare. Currently, there is a trend towards diversification and expansion of the boundaries of research on human settlements, and the spatial scales of research include the national, urban and regional levels. Generally speaking, the research on human settlements is becoming richer and richer, and more and more emphasis is being placed on quantitative research. However, in the face of the growing importance of the rural human settlement, domestic and foreign scholars have conducted fewer studies on the spatial scale of the village, and the conclusions of the studies are relatively limited. Therefore, expanding the spatial scale of the village as the object of study will be more conducive to a comprehensive examination of the human settlement.

At present, international scholars primarily focus their research on HS at two levels: urban and rural. Research on HS began with urban planning, and current studies mainly focus on factors affecting urban HS [5], and future development trends [6]. Research on rural environments primarily concentrates on counter-urbanization and rural migration [7], factors influencing RHS [8], and sustainable development of RHS [9]. International research on HS has developed over a long period, with urban HS being particularly thoroughly explored. Through constructing scientific and systematic evaluation systems, this research not only provides robust support for current urban construction but also makes reasonable predictions about future trends. In China, Academician Wu Liangyong proposed the establishment of a science of HS in the early 1990s, leading to a significant number of scholars beginning to engage in research on various aspects of HS, primarily focusing on urban HS construction evaluation [10], sustainable development of urban HS [11], and livability of urban HS [12]. The publication of 'Convenient Urban Science Evaluation Standards' demonstrates that China has established a scientific index system for evaluating urban residential areas. Research on RHS in China started later, initially focusing on regional barrier factors and current difficulties [2], with depth and breadth of research still needing improvement. In summary, current research on urban HS is quite comprehensive internationally, but there are many deficiencies in RHS research. On one hand, a scientific evaluation index system has not been formed, and on the other, there is less research on RHS in villages with historical and cultural heritage possessing diverse values. Research on traditional village HS is particularly weak. Traditional villages refer to those with relatively intact ancient architecture, traditional customs, and lifestyles, such as ancient towns and villages, as well as ethnic minority villages with ancient buildings and special customs [13,14]. From the 1930s, authoritative global institutions for cultural heritage preservation such as UNESCO, the International Council on Monuments and Sites (ICOMOS), and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) have successively issued a series of documents aimed at studying and protecting the HS of traditional villages. Such documents include the 'Convention Concerning the Protection of the World Cultural and Natural Heritage' (1972), the 'European Charter on Architectural Heritage' (1975), the 'Tlaxcala Declaration on the Revitalization of Small Settlements' (1982), and the 'Charter on the Built Vernacular Heritage' (1999), clearly indicating that the protection of traditional villages has become a hot topic in the field of international heritage conservation. Moreover, the diverse values and modern significance of traditional village HS have also become one of the focal issues for scholars worldwide [15,16].

Suitability is one of the key aspects in assessing the quality of RHS. The evaluation of the human settlements suitability (HSS) is a crucial engine and core goal for rural modernization and comprehensive environmental management. How to scientifically, comprehensively, and multilevel assess and improve the HSS is currently a hot topic among scholars worldwide. Current research mainly focuses on the assessment of the HSS system. From the perspective of assessment theoretical frameworks, many use analysis frameworks such as the Pressure-State-Response (PSR) model [17], the Pressure-Release (PAR) model [18], and the Ecology-Production-Life (EPL) Space [19] model for empirical studies on residential HSS. In terms of assessment indicators, the research generally focuses on the natural environment as the primary factor, incorporating social and economic factors to study urban living conditions [20,21]; and it also includes studies on the HS assessing single or several elements of natural or economic systems [22,23]. As for assessment methods, mainstream evaluation methods include survey methods [24], analytic hierarchy process [19], fuzzy comprehensive evaluation method [25,26], and GWR method [27–30]. The substantial results from research on the HSS provide theoretical references and methodological guidance for analyzing the traditional village human settlements suitability (TVHSS). However, existing research lacks a systematic analysis of the TVHSS. The research perspectives often focus on the assessment of TVHSS at specific time points and explore context-specific optimization strategies, lacking in the analysis of the spatio-temporal evolution of the TVHSS. Moreover, when considering the impact mechanisms, most studies only start from external influencing factors and neglect the role of intrinsic system relationships within the assessment system.

To address these research gaps, this study initially adopts the 'Pressure-State-Response' (PSR) model as the theoretical framework for assessing the TVHSS. This model focuses on the interrelationship between humans and the environment and is a significant model within the discipline of environmental quality assessment [31–33]. Introducing the PSR model into the TVHSS assessment helps to better understand the human-environment relationship in the study area and quantify the degree of TVHSS assessment. Secondly, this study conducts a detailed analysis of the TVHSS levels over a continuous period of 15 years by using long-term panel data and a spatio-temporal dual perspective. Thirdly, in analyzing the mechanisms of influence, this study will explore the intrinsic mechanisms and contribution levels between various subsystems of suitability from both internal and external dimensions using the VAR model (vector autoregression). Furthermore, by employing correlation models, OLS models, geodetector methods, and the Geographically and Temporally Weighted Regression (GTWR) model, this research investigates the intensity and direction of external impacts on the TVHSS, as well as analyzes the mechanisms of their evolution.

Furthermore, enhancing the quality of HS and the quality of life has become a new direction for international development. The core idea of New York's 2030 plan is to 'build a greener, better city,' while London's 2030 planning theme is 'building a more livable

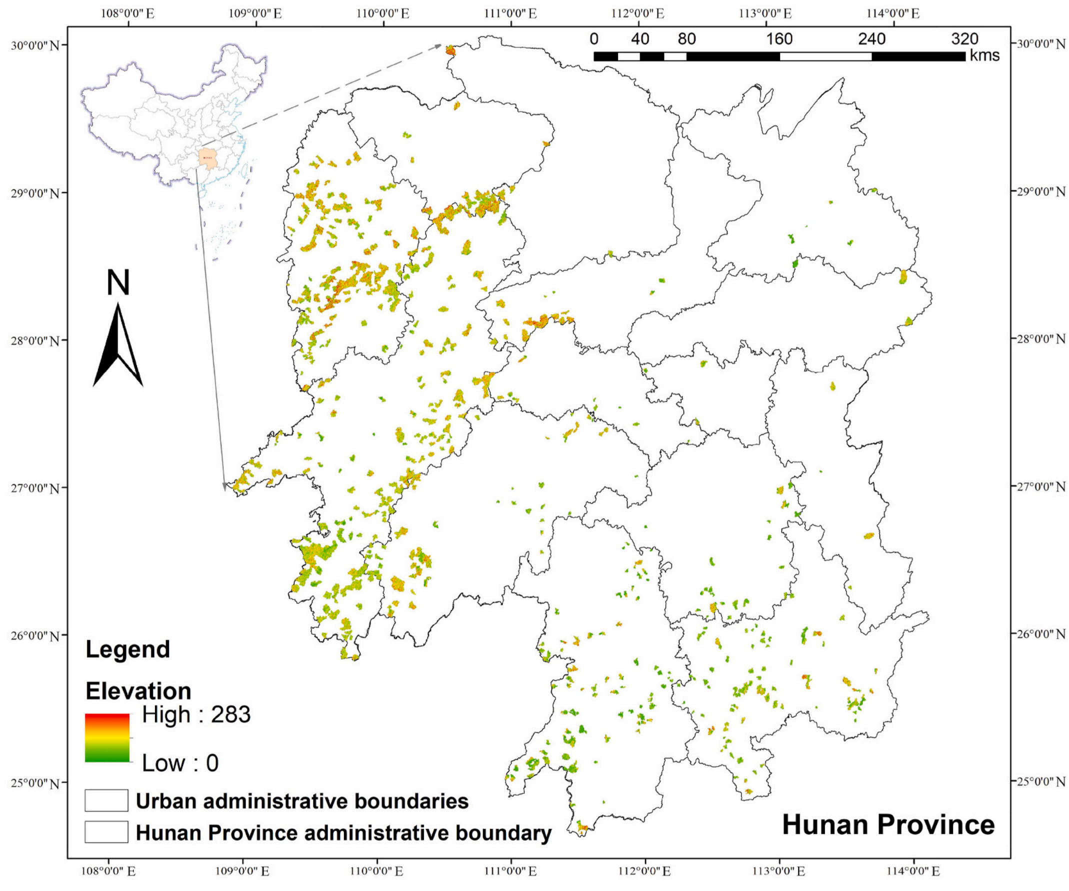

Fig. 1. Study area.

city.' In early 2014, General Secretary Xi Jinping emphasized the goal of making Beijing an 'internationally first-class harmonious and livable capital,' demonstrating that the future global development direction is to improve the HSS. This study is based on the hotspots of global concern about HSS. Through research on the TVHSS, it not only provides strong theoretical support for decision-makers to construct a reasonable framework for the protection and utilization of traditional villages but also serves as auxiliary material for related theoretical research on traditional villages, offering rich resources for the construction of think tanks for China's rural revitalization development strategy. It also enriches the content of geographical research, expands the perspectives and ideas of interdisciplinary research in geography, urban planning, ecology, and other disciplines, and paves new ways for the comprehensive integration of research on HS theories.

2. Methods

2.1. Study area

Situated in the south-central sector of China, Hunan Province is a captivating area characterized by its unique geographical positioning and diverse natural landscapes (Fig. 1). The region is endowed with abundant natural resources, including undulating hills, lakes, and rivers. These geographical elements have profoundly impacted the genesis and evolution of traditional villages within Hunan Province. In this study, "traditional villages" are defined as those communities that retain rich traditional attributes in architectural styles, social structures, and cultural heritage. These villages encapsulate the deep historical and cultural ethos of Hunan Province. Traditional villages in Hunan have an extensive and illustrious history, evolving and thriving across numerous centuries. They serve not only as the abode for residents but also as custodians of cultural and traditional heritage. Their architectural designs, societal frameworks, and lifestyles distinctly mirror the unique attributes of Hunan Province.

Currently, traditional villages in Hunan Province are encountering increasingly severe challenges due to urbanization and modernization. Accelerated urban expansion has precipitated issues such as alterations in land usage, cultural dilution, and environmental degradation [34]. These challenges threaten the preservation and sustainable development of traditional villages. This study selects traditional villages in Hunan Province as its research focus, aiming to gain an in-depth understanding of their HS characteristics and unveil the temporal-spatial influencing mechanisms. Specific objectives include assessing the TVHSS quality in Hunan Province, analyzing the temporal-spatial influencing mechanisms of urbanization and modernization on traditional villages, and providing policy recommendations to promote the sustainable development and cultural preservation of traditional villages. The significance of this study lies in its potential to advance cultural protection and sustainable development of traditional villages in Hunan Province, while also offering insights and strategies for the conservation and progression of similar regions and contributing to the enhancement of academic and practical knowledge in pertinent disciplines.

2.2. Research methodology

2.2.1. HSS assessment indicator system based on the PSR model

The PSR model utilizes the 'Pressure-State-Response' logic, reflecting the interactive relationship between humans and the environment. Humans obtain essential resources for survival and development from the natural environment through various activities, while simultaneously discharging waste into the environment, thereby altering the reserves of natural resources and environmental quality. Changes in the state of nature and the environment, in turn, affect human socio-economic activities and welfare. Society then responds to these changes through environmental policies, economic policies, and sectoral policies, as well as changes in awareness and behavior. This cyclical process forms the 'Pressure-State-Response' relationship between humans and the environment, and the model can be used to assess the ecological HSS. This model divides the assessment into three key dimensions: pressure, state, and

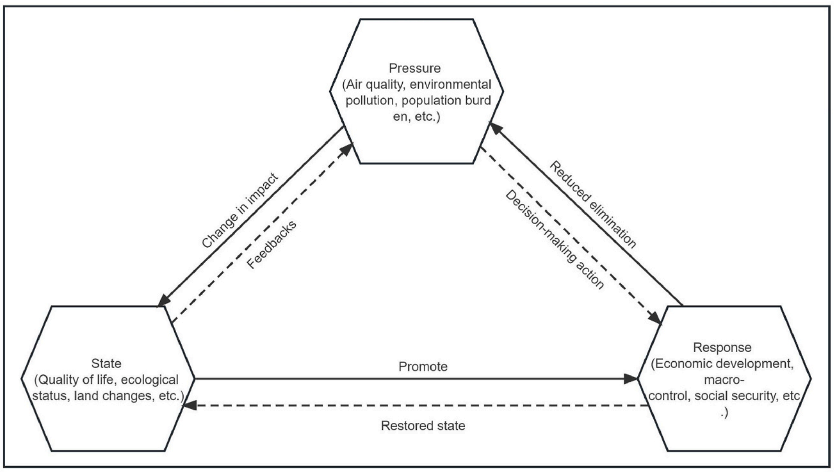

Fig. 2. Theoretical framework of TVHSS based on the PSR model.

response. The pressure dimension focuses on the external and internal pressures that traditional villages face, which may impact the HSS. The state dimension examines the current condition and quality of the TVHSS. The response dimension investigates the responses and measures taken by society, government, and residents to address HSS issues. Therefore, this study constructed a HSS evaluation index system based on the pressure-state-response (PSR) model (Fig. 2). It is an auxiliary tool for the comprehensive evaluation of the TVHSS in Hunan Province [31–33].

By examining the current circumstances in Hunan Province and leveraging existing research findings [17,25,26,35–42], constructed a TVHSS evaluation index system (Table 1). Took into consideration data availability during the construction phase, And adhered to the principle of selecting indicators that are systematic, effective and quantifiable. The indicator system can provide guidance for the government, social organizations and villagers to enhance the quality of TVHSS and implement sustainable development strategies.

To fully encapsulate the quality of the TVHSS in Hunan Province and ensure comparability, this study standardized the evaluation indicators. Furthermore, the entropy weighting method was employed measure the overall composite scores from 2005 to 2020. The findings of the study were visualized using ArcGIS and categorized into five grades. The grades from low to high are very low, low, medium, good and excellent.

2.2.2. Standardization of indicators and composite measurement calculation

To negate the impact of evaluation indicators with disparate units on the outcomes of HSS quality assessment, the raw data were processed using both positive and negative standardization methods. To circumvent subjectivity in the manual assignment of weights, the study utilized the entropy weighting method to determine the weights of each factor [43–45]. Firstly, using the entropy weight method to calculate the weight of each index and establish a comprehensive evaluation model. Based on this model, a comprehensive score is derived for the TVHSS.

The specific steps are as follows:

Normalization of indicator data. The following formula was used.

Normalization positive indicators
$$Z_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{1}$$

Normalization negative indicators
$$Z_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

In the formula, x_{ij} represents the standardized value of the jth indicator for the ith evaluation sample.

2) Entropy Weighting Method for Indicator Weight Calculation, with the formulas as follows.

Calculate the weight of the jth indicator for the ith evaluation sample:
$$Y_{ij} = Z_{ij} \Big/ \sum Z_{ij} \tag{3}$$

Calculate the information entropy value for the jth indicator:
$$e_j = -k \sum_{i=1}^{m} Y_{ij} \ln Y_{ij} \tag{4}$$

Calculate the information entropy redundancy for the jth indicator:
$$g_i = 1 - e_j \tag{5}$$

Calculate the weight for the jth indicator:
$$w_j = g_j \Big/ \sum_{j=1}^{n} g_j \tag{6}$$

Table 1
Indicator system for assessing the TVHSS.

Subsystem	Code	Variable	Influence	weighted value (%)
Pressure System (P)	P1	Annual Average Temperature	–	7.720
	P2	Annual Average Precipitation	–	1.910
	P3	Annual Average Wind Speed	–	0.494
	P4	Particulate Matter Emissions in Industrial Exhaust	–	0.413
	P5	Population Density	–	0.064
	P6	PM2.5 Emissions	–	1.745
State System (S)	S1	Local Government General Budget Revenue	+	9.573
	S2	GDP	+	10.859
	S3	Electricity Consumption for Urban and Rural Residents	–	0.455
	S4	Land Use Mix	+	2.057
	S5	NDVI	+	0.378
	S6	NPP	+	3.506
Response System (R)	R1	Per Capita Agricultural, Forestry, Animal Husbandry, and Fishery Output Value	+	5.354
	R2	Urban Fixed Asset Investment	+	15.657
	R3	Number of Full-Time Teachers per Thousand People	+	3.278
	R4	Per Capita Government Expenditure	+	7.932
	R5	Real Estate Development Investment	+	14.939
	R6	Hospital and Clinic Bed Capacity	+	6.575
	R7	Social Welfare Adoption Unit Bed Capacity	+	7.093

In the formula, Y_{ij} represents the weight value of the jth indicator for the ith evaluation sample; e_j represents the information entropy value of the jth indicator; g_j represents the information entropy redundancy of the jth indicator; and w_j represents the weight coefficient for the jth indicator.

3) Calculation of the Composite Index, with the weight calculation formula as follows:

$$HSI = \sum_{j=1}^{z} W_{P_j} \times P_j + \sum_{j=1}^{z} W_{S_j} \times S_j + \sum_{j=1}^{z} W_{R_j} \times R_j \tag{7}$$

In the formula, *HSI* represents the TVHSS Index; where P_j, S_j, R_j are the indices of the P, S, and R systems obtained using the positive and negative indicator standardization method, respectively, for the jth indicator; and W_{P_j}, W_{Sj}, W_{Rj} are the corresponding weights for the indices of each system.

2.2.3. VAR model

The Vector Autoregression (VAR) model is a multivariate time series model employed to analyze and forecast the dynamic interactions among multiple variables. Vector autoregressive models encapsulate the interdependencies and feedback loops among variables, leveraging the intrinsic dynamic of time series data [46–48]. The formula is as follows.

$$(t = 1, 2, \ldots, T)\ y_t = \beta_1 y_{t-1} + \beta_2 y_{t-2} + \cdots + \beta_h y_{t-h} + \partial x_t + u_t \tag{8}$$

In the formula, y_t represents the vector of endogenous variables; x_t represents the vector of exogenous variables; h represents the lag order; T represents the number of time samples; u_t represents the disturbance vector. Assuming that the endogenous variables in the model are stationary, pulse response and variance decomposition can be performed.

2.2.4. Methods for analyzing the impact mechanisms of spatial differentiation

The Geodetector is an effective tool for addressing issues of spatial correlation and interaction among geographic factors [49–52], making it particularly relevant to our study of TVHSS. In this research, this study employ the Geodetector's factor detection module to quantitatively assess the influence of various geographical factors on HSS. Specifically, this module has been pivotal in identifying and quantifying the driving impact of factor X on HSS Y. By integrating this approach, this study can dissect the complex interplay between geographic factors, providing a nuanced understanding of their contributions to HSS in Hunan Province's traditional villages. The model is as follows:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{h-1}^{L} N_h \sigma_h^2 \tag{9}$$

In the formula, q represents the impact strength of the influencing factor on the HSS. *h* represents the strata of factor *x*, with N_h and *N* representing the number of units in stratum *h* and the entire region, respectively. OH and O represent the variance of y values in stratum *h* and the entire region, respectively. The value range of q is [0, 1], with a larger value indicating a stronger explanatory power of factor *x* on attribute y, and vice versa.

The Geographically and Temporally Weighted Regression (GTWR) model is a spatial analysis method that extends from Geographically Weighted Regression (GWR). It is primarily used to analyze the complex relationships between spatial and temporal data, especially when these data exhibit trends and patterns that vary with geographical location and time. The GTWR model is particularly effective in handling data with spatiotemporal heterogeneity, providing a more detailed interpretation of local patterns. GTWR incorporates spatial and temporal weights into the regression analysis to address the variations in model parameters over time and location, thus more accurately reflecting complex spatiotemporal dynamics. Therefore, this study mainly applies the model to explore how external factors dynamically impact TVHSS levels as they vary over time and geographical locations. The model is as follows:

$$Y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i) x_{ik} + \epsilon_i \tag{10}$$

Note: Y_i is the response variable; u_i, v_i are the geographic spatial coordinates; t_i is the time coordinate; $\beta k(u_i, v_i, t_i)$ is the regression coefficients corresponding to the location (u_i, v_i) and time t_i; $x_{ik}$is the k-th explanatory variable of the i-th observation; ϵ_i is the error term.

2.3. Data collection

This study focused on 703 traditional villages in Hunan Province as the primary research units, examining their conditions in the years 2005, 2010, 2015, and 2020 [53–56]. Geospatial attribute data, including administrative divisions, were procured from the National Basic Geographic Information System (http://ngcc.sbsm.gov.cn). The compilation of traditional villages was derived from the website of the Chinese Ministry of Housing and Urban-Rural Development. Digital Elevation Model (DEM) data, meteorological data, and land-use remote sensing monitoring data were acquired from the Chinese Academy of Sciences Resource and Environmental Science Data Center (https://www.resdc.cn/). Road data was sourced from OpenStreetMap. Socio-economic statistical data predominantly relied on the National Economic and Social Development Statistics Bulletin of various counties in Hunan Province. For any missing data, SPSS interpolation methods were employed for data imputation.

3. Results

3.1. Comprehensive TVHSS scores

In this study, a comprehensive indicator evaluation was utilized to determine the comprehensive values of TVHSS over the study period (Table 2 and Figs. 3 and 4). The average values of TVHSS for the years 2005, 2010, 2015, and 2020 were 0.522, 0.613, 0.546, and 0.777, respectively. From a time-series analysis perspective (Fig. 3), the general trend of the comprehensive HSS scores exhibits an upward trajectory over the 15 years. The average score increased from 0.522 in 2005 to 0.777 in 2020, indicating a significant improvement in the TVHSS. However, there was a slowdown in development in 2015, suggesting a sudden adverse development in the TVHSS system in Hunan Province during that period. Meanwhile, although the overall comprehensive HSS score improved, there was no significant difference in scores among different villages over time. This indicates consistency in the implementation of urban development policies across villages.

In terms of overall development (Table 2 and Fig. 4a and b), traditional villages in Hunan Province have seen significant improvements in their HSS. A total of 89.33 % of traditional villages witnessed improvements in their HSS quality. Among them, 75.68 % of traditional villages showed a low level of improvement, with a range of 0–0.5. 12.09 % of traditional villages experienced better development. Additionally, only 1.56 % of villages saw a substantial improvement in HSS quality, indicating that these villages may have found suitable development models. Conversely, 1.14 % of villages experienced significant deterioration in their HSS quality, likely due to detrimental actions that harmed the ecological environment.

3.2. HSS subsystem and comprehensive measurement spatial differentiation characteristics

For data preprocessing, the range normalization method was utilized.Subsequently, the hunan province HSS composite index and the subsystem indices were calculated using equations (1-7). Spatial visualization was performed using ArcGIS 10.2, and the natural breakpoint classification method was employed to categorize the index into five grades: very low, low, medium, good and excellent (Fig. 5).

Based on the results in Fig. 5, the comprehensive TVHSS index in Hunan Province shows a spatial distribution pattern, generally manifesting an upward gradient from "lower in the northwest, moderate in the central, and higher in the southeast." The distribution of the comprehensive index is relatively concentrated, with elevated values predominantly located in Yongzhou, Hengyang, and Chenzhou, while diminished values are principally observed in Xiangxi Prefecture, Huaihua, and Shaoyang, among other regions. From a temporal perspective, the comprehensive index exhibits different trends across different regions. For example, the central part of Xiangxi Prefecture shows a wave-like growth in the comprehensive index, while the index for Yiyang City remains at a moderate level. Nevertheless, it is important to recognize that some local areas may exhibit slight fluctuations, such as more traditional villages in the central part of Xiangxi Prefecture recording the lowest values.

3.3. Internal system impact analysis based on VAR model

This paper investigates the VAR model utilizing longitudinal panel data covering 16 years from 2005 to 2020, with a sample size of 2812. Given the spatial and temporal variations of all geographical units of traditional villages, logarithmic transformations were applied to all variables (LNP, LNS, and LNR) to achieve stationarity in the dataset, while preserving the inherent characteristics and correlations of the time series.

3.3.1. Model testing

This paper used the ADF unit root test to check whether each endogenous variable is stable (Table 3), where LNP, LNS, and LNR represent the first-order difference sequences of the pressure system, state system, and response system, respectively.

Cointegration analyses confirmed the presence of cointegration relationships between variables (Table 4), suggesting a long-term stable equilibrium relationship between the three systems. The Granger causality test, conducted at a 5 % significance level, revealed

Table 2
Percentage of traditional villages in 2020 with different ranges of HS composite score differences from 2005.

Difference range	Proportion of villages
$X \le -1$	1.14 %
$-1 < X \le -0.5$	2.56 %
$-0.5 < X \le 0$	6.97 %
$0 < X < 0.5$	75.68 %
$0.5 \le X < 1$	12.09 %
$X \ge 1$	1.56 %

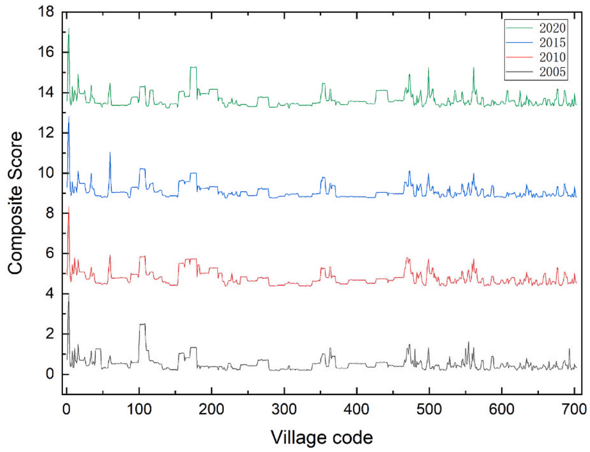

Fig. 3. Comparison of Composite TVHSS Scores. Note: "X" represents the differences in HS composite scores between 2020 and 2005 for various traditional villages.

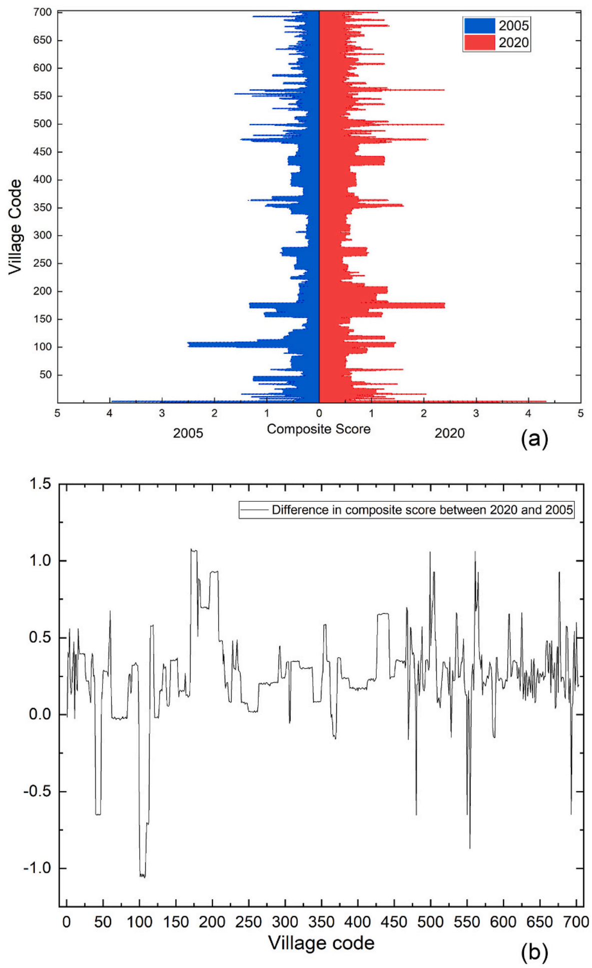

Fig. 4. Comparison of THVSS composite scores between 2020 and 2005, along with difference information.

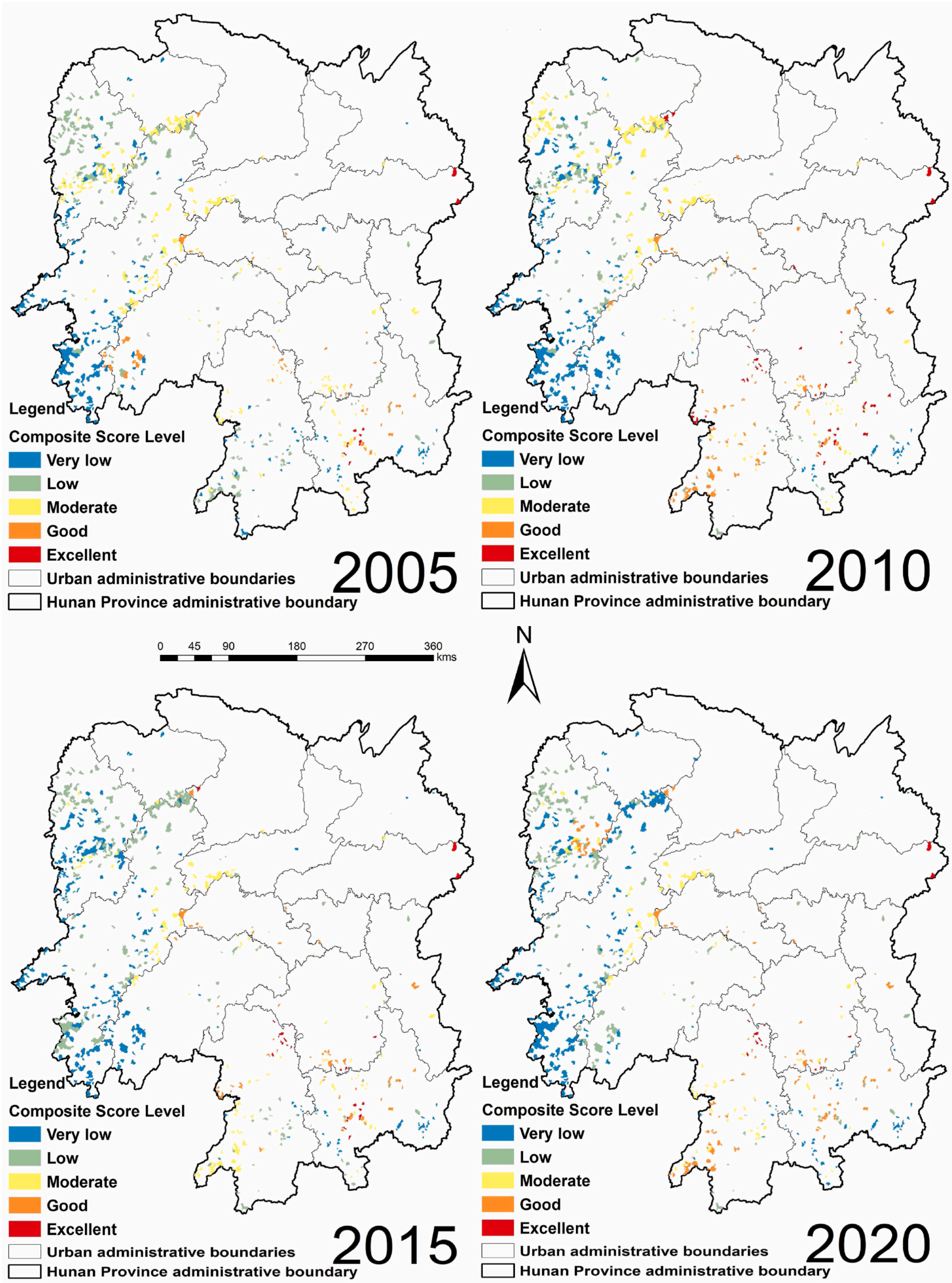

Fig. 5. Spatial and temporal pattern of the TVHSS composite scores.

bidirectional causality among the three variables (Table 5).

An AR characteristic root test was employed to verify the stability of the formulated model, and the outcomes indicated that all characteristic roots lay below 1, affirming the model's stability for further analysis. Fig. 6 illustrates the results of the AR unit root test for the VAR model, where all points are clearly within the unit circle, substantiating the stability and effectiveness of the established VAR model and corroborating the presence of a long-term stable equilibrium among the variables.

Table 3
ADF unit root test results.

Sequence	Statistic	P
P(LNP)	−7.777	0.000
S(LNS)	−11.867	0.000
R(LNR)	−10.813	0.000

Table 4
Cointegration test results.

Original hypothesis	Eigenvalues	Trace statistic	5 % critical value	P
None*	0.063	407.449	29.797	0.001
At most 1*	0.042	225.665	15.495	0.001
At most 2*	0.037	104.573	3.8415	0.001

Note: * indicates rejection of the original hypothesis at the 5 % significance level.

Table 5
Granger causality test.

Original hypothesis	F-statistic	P
LNP is not a Granger reason for LNS	5.068	0.001
LNS is not a Granger cause of LNP	3.074	0.009
LNR is not a Granger cause of LNS	6.295	8.E−06
LNS is not a Granger cause of LNR	26.923	1.E−26
LNR is not a Granger cause for LNP	7.685	3.E−07
LNP is not a Granger Reason for LNR	4.656	0.003

3.3.2. Impulse response

In order to explain the dynamic relationships and interactions between the three subsystems of the HSS, this study introduces impulse response analysis. By observing the curve graphs of the impulse response functions (Fig. 7), can observe the impact and interactions among the three variable systems.

According to the results depicted in Fig. 7, in the initial stages, the existing pressure system exerts a significant positive influence on the future pressure system. Nevertheless, this influence gradually diminishes in later periods and stabilizes after the 10th period. With regard to the effects of the status system and response system on the pressure system, it can be observed from Fig. 7b and c that during the 1st to 10th periods, they imposed negative influences on the pressure system. The influence of the status system on the pressure system slowly increased in the first 5 periods, decreased in the 6th period, and then remained stable. On the other hand, the influence of the response system on the pressure system exhibited a certain lag in the 1st period, showing a trend of initially decreasing and then increasing from the 1st to 5th periods, followed by stable negative impact from the 6th to 10th periods. Overall, the fluctuations during the 1st to 10th periods were relatively minimal. In summary, both the status system and the response system had a negative impact on

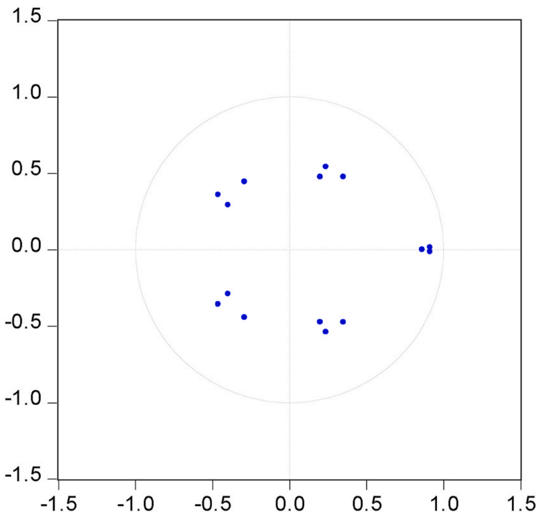

Fig. 6. Results of AR unit root test.

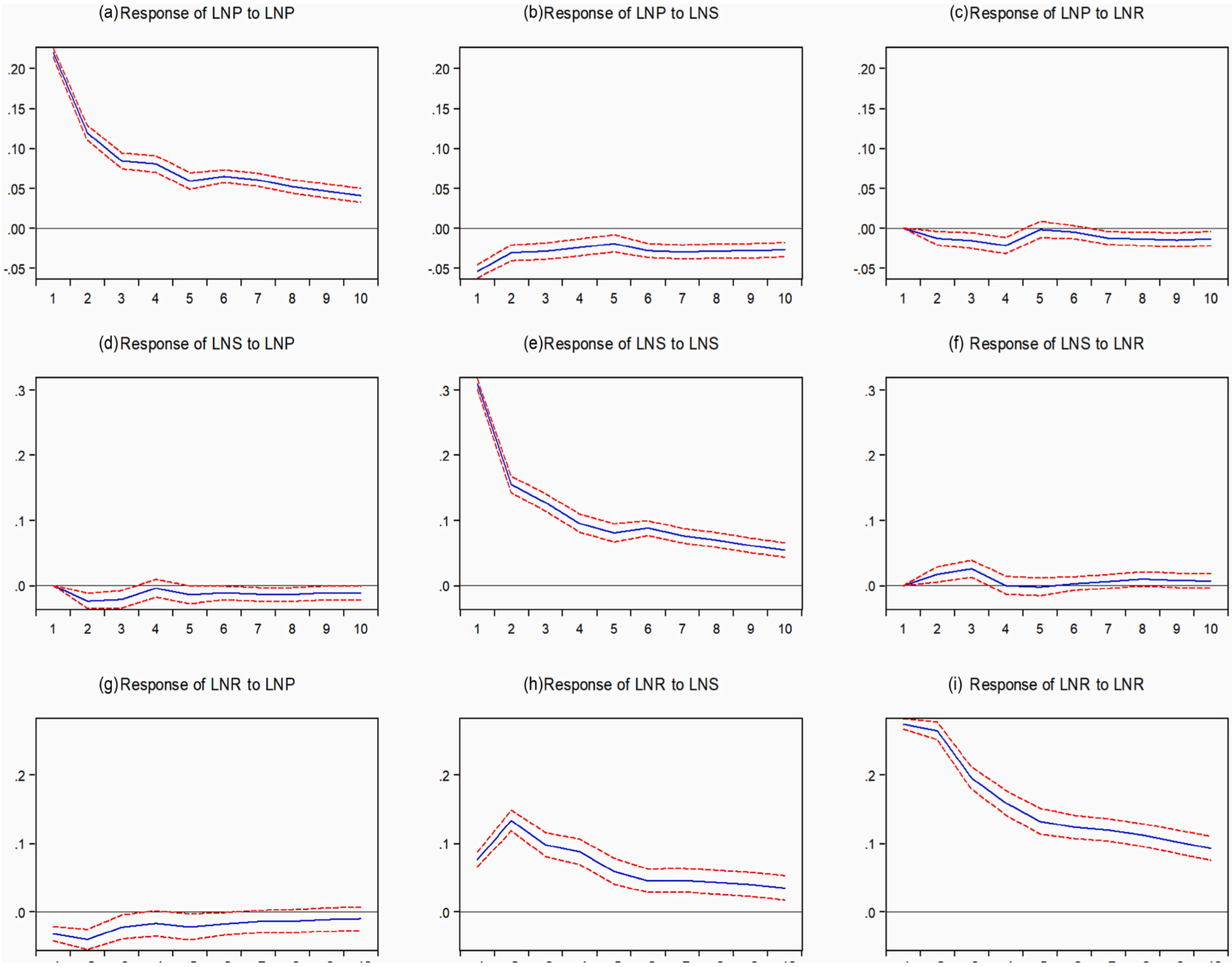

Fig. 7. Impulse response analysis results.

the pressure system, with the status system having a relatively larger impact.

Fig. 7d illustrates the negative impact of the status system on the pressure system, which persisted from the 1st to the 10th period. Simultaneously, Fig. 7g indicates that the response system also had a negative impact on the pressure system, exhibiting a clear upward trend from the 1st to the 10th period, followed by a relatively stable impact. This suggests that effective government decision-making, improvements in environmental quality, control of carbon emissions and pollutant emissions, and the establishment of sustainable economic development models can effectively mitigate climatic deterioration to a certain extent and facilitate spatial evolution.

Fig. 7e and i demonstrate the impacts of the status system and response system on themselves. These two graphs show that, after initially having a high positive impact in the 1st period, there is a gradual decline in the overall slope to the lowest point. This trend can be attributed to the fact that environmental investment and environmental policies can effectively mitigate the impact of the pressure system. However, the long-term accumulation of high pollution, greenhouse effects, and population buildup has led to insufficient sensitivity to these impacts. Fig. 7f and h display the opposite features, indicating a bidirectional impact relationship between the two systems. The response system always has a positive impact on the status system, while the status system has an initially positive impact on the response system, but this impact turns negative in the 5th period and then returns to being positive with smaller changes. This trend suggests that government management strategies in enhancing the quality of the TVHSS, and changes in the village's HSS will effectively feedback to the authorities, enabling them to take targeted measures. However, the feedback strength of the environmental system is substantially lower than the implementation strength of policies, indicating a lack of coordination. Therefore, maintaining synergy between implementation strength and feedback strength should become an important topic in the future.

3.3.3. Variance decomposition

Drawing on the results of impulse response analysis, the variance decomposition method was subsequently utilized to explore the contributions of various shocks to the changes in the three systems. Table 6 presents the results of the variance decomposition for the three observation periods: period 1, period 5 and period 10.

According to the results, the variations in the pressure system can be attributed to the status system, response system, and itself.

Throughout the entire period, the contributions of the status system and response system to the shocks range between (0–8.92 %) and (0–1.49 %), respectively. Regarding the changes in the status system, the breakdown of the contributions from the shocks to each endogenous variable indicates that the pressure system is the primary factor influencing the changes in the status system. This is because the contributions of the pressure system shocks range from 0 to 1.25 %, exceeding those from the response system (0∼0.66 %). This indicates that enhancements in residents' HS and social frameworks are, to a degree, limited by climate regulation, pollutant control, and population adjustments.

The transformations in the response system are ascribed to the impacts of the pressure system, status system, and self-shocks. Among these, the status system emerges as the chief determinant affecting alterations in the response system. The impact of the status system in the 1st period is approximately 7.12 %, and over the long-term development, its impact steadily increases to around 15.41 % by the 10th period. The impact of the pressure system on the response system is relatively small, with a stable impact of approximately 1.40 % over the long term.

In summary, based on variance decomposition, there is a discernible interdependence among the three systems, with the status system having the greatest impact on the response system.

3.4. Analysis of factors driving changes in the HS

According to the PSR model and HS criteria, external influencing factors of TVHSS were introduced, including ecological factors (Degree of relief, and Distance from water), economic factors (Business density, and Road density), and social factors (Distance from medical facilities, distance from educational institutions, and Distance from intangible cultural heritage sites). These factors collectively constitute the external influencing factors on TVHSS. Subsequently, indicator data were obtained to analyze the evolution of these external influencing factors in a spatiotemporal context.

3.4.1. Correlation test and collinearity test

First, using Origin software, a correlation analysis was conducted between the HS in the years 2005, 2010, 2015, and 2020 and the selected influencing factors, as shown in Fig. 8. According to the results of the correlation analysis, there are correlations between the TVHSS and factors (X2, X3, X4, X5, and X6), leading to the exclusion of factors X1 and X7. Secondly, a collinearity analysis was carried out using the linear regression model in SPSS software to investigate the TVHSS with the aforementioned factors that remained after the exclusions. As shown in Table 7, the VIF values of the indices are less than 7.5, and the Tolerance values are also less than 1, indicating that there are no collinearity issues in the model.

3.4.2. Factor detection analysis

The geodetector method was used to calculate the impact strength q-value of the driving factors (each individual indicator) on the TVHSS (Table 8). A higher q-value indicates that the independent variable X has a stronger explanatory power over the dependent variable Y. The results show that in terms of impact, only X5 did not produce a significant driving force on the TVHSS; temporally, the intensity and significance of the influence of each indicator on TVHSS in Hunan Province varied over different periods; in terms of driving force, the top-ranking q-value was for the ecological environment indicator (Degree of relief), followed by social environment indicators (Distance from medical facilities, Distance from educational institutions, and Distance from the intangible cultural heritage sites), while economic environment indicators did not produce a driving level. This indicates that the spatial differentiation of the TVHSS in Hunan Province is mainly driven by natural and social environments, and the economic environment has little influence on the HSS.

3.4.3. Spatiotemporal impact analysis

Based on the aforementioned geodetector model, it is known that in spatial terms, X2, X3, X4, and X6 can drive the TVHSS. Therefore, to better observe the spatiotemporal distribution patterns of these factors on the TVHSS, this study utilizes the Spatio-temporal Geographically Weighted Regression model to explore the mechanisms of their spatial distribution.

As shown in Fig. 9, X2 has a significant positive overall impact on the TVHSS in Hunan Province. However, the impact coefficient has decreased from −0.410∼1.477 in 2005 to −0.582∼1.115 in 2020, showing a downward trend. Spatially, it generally displays a 'high in the south, low in the north' distribution characteristic. In terms of local spatial changes, the TVHSS in western Hunan is

Table 6
Variance decomposition results.

Variable	s	LNP	LNS	LNR
LNP	1	0.944	0.059	0.000
	5	0.926	0.064	0.009
	10	0.896	0.089	0.015
LNS	1	0.000	1.000	0.000
	5	0.008	0.986	0.006
	10	0.013	0.982	0.007
LNR	1	0.012	0.071	0.916
	5	0.014	0.162	0.824
	10	0.014	0.154	0.832

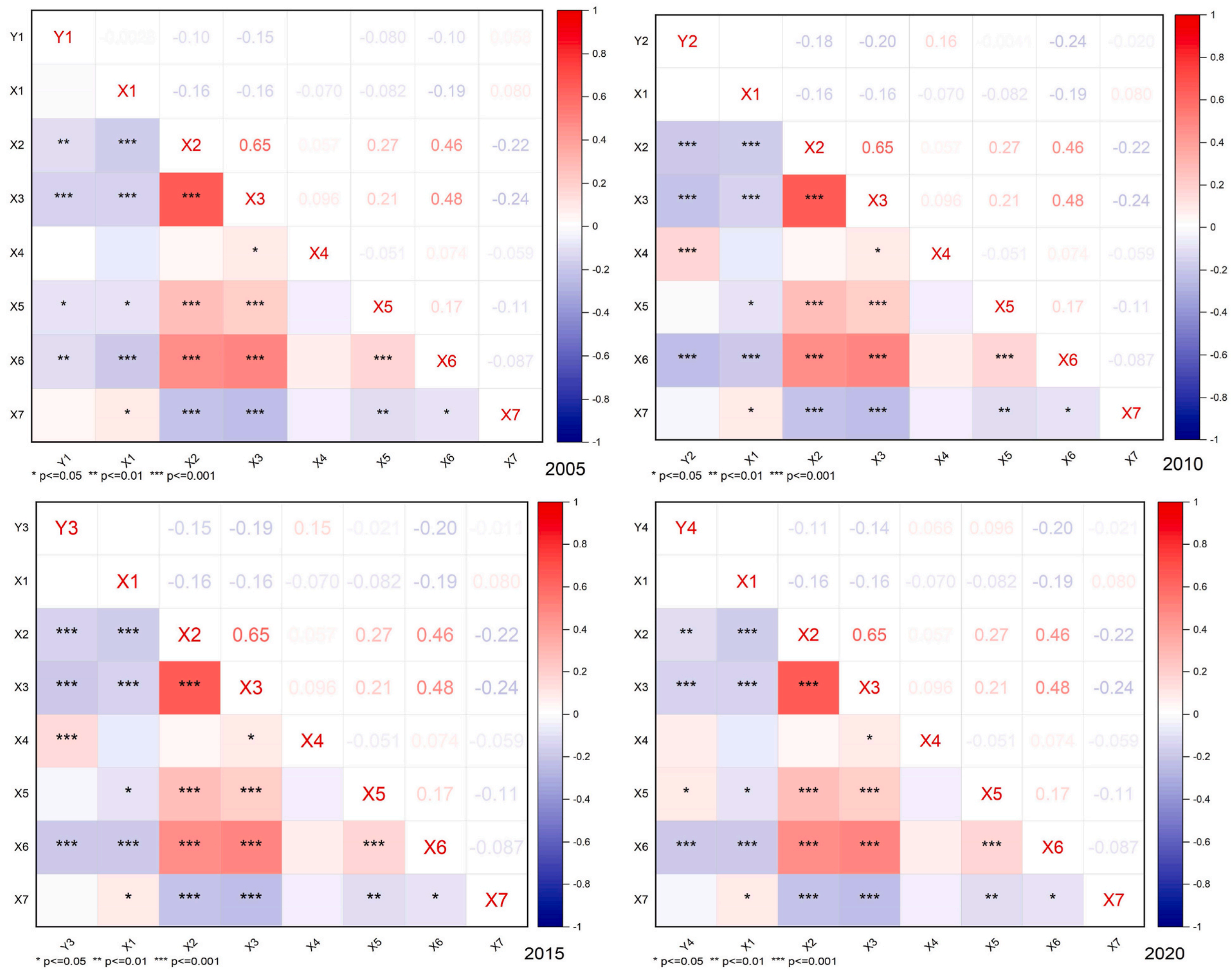

Fig. 8. Correlation Analysis of TVHSS in Hunan Province. Note: X2 represents Distance from medical facilities, X3 represents Distance from educational institutions, X4 represents Distance from the intangible cultural heritage sites, X5 represents Distance to water, X6 represents Degree of relief. Y1, Y2, Y3, Y4 represent the composite index of TVHSS in 2005, 2010, 2015 and 2020, respectively. When the $p < 0.1$, the significance test is passed; when the $p > 0.1$, the significance test is not passed.

Table 7
Collinearity test.

Variable	Tolerance	VIF
X2	0.530	1.887
X3	0.530	1.887
X4	0.984	1.016
X5	0.916	1.092
X6	0.727	1.375

Note: X2 represents Distance from medical facilities, X3 represents Distance from educational institutions, X4 represents Distance from the intangible cultural heritage sites, X6 represents Degree of relief.

continuously influenced by X2, with the impact changing from negative to positive. X2 has a continually declining positive impact on the TVHSS in Yongzhou and Chenzhou.

X3 has a significant overall negative impact on the TVHSS in Hunan Province, but the impact coefficient has risen from $-1.649\sim0.231$ in 2005 to $-1.455\sim0.240$ in 2020, showing a trend of initial decline followed by an increase. Spatially, it generally exhibits a 'high in the north, low in the south' distribution characteristic. In terms of local spatial changes, the impact of X3 on the TVHSS in the central-southern part of western Hunan Province has shifted from negative to positive. X3 has a negative impact on the TVHSS in Yiyang, with continuously increasing intensity.

Table 8
Analysis results of geodetectors.

variable	q	sig	q	sig	q	sig	q	sig	q-mean value
X2	0.022	*	0.038	***	0.032	**	0.020		0.028
X3	0.030	**	0.052	***	0.046	***	0.031	*	0.040
X4	0.012		0.071	***	0.056	***	0.022	*	0.040
X5	0.010		0.017		0.007		0.028		0.015
X6	0.029	*	0.092	***	0.070	**	0.064	**	0.064

Note: X2 represents Distance from medical facilities; X3 represents Distance from educational institutions; X4 represents Distance from the intangible cultural heritage sites; X5 represents Distance from water; X6 represents Degree of relief.

X4 has a significant positive overall impact on the TVHSS in Hunan Province, with the impact coefficient rising from −0.005~0.111 in 2005 to −0.005~0.131 in 2020, showing a continuous upward trend. Spatially, it generally exhibits an 'high in the east, low in the west' distribution characteristic. In terms of local spatial changes, the positive impact of X4 on the TVHSS in the north-central part of western Hunan is continuously rising. Although there are changes in other regions, the final results are essentially consistent with the initial outcomes.

X6 has a significant overall negative impact on the TVHSS in Hunan Province, but the impact coefficient shows a clearly declining trend. Spatially, it generally exhibits a 'high in the north, low in the south' distribution characteristic. In terms of local spatial changes, areas such as western Hunan, Huaihua, and Yiyang are all negatively impacted by X6, with the intensity of the impact continuously increasing.

4. Discussion

4.1. Analysis of the causes of composite scores

This investigation observed that from 2005 to 2020, the TVHSS comprehensive index in Hunan Province exhibited a pronounced upward trajectory trend. This trend aligns with prior scholarly investigations, which demonstrated an overall improvement in RHS across China due to urbanization and policy reforms [5,20,57]. However, an intriguing phenomenon was observed in 2015, where the rate of improvement seemed to decelerate. This could be ascribed to specific policy adjustments or external factors. As existing research suggests, changes in government policies can have a significant effect on RHS [17,21,38,58], and further analysis is needed to explain this phenomenon.

While the overall scores for the HS improved, the disparities among different villages did not noticeably decrease. This aligns with previous research results, indicating that variations in resource allocation and policy implementation across regions can engender disparities in rural development [13,59–61]. This underscores the importance of regional policies to meet the diverse needs of different villages [60,62].

Furthermore, most traditional villages experienced an importance in their HS quality, but the extent of improvement varied. This corresponds to the findings of other research, which highlighted that differing development paths and strategies among villages can result in varying degrees of improvement in HS [63–65]. This emphasizes the crucial role of individual villages in sustainable development. In addition, some villages experienced a significant deterioration in HS quality, which is also a matter that requires in-depth research. Referring to previous studies can elucidate the underlying causes behind this deterioration and facilitate the formulation of appropriate policies and intervention measures.

4.2. Analysis of the impact results

Based on the study, it is evident that the spatial variation in the TVHSS in Hunan Province is primarily driven by the degree of relief, proximity to medical facilities, educational institutions, and intangible cultural heritage sites. Among these factors, the degree of relief has a significant negative impact on the HSS, and its influence has been increasing over the years. This finding aligns with previous research, Xu et al. (2023) on Yunnan Province, which shares similar geographical features with Hunan, shows that rural settlements are sparse in areas with high relief amplitude, incision depth, and surface roughness due to the harsher natural environment and limited accessibility. These topographic features discourage dense settlement due to difficulties in transportation, infrastructure development, and land use efficiency [66]. Wang et al. (2020) highlights how topography influences plant communities within rural settlements, which indirectly affects human habitation through changes in local ecology [67]; Distance from medical facilities has an increasingly positive impact on the HSS year by year. This is likely due to broader trends in health infrastructure development, enhanced health care and insurance coverage due to urbanization, and focused government initiatives aimed at improving rural health outcomes. Studies have found that the spatial distribution of medical services in certain areas, such as Beijing, is not always aligned with population demands, suggesting that similar patterns might exist in Hunan. Improving access to medical facilities can have a substantial impact on the attractiveness and livability of rural areas [68]; Distance from educational institutions has a nuanced negative impact on the quality of HSS, initially decreasing and then increasing over time. This effect may relate to the methods of distributing educational resources and geographic isolation. Research indicates that centralized educational reforms—such as closing small rural schools and establishing larger schools in urban centers—can enhance the quality of educational resources. However, these

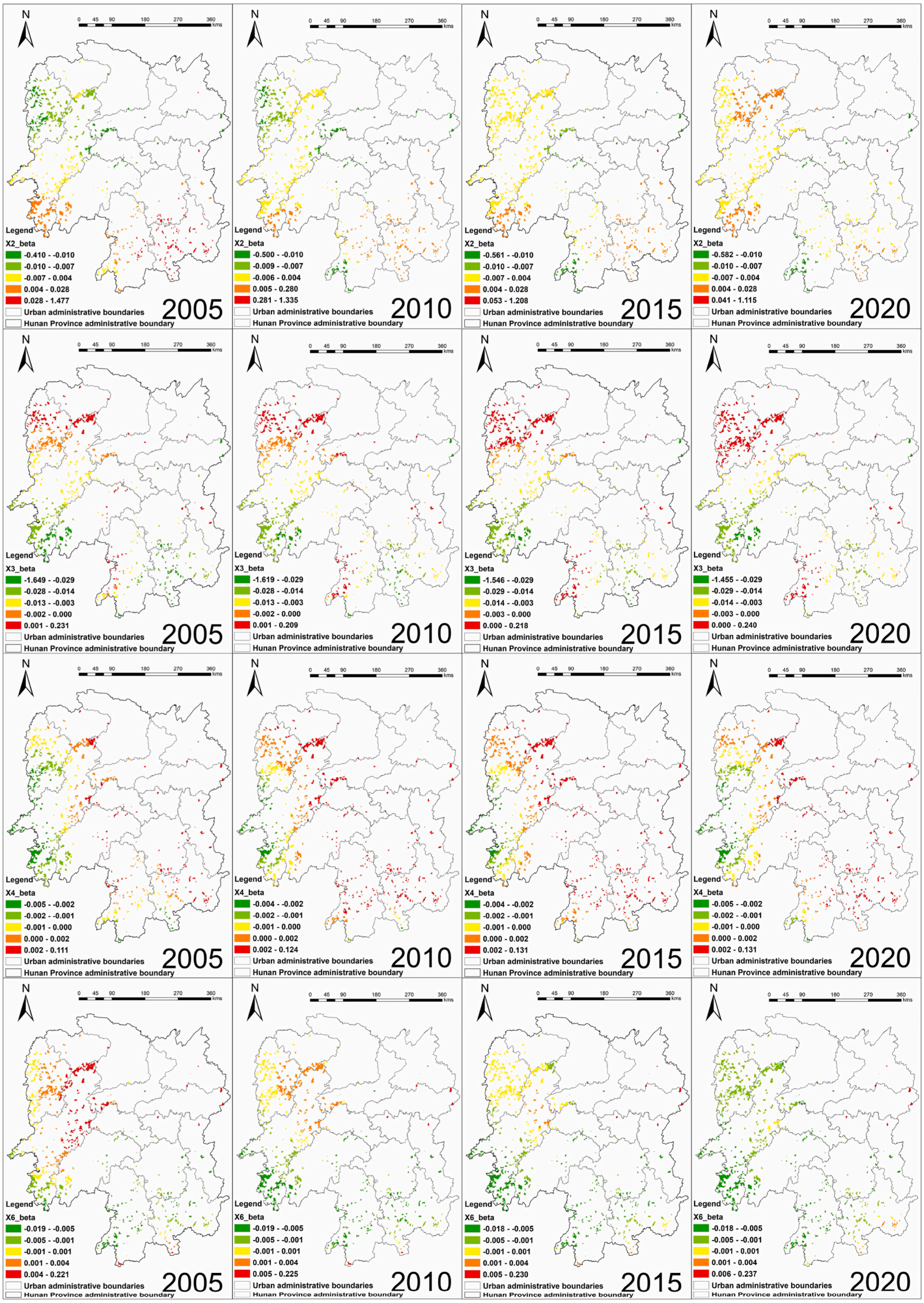

Fig. 9. Results of the spatio-temporal influence of the driving factors on the TVHSS based on the GTWR model. Note: X2 represents Distance from medical facilities, X3 represents Distance from educational institutions, X4 represents Distance from the intangible cultural heritage sites, X6 represents Degree of relief.

reforms also increase the commuting distance for students, adversely affecting the learning opportunities for rural students. Particularly, the increase in both physical and social distances may negatively influence students' social relationships and educational integration. This phenomenon could explain why increased distances impact the quality of TVHSS in Hunan Province [69]; Conversely, Distance from the intangible cultural heritage sites progressively enhances the quality of TVHSS in Hunan Province. The geographic location of cultural heritage sites positively influences local cultural tourism and the preservation of traditional villages. As residents live closer to these heritage sites, their awareness of cultural preservation may strengthen, also attracting more tourism activities. These factors collectively enhance the quality and sustainability of HSS. For instance, Yuan et al. (2022) investigated how integrating cultural tourism can revitalize intangible cultural heritage. Using GIS spatial technology, they analyzed the spatial aggregation of intangible cultural heritage resources in Hunan Province and studied the interrelationship between tourism and intangible cultural heritage. Their findings demonstrate how tourist attractions can promote the development of intangible cultural heritage resources, and how integrating tourism with cultural heritage can rejuvenate intangible cultural heritage. This not only helps maintain cultural diversity and continuity but also indirectly improves the quality of local HS by enhancing the area's tourist appeal [70].

Based on the results of spatiotemporal differentiation, it can be observed that the impact of distance from medical facilities on the TVHSS in Xiangxi Autonomous Prefecture has gradually intensified and shifted from negative to positive. With the improvement of regional health infrastructure and medical services, the negative impact associated with villages being far from medical facilities is likely diminishing. Additionally, the longer distances might correlate with quieter surroundings and a higher quality of life, which could explain the shift toward positive impacts. Moreover, as medical technology and transportation improve, even remote villages can access medical services more quickly, reducing the adverse effects of distance. This aligns with existing research; for example, Yin et al. (2018) discussed the spatial accessibility of medical services across different regions in China and the inequality therein, providing a macro-level understanding of the phenomenon [71]. Similarly, the situation in Yongzhou and Chenzhou cities shows that as medical resources increase and are more evenly distributed, the convenience of accessing medical services for village residents improves regardless of their proximity to these facilities. Hence, the impact of distance to medical facilities on the HSS has decreased. Jin et al. (2015) analyzed the spatial inequalities in urban and rural medical services through a county-level case study, which aids in understanding the conditions in Yongzhou and Chenzhou cities [72]; Secondly, the spatial distribution of educational resources has a clear geographical disparity in relation to the quality of the TVHSS. In the south-central area of Xiangxi, the impact of distance from educational institutions on the HS has shifted from negative to positive, likely due to the strengthening and better integration of educational resources in the region. As educational resources increase, they may bring more employment opportunities, improved community services, and infrastructure development, which collectively enhance the HSS's quality. The sustained negative impact of distance from educational institutions on the TVHSS in Yiyang may relate to the over-concentration and uneven distribution of educational resources. Greater distances to educational facilities could lead to decreased community vitality and the loss of young talents, thus negatively affecting the HSS. For instance, Zhao and Barakat (2015) studied the reorganization of rural schools in China, noting that the centralization of educational resources could increase travel distances for students, impacting families and students alike. This situation may be similar in the Yiyang area, where the concentration of educational resources has led to a scarcity in some regions [69]; Thirdly, the north-central area of Xiangxi is notably affected by the spatiotemporal impacts of distance from intangible cultural heritage sites. These changes may be directly related to regional cultural preservation, tourism development, and community engagement. For example, research by Li et al. (2023) highlighted significant regional differences in the spatial distribution characteristics and influencing factors of traditional villages in Hunan Province, where cultural factors often correlate positively with the spatial distribution of traditional villages [73]. Furthermore, the integration of cultural tourism not only enhances the awareness of cultural heritage protection but also promotes regional economic and cultural development through the coupling of cultural heritage and tourism resources, as shown in the studies by Yuan et al. (2022) in Hunan Province [70]. Lastly, in areas such as Xiangxi, Huaihua, and Yiyang in Hunan Province, TVHSS are negatively impacted by the degree of relief, which is closely related to the influence of topography on climate, soil, and water resource distribution. The varying terrain may limit agricultural production spaces and increase the accessibility costs for transportation and services, thereby affecting the quality of life and socio-economic development of the residents. In these regions, the complex and variable terrain not only restricts infrastructure development and economic activities but may also increase the risk of natural disasters such as landslides and floods, further deteriorating the HSS. For instance, Chen et al.,. (2007) analyzed the impact of topography on landscape-level net primary productivity using coupled terrestrial carbon and hydrological models, finding significant effects of topography on climate variables distribution and groundwater flow, which indirectly affect ecosystem productivity [74].

4.3. Analysis of responses

Based on the results of the impact analyses and taking into account the influence of external factors, this investigation highlights that the degree of relief is the predominant constraining factor. Additionally, the social environment emerges as a critical element in further enhancing the TVHSS. Therefore, terrain preservation and restoration, as well as the rational utilization of social environmental resources, emerge as pivotal points for advancing the construction of TVHSS. Therefore, the government should prioritize the following strategies in the future Firstly, the government should carry out terrain restoration work and rehabilitate damaged terrain and landscapes. Policies should also be formulated to encourage the preservation of natural landforms such as mountains, hills, rivers and lakes. Secondly, the government should strategically plan the placement and design of infrastructure, roads and bridges according to the characteristics of the level of mitigation. It should be able to ensure that villages have easy access to the interior and smooth connections to the exterior. Thirdly, the government should develop and improve health care facilities. The government should also recruit and train medical professionals to ensure that traditional villages and their surrounding areas have adequate healthcare facilities. Invest in schools and educational facilities to provide comprehensive educational opportunities, ensuring high-quality educational resources for traditional villages and their surrounding areas. Fourthly, the government should create foundations for the protection of intangible cultural heritage. They can provide venues and resources for the preservation, transmission and display of the intangible cultural heritage of traditional villages. Fifthly, the government should guarantee an equitable distribution of social resources. The development needs of traditional villages and their neighborhoods should be met. These strategies aim to provide healthcare resources, develop educational resources, protect and inherit intangible cultural heritage, support community involvement, and promote fair distribution and sustainable development. These strategies provide valuable guidance and references for decision-makers, governments, and scholars in improving the TVHSS.

Furthermore, based on the impulse response and variance decomposition analysis results from the VAR model, the development of the pressure system is a key driving force in the construction of the HS. It exerts a strong influence on the status system and the response system. Therefore, mitigating the impact of the pressure system is crucial for ensuring the sustainability and stability of TVHSS construction. Combining previous research findings, this study identifies that the greenhouse effect exacerbates climate change, affecting the climate comfort of traditional villages. Air pollution is a severe problem, posing risks to residents' health and HS. Population growth subjects' traditional villages to challenges such as urban expansion and land resource pressures. Therefore, this research should adopt measures such as reducing greenhouse gas emissions, improving air quality, implementing population management, strengthening environmental awareness, protecting the ecological environment, and providing policy support and enhancing international cooperation. These strategies will help improve the quality of the TVHSS and achieve its sustainable development. However, further research and practical exploration are necessary to better address these challenges in practical implementation.

5. Conclusion

The main conclusions of this study are as follows. First, the comprehensive index of the TVHSS in Hunan Province from 2005 to 2020 was generally high, showing a general upward trend and obvious development momentum. The average value increased from 0.522 to 0.777. However, there was a slowdown in development in 2015. Spatially, it exhibited an upward-sloping distribution pattern, characterized by low in the northwest, moderate in the central region, and high in the southeast. Secondly, the state system is the main driver affecting changes in the response system and is the primary factor influencing changes in the pressure system. Changes in the state system are mainly influenced by the impacts of the pressure system. Thirdly, Distance from medical facilities, Distance from educational institutions, Distance from the intangible cultural heritage sites, and Degree of relief are the four most important driving factors affecting the TVHSS in Hunan Province. At the same time, Distance to medical facilities and Distance to intangible cultural heritage sites have a positive impact, while Distance to educational institutions and Degree of relief have a negative impact. Fourly, these four factors have a significant spatiotemporal impact on the TVHSS in the Xiangxi region. Examining the TVHSS can help achieve cultural, economic, and environmental sustainability, balancing the relationship between preservation and utilization. This research can promote the sustainable transformation and development of traditional villages. The findings of this study have implications for the conservation and sustainable development of traditional villages in other regions. Researchers and practitioners can refer to the research methods and analytical framework used in this study for their own historical village studies and practices, thereby enhancing the level of protection and sustainable development capabilities of traditional villages.

This study has the following limitations. Firstly, this study considered several independent variables in the GTWR model. It includes distance from educational institutions, distance from the intangible cultural heritage sites, distance from water, and degree of relief, etc. However, there are many other factors that may influence the TVHSS, such as climate factors, agricultural activities, land use, and more. Future research could consider incorporating more relevant factors to gain a more comprehensive understanding of the drivers of HS differentiation. Second, this study primarily focused on four time points: 2005, 2010, 2015, and 2020, to observe changes in influencing factors. However, for a better understanding of long-term trends and sustainable development, data with a longer time span might be more valuable. Future research could consider extending the time span to better capture the long-term evolution of TVHSS. Third, this study focuses primarily on Hunan Province as a whole. However, Hunan Province is a region rich in geographical and cultural diversity, with significant variations between different regions. Future research could conduct more detailed analyses, considering the characteristics of different regions to provide more specific policy recommendations.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Availability of data

The data will be provided upon request.

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CRediT authorship contribution statement

Tianxiang Long: Writing – original draft, Software, Methodology, Formal analysis. **Cem Işık:** Software, Methodology, Conceptualization. **Jiale Yan:** Validation, Resources, Data curation. **Qikang Zhong:** Writing – review & editing, Visualization.

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.

Abbreviations

HS	human settlement
RHS	rural human settlement
HSS	human settlement suitability
TVHSS	traditional villages human settlement suitability

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