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Adaptation of Chinese traditional villages from the perspective of locality preservation

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Abstract

Recently, traditional villages in China have received multiple policy protections and capital injections. While these external interventions protect the cultural heritage of traditional villages and provide opportunities for development, they have gradually eroded their intrinsic adaptive cycle system. This study focused on 6819 traditional villages, revealed the characteristics and transitions of the adaptive cycle stages in traditional villages and described the internal mechanisms of adaptability within these villages. The research findings are as follows: Regarding adaptability characterisation, the adaptability of traditional villages has developed a regionally significant imbalance. The highest proportion of adaptability cycle stages was found in the poverty trap, exploration (r) and gambling traps. Traditional villages are mostly in a rigid state, with a few adaptive processes shifting between the poverty trap and exploration (r), requiring a new impetus to guide positive cycles. In terms of adaptability mechanisms, there was a significant negative relationship between locality, mobility and resilience in traditional villages. Intrinsic adaptive mechanisms gradually disintegrate, and there is an increasing risk of falling into a lock-in trap. This study provides empirical evidence for analysing the issues in traditional villages and offers recommendations for long-term planning and policy formulation of locality protection in traditional villages.

Keywords

Adaptability, Locality, Mobility, Resilience, Traditional village

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Introduction

Human settlements established in specific natural environments continuously gain impetus for development, forming communities in which humans coexist harmoniously with nature.[1] These settlements, influenced by human activities such as war and trade as well as natural disruptions such as floods and epidemics, have developed intrinsic adaptability. Some have persisted to this day and are now officially recognised as traditional villages worthy of preservation. Adaptability in this context can be understood as a process of self-organisation and response to environmental changes by the system.[2] Over the course of a long-term adaptive process, these traditional villages have become crucial sites for the birth and evolution of human civilisation,[3] serving as core zones for agricultural production.[4] They also function as living museums of architecture, craftsmanship, language and local customs,[5] embodying rich wisdom in human habitation.[6]

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However, owing to differences in preservation and development capabilities, there is a significant variation in the adaptability of these traditional villages.[7] As traditional Chinese villages gradually integrate into globalised and modernised urban–rural networks, some traditional villages face maladaptation crises. Many traditional villages exhibit human-induced fragmentation and natural damage, with inadequate infrastructure, poor environmental hygiene and serious issues related to rubbish and wastewater.[8] Some conservation measures have resulted in the deterioration of village appearance and historical information has become lost.[9] Some old villages gradually become uninhabited as young people migrate for work and housing, leading to the abandonment and collapse of many traditional buildings due to a lack of maintenance.[10] Concurrently, traditional villages, constrained by their geographical environment and long-term environmental changes, face severe challenges, such as resource constraints and environmental adaptation.[11] Adaptability is a long-term issue for the sustainable development of human settlements, and the adaptability patterns of traditional villages need to be explored urgently to address the phenomenon of villages deviating from order and patterns in their development.

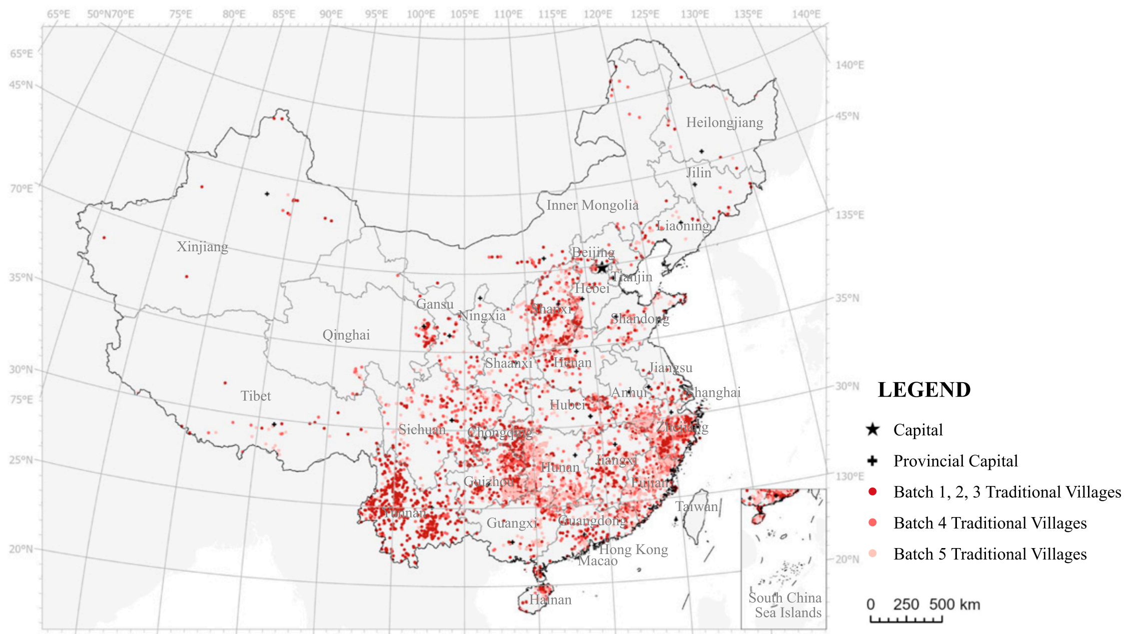
Current research on the adaptability of traditional villages mainly focuses on characterisation and assessment analysis based on village case studies. This includes evaluating the sustainability of traditional villages as tourist destinations,[12] examining sunken architectural courtyard spaces generated by traditional villages in adapting to their environments,[13] and studying agricultural production and economic development in traditional villages under climate change conditions.[14] In terms of adaptation patterns, research on rural adaptability rarely involves the holistic spatial pattern study of traditional villages. There is a particular lack of adaptive evolution dynamic analysis at a macro scale. In the spatial dimension, there should be further consideration on micro or meso scales, especially focusing on small-scale systems such as buildings,[15] communities[16] and village settlements.[17] In terms of adaptive processes, studies on the adaptability of rural regions rely heavily on theoretical and qualitative analyses of individual cases.[17] There is a lack of quantitative methods for depicting a more complete and accurate adaptive process. In terms of adaptive elements, current research primarily analyses 'adaptability' as a passive outcome or an inherent property of the system itself, lacking inductive reasoning about causality and mechanisms. However, the adaptive elements affecting traditional villages are complex and variable, involving not only natural environmental factors such as climate change and disaster risk but also socio-economic factors such as politics, culture and industry.[18] In the context of urbanisation and technological revolution, traditional villages face the dual dilemma of preservation and development. The study of their adaptive patterns from a more macro perspective is necessary, to understand more comprehensive adaptive processes and consider more holistic adaptive elements. This approach would facilitate macro-level regulation and enable precise policy-making at various stages of rural development.

Therefore, this study conducted a quantitative analysis of the adaptability of traditional villages on a national scale in China by integrating multiple factors such as economy, society and culture. This research primarily addressed around two questions: (1) What have been the characteristic patterns of adaptability in traditional villages in China over the past two decades? Are there spatial differences or clustering patterns? (2) What are the operational patterns of adaptability systems in traditional Chinese villages? Based on these questions, this study investigated the current issues and weaknesses in the adaptive development of traditional villages in China. It aimed to provide insights and experiences for traditionally non-adaptive villages and serve as a basis for rural preservation in developing countries undergoing transformation and rapid urbanisation on a global scale.

Research design

Research objects

To reflect the impact of China's protection policies on the adaptability of traditional villages over the past 20 years, this study selected 6819 traditional villages officially recognised by the Chinese government as research objects (Figure 1). These 6819 traditional villages represent stable elements of various built environments under the interaction of natural and human factors and are mainly distributed in regions with developed river networks, suitable temperatures and abundant precipitation. In terms of the time scale, the study chose 2000 to 2020 as the time range and analysed five time cross-sections (2000, 2005, 2010, 2015 and 2020) of the 6819 traditional villages. Since 2002, China has initiated policies targeting the protection and economic development of specific villages and towns. This period marks the most intensive phase of protective intervention for traditional villages. Concurrently, the past two decades have witnessed rapid development in China, with a notable urban–rural divide resulting from the prioritisation of urban development. This has indirectly led to issues such as population loss in traditional villages and significant developmental interference. Over the past two decades, global warming and frequent extreme disasters have become prominent issues worldwide. Traditional villages that rely on natural environments as intrinsic drivers are particularly vulnerable to increasing trends of natural disturbances. Over the past 20 years, traditional villages have faced unprecedented challenges due to a variety of influences, including natural disturbances, human activities, protection and



Area	Full Name of Provinces	Abbreviations of Provinces	Area	Full Name of Provinces	Abbreviations of Provinces
Northeastern China,	Heilongjiang	HL	Southern China	Guangxi	GX
	Jilin	JL		Hainan	HI
	Liaoning	LN		Hong Kong	HK
Northern China	Beijing	BJ		Macao	MO
	Tianjing	TJ	Central China	Henan	HA
	Hebei	HE		Hubei	HB
	Shanxi	SX		Hunan	HN
	Inner Mongolia	NM	Northwestern	Shaanxi	SN
Eastern China	Shanghai	SH		Xinjiang	XJ
	Jiangsu	JS		Ningxia	NX
	Shandong	SD		Gansu	GS
	Zhejiang	ZJ		Qinghai	QH
	Anhui	AH	Southwestern China	Chongqing	CQ
	Jiangxi	JX		Sichuan	SC
	Fujian	FJ		Guizhou	GZ
	Taiwan	TW		Yunnan	YN
Southern China	Guangdong	GD		Tibet	XZ

Figure 1. The geographic distribution of 6819 traditional villages in China.

development, which pose significant challenges to their intrinsic adaptability.

Theoretical framework

Traditional Chinese villages constitute a complex system that has evolved through the long-term adaptive processes of human–nature interaction. They exhibit the following fundamental characteristics.

Locality. Locality refers to the objective characteristics of a location, including its natural qualities and cultural features. This is the result of the coupled adaptation of the artificial and natural environments and is a key factor in urban and rural landscapes used to demonstrate and maintain people's self-identity and local identity.[19] The locality of traditional villages is reflected in various aspects, including the physical spatial characteristics of village buildings and courtyards,[20] the intangible cultural heritage embodied in village religions and customs,[21] and the site selection and layout of the villages.[22] Locality includes not only the features and attributes of a particular place but also embodies the long-term coexistence and adaptation of humans with nature. In this study, architectural courtyards, sacred spaces, traditional customs and landscape patterns were chosen as indicators of locality.

Mobility. Mobility in urban and rural spaces refers to the movement and exchange of human and nonhuman elements.[23] Throughout history, the reasons for mobility in traditional villages have included market transactions, social interactions, disaster avoidance and business activities. The mobility of traditional villages has undergone significant changes in the context of modern adaptation.[24] Enhanced mobility capabilities owing to modern transportation have led to new reasons for mobility amongst villagers, such as education, healthcare and employment. Additionally, external populations visit traditional villages for tourism, scientific research and industrial development. In the rapidly changing context of mobility, the human–land adaptation process in traditional villages is continuously evolving. We selected employment mobility, educational mobility, healthcare mobility, administrative mobility and tourism behaviour as assessment indicators of mobility.

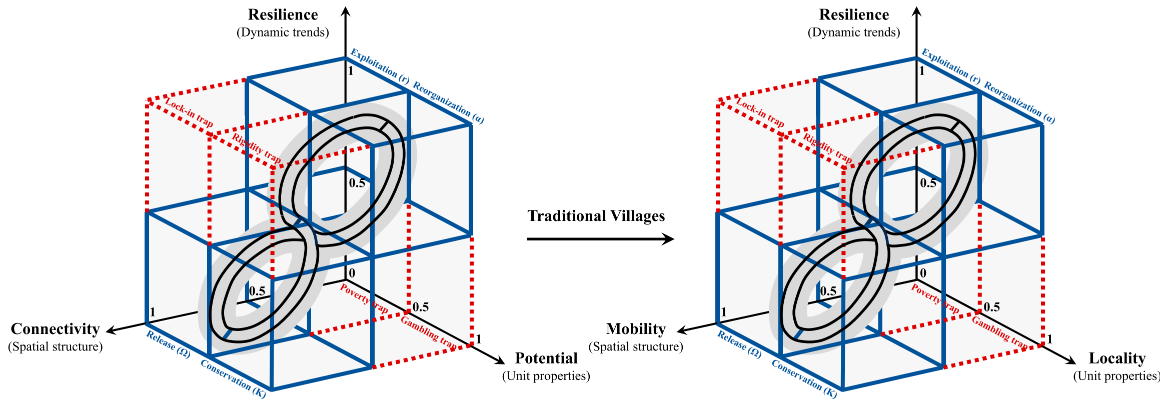
Resilience. Resilience refers to the ability of a system to adapt to external environmental changes, including absorption, adaptation, rapid recovery and learning.[25] Traditional villages, as complex human–land systems, are influenced by multiple dimensions, such as ecology, population and economy, in terms of resilience.[26] In recent years, traditional villages have faced increasingly complex external disturbances, such as deforestation, population loss, soil erosion, reduced land fertility and tourism. These factors have altered the resilience of traditional villages and consequently affected their adaptability. In this study, we chose vegetation coverage, precipitation, river distance, intergenerational transmission, population, production, sunlight exposure, temperature and economy as assessment indicators for resilience. These indicators encompass multiple dimensions, including ecology, population and economy.

Theoretical construction of the adaptive cycle in traditional villages. Holling[27] proposed the Adaptive Cycle Theory, emphasising the dynamic nonequilibrium state, proactive adaptability and transformative capacity of systems. It gradually became the core theory explaining the operating cycles of human–land systems, incorporating three characteristic attributes: potential, connectivity and resilience.[27] Potential encompasses the ecological, economic, social and cultural resources accumulated by a system, including mutations and innovations that determine the range of future possibilities. Connectivity refers to the number and frequency of interactions between various components of a system, indicating the degree to which the system controls its own state. Resilience measures the vulnerability of a system to unexpected or unpredictable disturbances and can be considered a concept related to system fragility. Changes in these three characteristic attributes express the dynamic response mechanisms of the developmental stages of the system during the adaptive cycle under external stimuli. A sustainable and resilient system can continually evolve and cycle through exploration, conservation, release and reorganisation. However, a system may also enter another cycle owing to low resilience, leading to challenges such as poverty, rigidity, lock-in and gambling.

Holling's Adaptive Cycle model[27] was initially developed for application in ecology and addresses a wide range of systems. However, applied to the study of traditional villages, optimisation based on their specific characteristics is required to construct a more precise indicator system for accurate characterisation. The original model faces challenges in village studies as it may lead to fuzzy dimensionality and difficulties in constructing quantitative evaluation indicators. Building on Holling's Adaptive Cycle Theory,[27] this study focuses on the characteristics of the adaptive evolution of traditional villages. It replaces potential with locality, a fitting attribute for the unit properties of traditional villages, replaces connectivity with mobility, which is more aligned with the spatial structure of traditional villages and retains resilience as a dynamic trend. This results in the creation of the 'Locality–Mobility–Resilience' model for the adaptability of traditional villages,[28] as illustrated in Figure 2. The adaptability of traditional villages is jointly determined by high or low values of locality, mobility and resilience, encompassing eight adaptability stages as outlined in Figure 2.[29]

Data processing

Point data for the traditional villages used in this study were obtained from the Global Change Science Data Publishing System (https://www.resdc.cn/). The spatial coordinates of data were extracted with reference to Baidu Maps and Google Earth imagery based on village name prompts and the geometric centre of the village shapes. The extraction was complemented by roof imagery of traditional buildings to assist in judging the material and ensure the accuracy of the spatial location of the villages. The data included traditional villages from five batches, totalling 6819 entries. This study utilised the ArcGIS platform to geometrically rectify different geographic data based on the World Geodetic System 1984, ensuring precise alignment to a spatially unified reference coordinate system. These serve as foundational data for studying the adaptability of traditional villages. Based on this, we



Adaptive cycle stages		Locality	Mobility	Resilience
Cycle stages	Exploration (r)	Low	Low	High
	Conservation (K)	High	High	Low
	Release (Ω)	Low	High	Low
	Reorganization (α)	High	Low	High
Pathological stages	Poverty trap	Low	Low	Low
	Rigidity trap	High	High	High
	Lock-in trap	Low	High	High
	Gambling trap	High	Low	Low

Figure 2. The analytical framework for this study (modified based on Wang et al.[28]).

constructed an indicator system for the adaptability of traditional villages with the specific indicator data sources outlined in Table 1.

Methods

Entropy method

To obtain the weights of the indicators for locality, mobility and resilience, this study used the entropy method for objective weighting. The smaller the information entropy, the greater the importance of the indicator in a comprehensive evaluation and, consequently, the greater the weight. Equations (1)–(4) are the formulas used:

$$X_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{1}$$

$$e_j = -\sum_{i=1}^{m} \frac{X_{ij} \times \ln X_{ij}}{\ln m \left(0 \le e_j \le 1\right)} \tag{2}$$

$$d_j = 1 - e_j \tag{3}$$

$$W_j = \frac{d_j}{\sum_{i=1}^{n} d_j} \tag{4}$$

In the formula, X_{ij} represents the weight of the j^{th} indicator in the i^{th} village, x_{ij} is the standardised indicator value, e_j is the entropy of the indicator, d_j is the information redundancy, W_j is the indicator weight, and i represents the number of research areas (i = 1,2,…,6819), while n is the number of indicators.

Global spatial autocorrelation

To assess the geographical spatial clustering patterns of locality, mobility, resilience and adaptability amongst the 6819 traditional villages, this study used both global and local spatial autocorrelation for spatial analysis. In this study, global autocorrelation was utilised to describe the overall distribution using the Moran Index, calculated by equation (5):

$$I = \frac{n \times \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - x) \times \left(x_j - x\right)}{\left(\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}\right) \times \sum_{i=1}^{n} (x_i - x)^2}, i \neq j \tag{5}$$

Table 1. The comprehensive indicator system for the adaptability of traditional villages in China.

Criterion	Indicator	Data	Data resource
Locality	Architectural courtyards	Distance to the nearest cultural heritage protection unit	8 batches of China's key cultural heritage protection units, State Administration of Cultural Heritage
	Sacred spaces	Distance to the nearest sacred space	2021 POI data for temples, ancestral halls, and other sacred spaces, Amap (https://lbs.amap.com)
	Traditional customs	Distance to intangible cultural heritage	5 batches of national-level intangible cultural heritage projects, State Council
	Landscape pattern	Terrain undulation	China's elevation data (DEM) spatial distribution, Shuttle Radar Topography Mission (SRTM)
Mobility	Employment mobility 1 (adjacent counties and towns)	Distance to the nearest road	Road and railway data for the years 2000, 2009, 2016, and 2020, Peking University Geographic Data Platform (https://geodata.pku.edu.cn) and OpenStreetMap (https://www.openstreetmap.org)
	Employment mobility 2 (distant cities)	Distance to the nearest train station	2021 POI data for train stations, Amap (https://lbs.amap.com)
	Educational mobility	Distance to the nearest school	2021 POI data for schools, Amap (https://lbs.amap.com)
	Medical mobility	Distance to the nearest medical facility	2021 POI data for medical services, Amap (https://lbs.amap.com)
	Administrative mobility	Distance to the nearest government	2021 POI data for city and county government offices, Amap (https://lbs.amap.com)
	Tourism behaviour	Distance to the nearest A-level scenic area	2021 POI data for A-level scenic areas, Amap (https://lbs.amap.com)
Resilience	Vegetation coverage	NPP change trend	NPP (Net Primary Productivity) grid data (500 m) for the years 2000, 2005, 2010, 2015, 2020, MODIS (https://lpdaac.usgs.gov/)
	Precipitation	Amount of precipitation	Precipitation grid data (1 km) for the years 2001, 2005, 2010, 2015, 2020, National Earth System Science Data Centre (https://www.geodata.cn)
	Distance to rivers	Distance to the river system	China's basin and river network dataset, Chinese Academy of Sciences Resource and Environmental Science and Data Centre (https://www.resdc.cn/data.aspx?DATAID=335)
	Intergenerational inheritance	Distance to the location of intangible cultural heritage inheritors	5 batches of inheritors of national-level intangible cultural heritage projects, State Council
	Population	Population density	China's population distribution kilometre grid data (1 km), Chinese Academy of Sciences Resource and Environmental Science and Data Centre (https://www.resdc.cn/data.aspx?DATAID=335)
	Production	Replanting of cultivated land	CropWatch team of the Aerospace Information Research Institute of the Chinese Academy of Sciences (30m) [30]
	Sunshine duration	Solar radiation	Solar radiation grid data (1 km) for the years 2000, 2005, 2010, 2015, 2018, China Meteorological Data Network
	Temperature	Temperature	Temperature data for the years 2000, 2005, 2010, 2015, 2020, China Ground Climate Data Daily Value Dataset V3.0
	Economy	Per capita GDP of prefecture-level cities	Per capita GDP of prefecture-level cities for the years 2000, 2005, 2010, 2015, 2019, 'China Urban Statistical Yearbook', 'China Urban Construction Statistical Yearbook', 'China Statistical Yearbook', 'China Urban Economic Yearbook'

In the formula, n represents the number of traditional village samples studied; w_{ij} is the spatial weight coefficient between regions i and j. In this study, w_{ij} is generated using the inverse distance method to create a spatial weight file; x_i corresponds to the numerical values of locality, mobility, resilience and adaptability in traditional villages; x represents the average numerical values of locality, mobility, resilience and adaptability in all traditional villages within the study area. Moran's I index takes values between −1 and 1.

The Z_I score for the global Moran's I statistic is calculated using equation (6):

$$Z_I = \frac{I - \left(\frac{-1}{n-1}\right)}{\sqrt{\left(E\left[I^2\right] - E[I]^2\right)}} \tag{6}$$

When analysing the locality, mobility, resilience and adaptability of the 6819 traditional villages in China based on ArcGIS spatial autocorrelation, the significance of this index was evaluated by calculating Moran's I index value, z-score and p-value. If the p-value did not reach statistical significance, the spatial distributions of locality, mobility, resilience and adaptability were considered random. If the p-value was statistically significant and the z-score was positive, the spatial clustering of high or low values of locality, mobility, resilience and adaptability was higher than expected. If the z-score was negative, the spatial distributions of the high and low values of locality, mobility, resilience and adaptability were more dispersed than expected.

Local spatial autocorrelation

To identify the spatial clustering patterns of high or low levels of locality, mobility, resilience and adaptability amongst traditional villages, the Local Moran's I index was used. The formulas for Local Moran's I are shown in equations (7)–(9):

$$I_i = \frac{x_i - x}{\frac{\sum_{j=1, j\neq i}^{n}\left(x_j - x\right)^2}{n-1} - x^2} \sum_{j=1, j\neq i}^{n} W_{i,j}\left(x_j - x\right) \tag{7}$$

$$Z_{Ii} = \frac{I_i - E[I_i]}{\sqrt{E\left[I_i^2\right] - E[I]^2}} \tag{8}$$

$$E[I_i] = -\frac{\sum_{j=1, j\neq i}^{n} W_{i,j}}{n-1} \tag{9}$$

In the equations, x_i and x_j, respectively, represent the observed values of a phenomenon in spatial units i and j; other symbols are the same as those in global autocorrelation. A positive value of I indicates that features with similarly high or low attribute values are found amongst neighbouring features, and the feature is a part of a cluster. A negative value of I indicates that features with different values are found amongst neighbouring features, and the feature is an outlier.

Geographically weighted regression

This study uses a geographically weighted regression (GWR) model as shown in equation (10) to analyse the adaptive mechanisms between mobility, locality and resilience in traditional villages.

$$y_i = \beta_0(\mu_i, v_i) + \sum_{j=1}^{k} \beta_j(\mu_i, v_i) x_{ij} + \varepsilon_i \tag{10}$$

In the equation, y_i represents the mobility, locality and resilience values of the i th sample point; (μ_i, v_i) are the spatial geographic coordinates of the i th sample point; $\beta_j(\mu_i, v_i)$ is the j th regression parameter at the i th sample point; x_{ij} is the influencing factor (control variable) and ε_i is the random error term.

Result and discussion

Adaptability characterisation of traditional villages

Spatiotemporal locality characteristics. Based on the evaluation system of adaptability indicators for traditional villages constructed in this study, the weights calculated using the entropy method comprehensively calculated the locality of traditional villages, as shown in Figure 3(a). Overall, the spatial differentiation of traditional village locality is significant, with a notable clustering effect and stable pattern changes. The locality attribute values in the Southwestern and Northwestern China were the highest, followed by those of HA, SX, ZJ and FJ. The locality of the other regions was significantly lower than that of the above regions, proving that locality exhibits clear spatial heterogeneity on the macro scale. In terms of temporal evolution, the overall locality changes were weak, and the high- and low-value regions had already developed stable patterns. The median and mean values did not change within 5 years (Table 2). This indicates that as an inherent driving force of traditional villages, locality has entered a mature and stable stage in the past 20 years. The locality macro pattern of 'high in the west and low in the east' is gradually solidifying, and localities in certain areas are stagnant and urgently need external vitality injection.

We conducted a global spatial autocorrelation analysis of the 6819 traditional village locality and presented the results using descriptive statistics and spatial visualisation. Table 3 shows that over the past 20 years, Global Moran's I for the locality in traditional Chinese villages has been consistently positive and passed the significance test ($p < 0.001$), indicating a positive spatial correlation and significant global spatial clustering characteristics of the locality in traditional Chinese villages. Moran's I index values for locality from 2000 to 2020 did not show significant fluctuations, indicating a stable trend in spatial clustering. Figure 4(a) illustrates the spatial distribution characteristics of local spatial autocorrelation results for traditional villages. For the locality, the various clustering results for each 5-year period remained consistent, indicating that the spatial clustering relationships of the locality remained relatively stable over the 20-year period. Amongst the samples, 19% belonged to the HH cluster, which was mainly distributed in Southwestern and Northwestern China; 49% belonged to the LL cluster, representing the largest proportion, and were distributed in Northeastern, Northern, Eastern, Northwestern and Central China; 12% belonged to the HL cluster; and 3% belonged to the LH cluster, representing localised high- and low-value heterogeneous areas of the locality.

Spatiotemporal mobility characteristics. Overall, the spatial differentiation of mobility in traditional villages is not significant, the clustering effect is not clear and the degree of pattern change is moderate (Figure 3(b)). In 2000, there was a significant polarisation in mobility, which may be due to some traditional villages historically serving as key nodes for land and water transportation. Naturally, these villages have conditions conducive to higher mobility. Other traditional villages that have been preserved are located in remote areas with abundant natural resources but limited access to transportation facilities. However, by 2020, a gradient change in mobility is evident, with some villages with lower mobility gradually gaining access to national transportation networks. Villages with higher mobility were relatively evenly distributed nationwide, with little significant change from 2000 to 2020, indicating that villages that originally held a mobility advantage maintained relatively stable mobility. Over the 20 years of transportation development, the overall mobility has increased, with the median value rising from 0.001 to 0.002 and the mean value increasing from 0.004 to 0.005 (Table 2), indicating a gradual reduction in villages with low mobility and a significant increase in villages with median mobility. Additionally, the uniform distribution in 2000 was gradually disrupted, with a clustering trend emerging in the southern provinces and small clusters gradually appearing in SX, SN and HA provinces. With urbanisation, the growth trend of mobility in traditional villages at the national scale is not uniform, leading to regional disparities.

Table 3 shows that over the past 20 years, Global Moran's I for mobility in traditional Chinese villages has been consistently positive and passed the significance test ($p < 0.001$). However, because of the small Moran's I index, the values for each 5-year period are approximately 0.06, indicating that mobility in traditional Chinese villages exhibits a positive spatial correlation; however, this positive influence is very weak. Despite a significant improvement in the overall accessibility in the context of transportation infrastructure development, there was no apparent clustering trend. This may be because the overall improvement in traditional villages is relatively uniform, without clear winners or losers. However, it is possible that infrastructure construction has not radiated to traditional villages, thus failing to directly increase their mobility. Consequently, traditional villages exhibit relatively low overall accessibility, which prevents the emergence of clustering relationships. The fit of the local spatial autocorrelation is not high, indicating that while mobility exhibits a global correlation, the explanatory power of local clustering relationships is not significant.

Spatiotemporal resilience characteristics. In 2000, resilience was concentrated at only a few high-value points in the GD, FJ and ZJ provinces (Figure 3(c)), decreasing from southeast to northwest; however, the difference was not significant, indicating that there was little geographical difference in the resilience of traditional villages in 2000. Overall resilience significantly increased over time. As shown in Table 2, the median resilience was increased from 0.030 to 0.044, and the mean was increased from 0.031 to 0.046, indicating that the cultural and economic resources of traditional villages have gradually developed over the past 20 years, strengthening their overall resilience. However, this strengthening trend gradually shows geographical differences, with a significant decrease from southeast to northwest. The regions with the highest values were concentrated in Eastern and Southern China, indicating a significant improvement in the overall economic, population and ecological benefits of the traditional villages in these areas. In contrast, resilience in Northwestern China has not changed significantly in the last 20 years. This may be because they retain traditional endogenous production and lifestyles. Alternatively, this may be because the positive benefits brought about by village development, such as economic improvement, are offset by negative effects, such as ecological threats and population loss.

Table 3 shows that over the past 20 years, the Global Moran's I of resilience in traditional villages in China has been positive and passed a significance test ($p < 0.001$), indicating a positive spatial correlation and significant global spatial clustering characteristics of resilience in traditional villages in China. From 2000 to 2020, the values of Moran's I for resilience were significantly increased from 0.354962 in 2000 to 0.458737 in 2020, an increase of approximately 10%. This indicates that the clustering effect of resilience in traditional villages has become more apparent over time, and that spatial clustering shows an increasing trend. Figure 4(b) shows that the clustering results of the five categories of traditional village resilience became

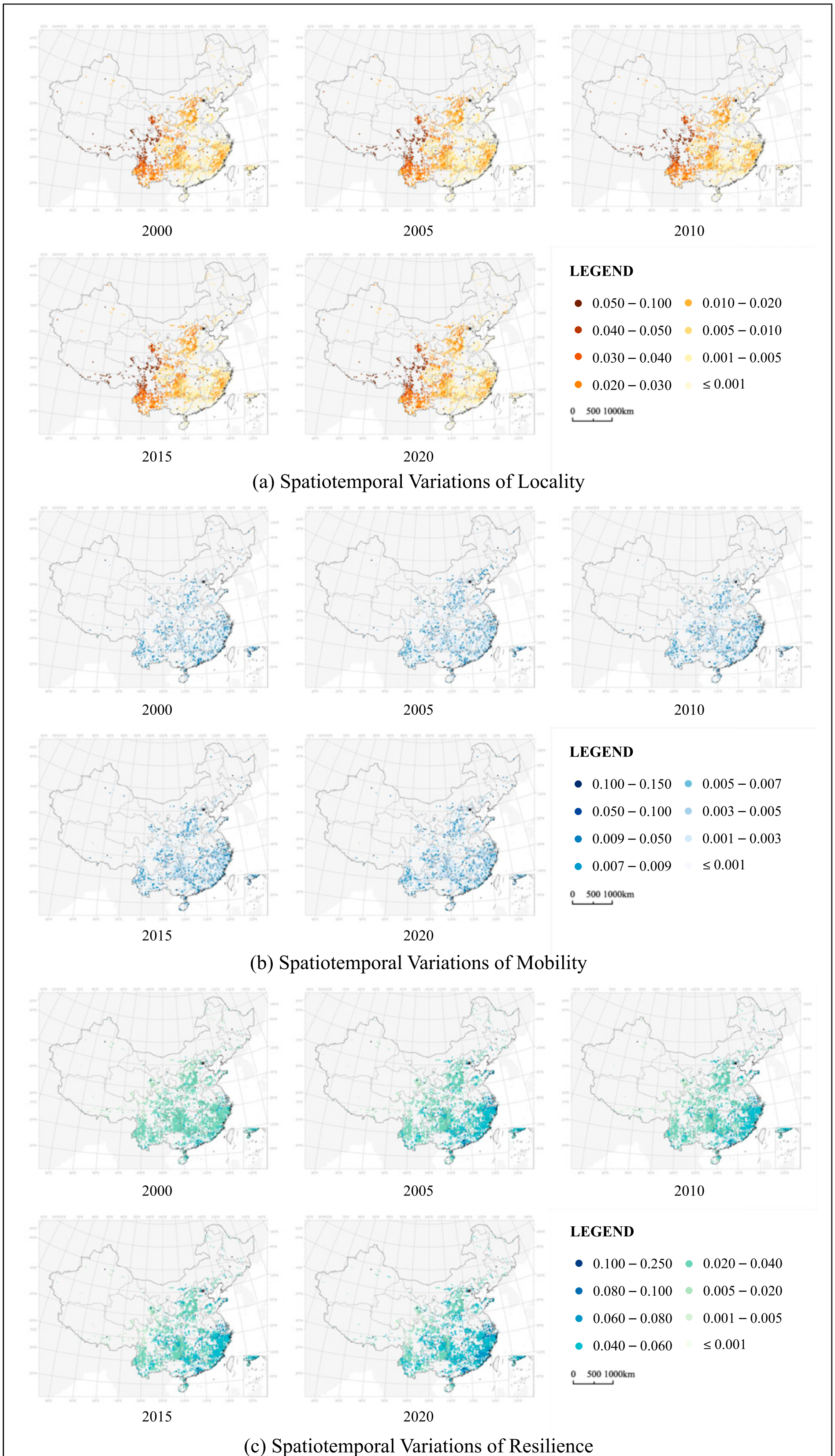


Figure 3. Spatiotemporal variations in locality, mobility and resilience.

Table 2. Descriptive statistics of locality, mobility and resilience in traditional villages.

	Year	Mean ± SD	Var.	25th Pct.	Med.	75th Pct.	SE	Mean 95% CI(*LL*)	Mean 95% CI(*UL*)
Locality	2000	0.013 ± 0.013	0.000	0.004	0.009	0.019	0.000	0.013	0.013
	2005	0.013 ± 0.013	0.000	0.004	0.009	0.019	0.000	0.013	0.013
	2010	0.013 ± 0.013	0.000	0.004	0.009	0.019	0.000	0.013	0.014
	2015	0.013 ± 0.013	0.000	0.004	0.009	0.019	0.000	0.013	0.014
	2020	0.013 ± 0.013	0.000	0.004	0.009	0.019	0.000	0.013	0.014
Mobility	2000	0.004 ± 0.008	0.000	0.001	0.001	0.004	0.000	0.004	0.004
	2005	0.005 ± 0.008	0.000	0.001	0.002	0.004	0.000	0.004	0.005
	2010	0.005 ± 0.008	0.000	0.001	0.002	0.004	0.000	0.004	0.005
	2015	0.005 ± 0.009	0.000	0.002	0.003	0.005	0.000	0.005	0.006
	2020	0.005 ± 0.008	0.000	0.001	0.002	0.005	0.000	0.005	0.005
Resilience	2000	0.031 ± 0.010	0.000	0.026	0.030	0.035	0.000	0.031	0.031
	2005	0.040 ± 0.013	0.000	0.032	0.038	0.046	0.000	0.040	0.040
	2010	0.037 ± 0.012	0.000	0.030	0.036	0.043	0.000	0.037	0.038
	2015	0.040 ± 0.013	0.000	0.032	0.039	0.048	0.000	0.039	0.040
	2020	0.045 ± 0.015	0.000	0.034	0.044	0.054	0.000	0.045	0.046

Table 3. Descriptive statistics of the global spatial autocorrelation results for the traditional villages.

	Year	Global Moran's I	Z-score	*p*-value
Locality	2000	0.586558	228.195820	<0.001
	2005	0.588122	228.801980	<0.001
	2010	0.582468	226.601320	<0.001
	2015	0.582080	226.450380	<0.001
	2020	0.582100	226.458100	<0.001
Mobility	2000	0.064666	25.309094	<0.001
	2005	0.066321	25.952937	<0.001
	2010	0.066803	26.139340	<0.001
	2015	0.066522	26.019710	<0.001
	2020	0.066381	25.968244	<0.001
Resilience	2000	0.354962	138.907270	<0.001
	2005	0.419473	163.533110	<0.001
	2010	0.418920	163.485780	<0.001
	2015	0.436700	170.231440	<0.001
	2020	0.458737	178.655100	<0.001

more evident over time. HH clusters were mainly distributed in Eastern and Southern China, and the proportion of traditional villages in HH clusters was decreased from 21% in 2000 to 9% in 2020, indicating a reduction in the spatial extent of high-value clustering. The LL clusters were mainly distributed in the Northeastern, Northern, Northwestern and Southwestern China. The proportion of traditional villages in LL clusters was gradually increased from 29% in 2000 to 45% in 2020, indicating an increasing spatial extent of low-value clustering. The proportion of non-significant clusters was decreased from 38% in 2000 to 30% in 2020, indicating a significant annual trend in resilience clustering in traditional villages.

Spatiotemporal characteristics and cyclic patterns of adaptability. As shown in Figure 5, the distribution of the eight adaptive states exhibited some spatial differentiation, with more villages in a cycle stage located in the Eastern and Southern China, whereas relatively more villages in a pathological state were distributed in the Northeastern, Northern, Central, Northwestern and Southwestern China. From 2000 to 2020, there was no significant change in the spatial distribution of the eight adaptive states, indicating that the adaptive states of traditional villages have developed a strong geographical differentiation pattern, which appeared relatively stable over time. Traditional villages in regions with relatively better economic development have more opportunities and channels to enter the cycle stage, whereas economically underdeveloped areas are more likely to solidify into a pathological state.

Figure 5(a) depicts the spatiotemporal distribution of the cycle stages, with the main states being the exploitation (r) and reorganisation (α) stages. The exploitation (r) stage is primarily distributed in Eastern China, indicating that

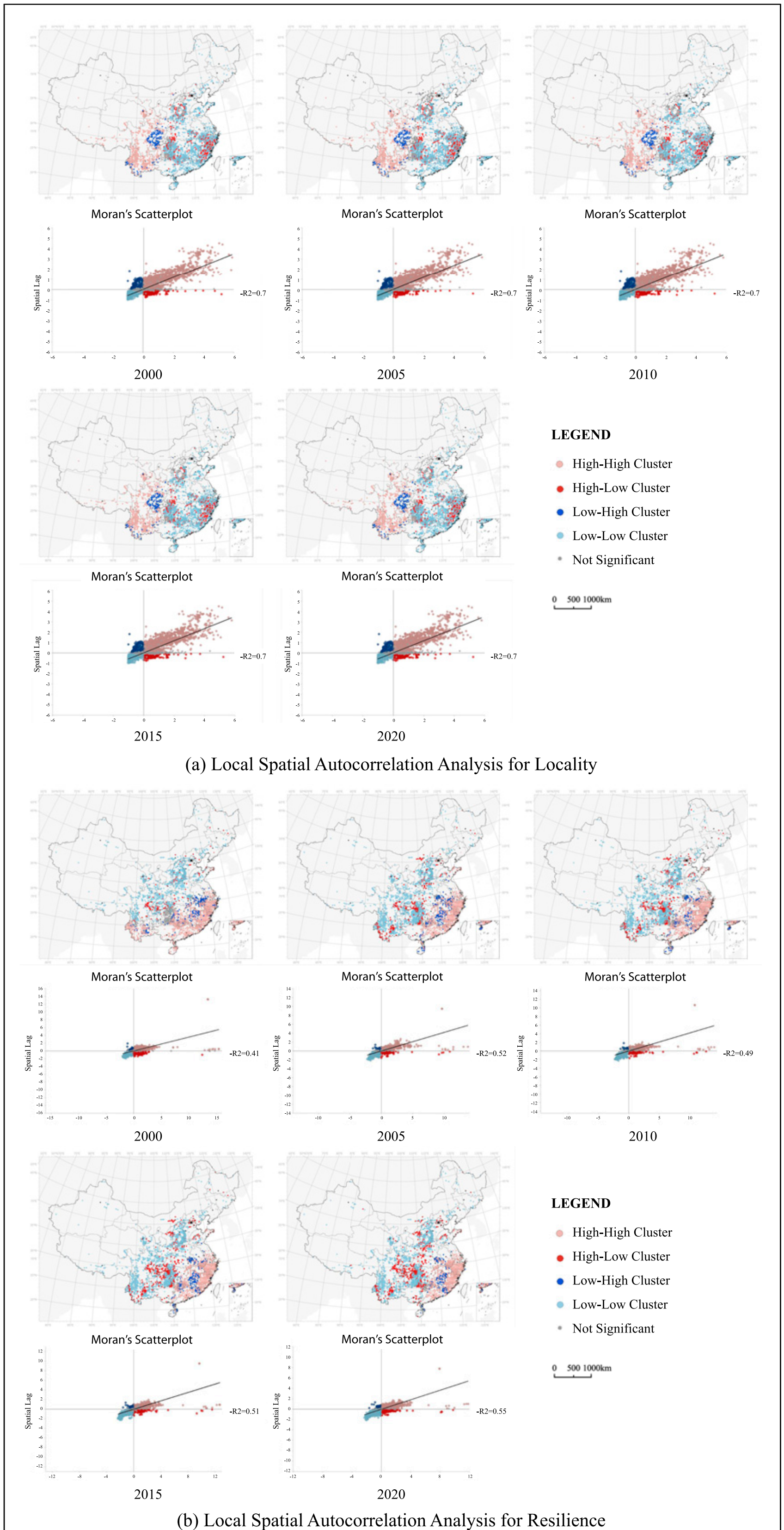


Figure 4. Local spatial autocorrelation analysis for locality and resilience.

traditional villages in this region are undergoing a period of rapid development under policy protection and capital injection. The reorganisation (α) stage is mainly distributed in YN, ZJ and FJ, indicating that traditional villages in these three provinces have passed the stage of rapid development and entered an unstable phase of reorganisation or innovation after development overload. Conservation (K) and release (Ω) are randomly distributed across the entire region. Figure 5(b) illustrates the spatiotemporal distribution of the pathological stages of adaptability, with poverty and gambling traps as the main states. The poverty trap is mainly distributed in the central and northern provinces, where excessive resource exploitation and economic collapse have caused these provinces to surpass the threshold of the developmental stage and fall into the poverty trap. The distribution of gambling traps exhibited significant clustering characteristics, which were mainly concentrated in YN and SX. The lock-in trap is particularly concentrated in AH, ZJ, GD and FJ, where the degree of policy protection and capital injection is high. However, because of the limited resources of traditional villages in these areas, they are unable to undergo better upgrades and optimisations. The proportion of traditional villages in the rigidity trap was relatively small, and their distribution was random.

Figure 5(c) depicts the variation in the number of traditional villages in different stages across 31 provinces in China over 5 years. The eight distinct colours correspond to the final stages in 2020, with the thickness of each coloured bar indicating the quantity of traditional villages in that particular stage. The transfer of bars between adjacent years represent the transition process between different stages. The data reveals that the proportions of the eight stages remained relatively stable from 2000 to 2020, with the ranking from highest to lowest being: poverty trap, exploitation (r), gambling trap, reorganisation (α), lock-in trap, release (Ω), conservation (K) and rigidity trap. The number of villages in the cycle and pathological states remained relatively constant over the 5 years. From 2000 to 2020, some traditional villages underwent transformation but maintained overall dynamic stability. The transformations of the four-cycle stages (exploitation (r), conservation (K), release (Ω) and reorganisation (α)) have been relatively strong, whereas the transformations of the four pathological stages (poverty trap, gambling trap, lock-in trap and rigidity trap) have been relatively weak, indicating that the list of villages in pathological states has remained stable and gradually solidified. Traditional villages in most cycle stages, when faced with external disturbances, transitioned from the previous cycle stage to the next, maintaining a dynamic and healthy state. Only a few villages exceeded the threshold of the cycle stages and entered a pathological state. The most intense transformations occurred from 2000 to 2005, whereas transformations in other years were relatively balanced. This indicates that traditional villages experienced the greatest external disturbances between 2000 and 2005, with other periods showing relatively stable cyclical transformations. The transformation paths of conservation (K), release (Ω), rigidity trap and lock-in trap over the 5 years (2000, 2005, 2010, 2015 and 2020) have been relatively stable, with only a few village states undergoing cyclical transformations. Exploitation (r) and poverty traps were two types with relatively high degrees of transformation, with villages consistently and evenly transitioning between these states over the five periods. Additionally, from 2000 to 2005, the number of villages transitioning from reorganisation (α) to gambling trap is also quite noticeable.

Adaptive mechanisms of traditional villages

Interaction mechanisms between locality and mobility. Geographically weighted regression models were constructed for mobility and locality in 2000, 2005, 2010, 2015 and 2020. Positive and negative regression coefficients represent the direction of the effect of mobility on locality, whereas the absolute values indicate the strength of the effect. When locality was used as the dependent variable and mobility as the independent variable, the R^2 values for the 5 years remained approximately 0.57 (Table 4), indicating that the explanatory power of mobility on locality was relatively strong and stable. The impact of mobility on locality was primarily negative (Figure 6). This suggests that in the context of mobility development, the production and lifestyle of traditional villages have been affected, leading to significant population loss, abandonment of built environments, and a lack of successors in traditional skills and folk arts due to increased mobility for employment, education and healthcare purposes. This resulted in the destruction of the locality. The median change in the regression coefficients was not significant, indicating that the negative impact of mobility on locality was sustained over many years.

The regression coefficients of mobility exhibited significant regional variations, with the strongest negative impacts on locality concentrated in XZ, QH, SC and GS. However, there are also local traditional villages where the regression coefficients are positive, distributed in the remote provinces of China, including XJ and NM. These areas experience weaker suction effects than major cities, leading to lower costs of injecting external capital in the context of increased mobility. In turn, this activates the locality through specific protection, planning, management and development methods.

When mobility was used as the dependent variable and locality as the independent variable, a geographic weighted regression was conducted for the data from 2000, 2005,

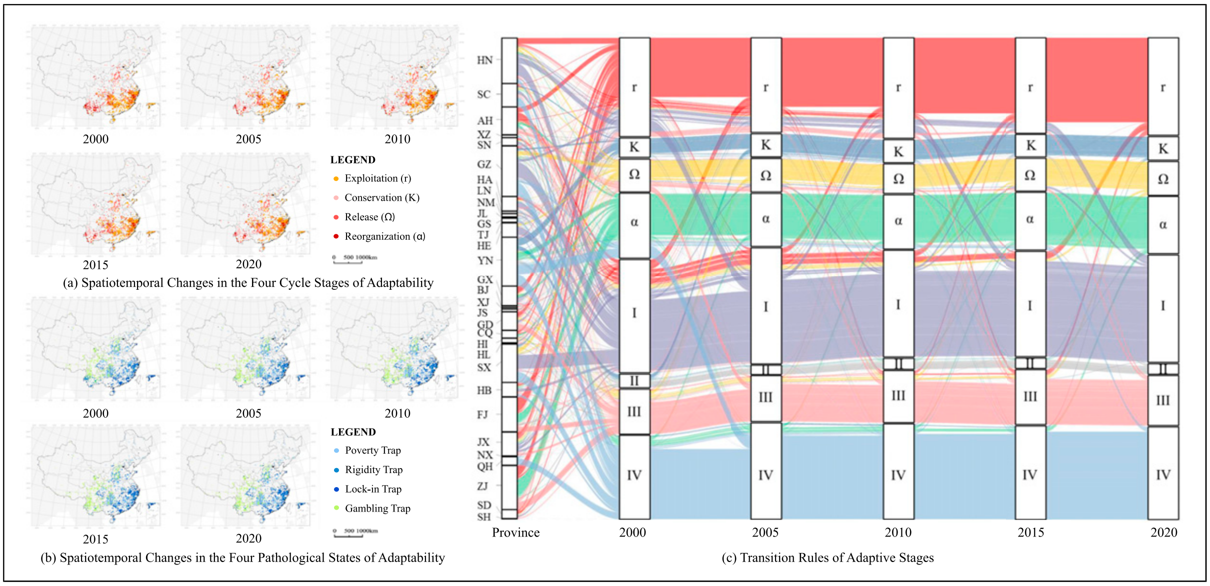


Figure 5. Spatiotemporal change patterns and transition rules of adaptive stages.

2010, 2015 and 2020. The R^2 values for the 5 years remained at approximately 0.04 (Table 4), indicating that locality does not have explanatory power for mobility. This may be due to the fact that changes in mobility in China are primarily driven by external factors such as government-led infrastructure development in traditional villages. Overall, the inherent value of locality in villages does not significantly influence the construction of infrastructure such as roads, stations, schools, hospitals and administrative facilities. This suggests that villages are unable to enhance their mobility significantly through the intrinsic value of their locality and require the injection of external factors.

Interaction mechanisms between locality and resilience. When using locality as the dependent variable and resilience as the independent variable, geographically weighted regression for the 5 years had resulted in R^2 values remaining at approximately 0.62 (Table 4), indicating that resilience has a relatively strong and stable explanatory power for locality. As shown in Figure 7, the regression coefficients for resilience were predominantly negative, suggesting an overall negative impact of resilience on locality. There are two likely reasons for the significant increase in resilience over the past two decades. Firstly, in the economic development process of most traditional villages, renovation and development have been influenced by urban planning design concepts and commercial logic, disregarding regional traditional knowledge and experience, which has severely damaged the local style and culture and has led to a decline in locality. Secondly, the emphasis on increasing food production and economic benefits has led to the overuse of pesticides, fertilisers and antibiotics as well as the excessive exploitation of water and soil, resulting in serious environmental issues in rural areas and disrupting the relationship between people and land in traditional villages. The mean value of the regression coefficients was gradually increased from −0.172 in 2000 to −0.136 in 2020, indicating a weakening fluctuation in the negative impact of resilience on locality over time.

The regression coefficients of resilience exhibited significant regional differences in geographic space. Positive-value areas were mainly distributed in Eastern and Southern China, with a few in XJ and NM. This indicates that in these regions, resilience has a positive impact on the locality, with moderate industrial development and rational utilisation of nature, effectively promoting the protection and renewal of traditional village residences and buildings, as well as fostering the revival and development of traditional culture and crafts. In other regions, the regression coefficients for resilience are negative, decreasing from the southeastern to the northwestern, with the lowest coefficients in Northwestern China and Southwestern China, indicating severe issues related to over-commercialisation, resource and environmental overload, and the loss of village memory. Over time, the coverage of positive-value areas gradually shifted southward. The overall regression coefficients for the negative-value areas are increasing, especially in YN, suggesting that the negative impact of resilience on locality in this region is decreasing over time, possibly due to the transformation of its tourism development model generating some positive benefits, although there is still significant room for improvement.

When resilience was used as the dependent variable and locality as the independent variable, the R^2 for the geographically weighted regression over 5 years was gradually increased (Table 4). This indicates that the explanatory power of locality for resilience was steadily increasing each year,

Table 4. R^2 values from geographic weighted regression between locality, mobility and resilience for 2000, 2005, 2010, 2015 and 2020.

	Independent variable			
	Dependent variable	Locality	Mobility	Resilience
2000	Locality	—	0.57	0.62
	Mobility	0.04	—	0.03
	Resilience	0.32	0.17	—
2005	Locality	—	0.57	0.63
	Mobility	0.04	—	0.03
	Resilience	0.39	0.38	—
2010	Locality	—	0.56	0.61
	Mobility	0.04	—	0.03
	Resilience	0.38	0.37	—
2015	Locality	—	0.57	0.62
	Mobility	0.04	—	0.03
	Resilience	0.40	0.38	—
2020	Locality	—	0.57	0.61
	Mobility	0.04	—	0.03
	Resilience	0.43	0.41	—

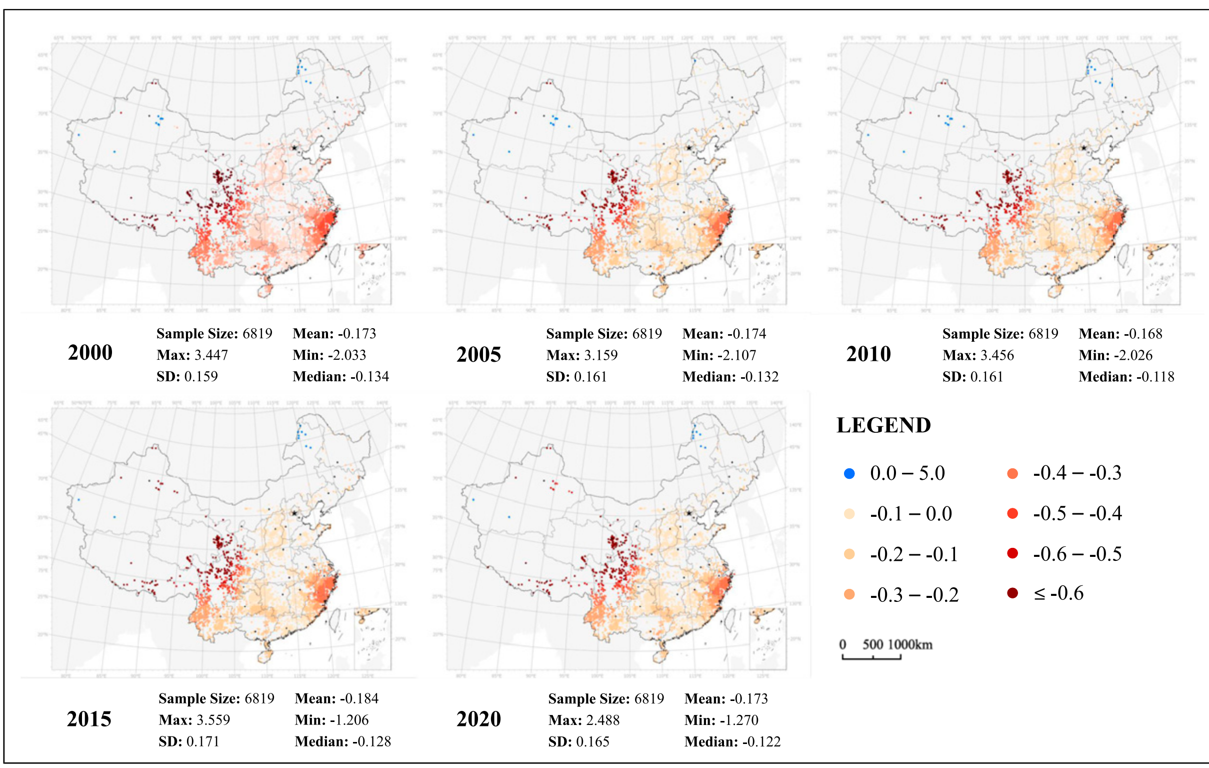


Figure 6. Geographically weighted regression coefficient for locality–mobility.

and the coupling relationship of the locality–resilience system was also increasing. The median of the regression coefficients was decreased from −0.087 in 2000 to −0.139 in 2020, and the mean was decreased from −0.085 in 2000 to −0.154 in 2020 (Figure 8), suggesting that the negative impact of locality on resilience was increasing. This may be because of the increasing number of policies aimed at protecting the locality in traditional villages in recent years. While these policies have preserved the physical space and, to some extent, improved the economic indicators of traditional villages in the dimension of resilience, without achieving harmonious unity of production, living and ecology, they may fall into a pathological state.

The regression coefficients of locality were predominantly negative globally, with significant regional differences in geographic space. Positive-value areas were mainly distributed in Eastern China, Southern China and the XJ Province, indicating that these regions' exploration and preservation of the value of locality has led to increased resilience in traditional villages, resulting in economic growth, population return and ecological protection. The regression coefficients for XJ, JS, SH and ZJ largely shifted from positive to negative. QH-SC-GS, GX-GZ-HN and SD-BJ-LN-JL gradually formed three clusters with continuously decreasing regression coefficients. In these regions, traditional villages are facing an increasingly negative impact of locality on resilience year by year, highlighting the need to be vigilant against the excessive commercial development of localities, leading to the disruption of traditional cultural heritage and collective memory, as well as crises of overloading natural carrying capacity.

Interaction mechanisms between mobility and resilience. Using resilience as the dependent variable and mobility as the independent variable, in the results of the geographically weighted regression, the R^2 over 5 years has increased gradually from 0.17 in 2000 to 0.41 in 2020 (Table 4). This indicates that the explanatory power of mobility for resilience was steadily increasing each year, and the resilience–mobility system was gradually being established. The median of the regression coefficients fluctuated from 0.051 in 2000 to 0.070 in 2020 and the mean was increased from 0.063 in 2000 to 0.102 in 2020 (Figure 9). Overall, mobility had a positive impact on resilience, as increased mobility enabled traditional villages to have frequent exchanges of materials, personnel, culture and information, leading to increased industrial and service industry opportunities, enhanced commercial capabilities, and the ability to exchange agricultural and sideline products, light industrial products, and resource-based products with the outside world through commercial mechanisms. This increased employment opportunities and attracted villagers to return, thereby improving the resilience of traditional villages.

The regression coefficients of mobility exhibited significant regional differences in geographic space. In 2000, the impact of mobility on resilience was predominantly positive with three significant clusters showing negative values: YN, CQ-HB and AH-ZJ-JX-FJ. Over time, two of the three negative clusters gradually disappeared, leaving only the YN cluster with a stable pattern of negative values. This may be due to the fact that the economic benefits brought about by the increased mobility in YN cannot compensate for the ecological damage and population loss

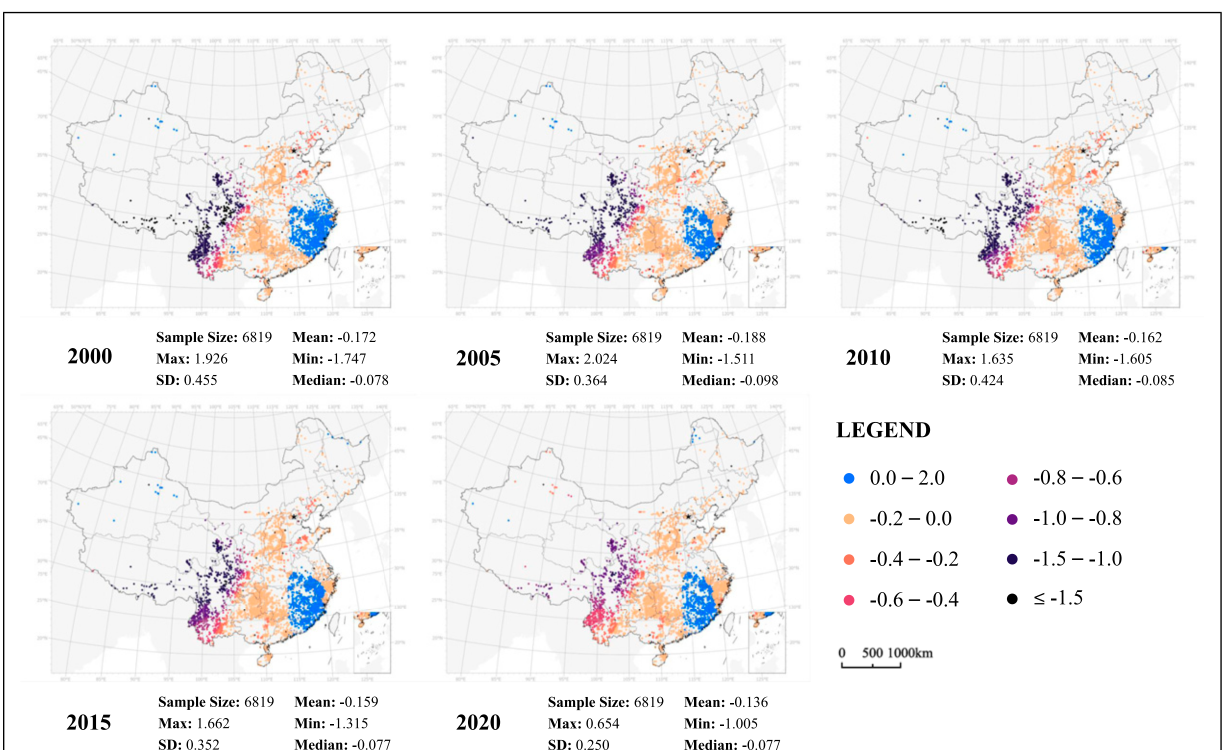


Figure 7. Geographically weighted regression coefficient for locality–resilience.

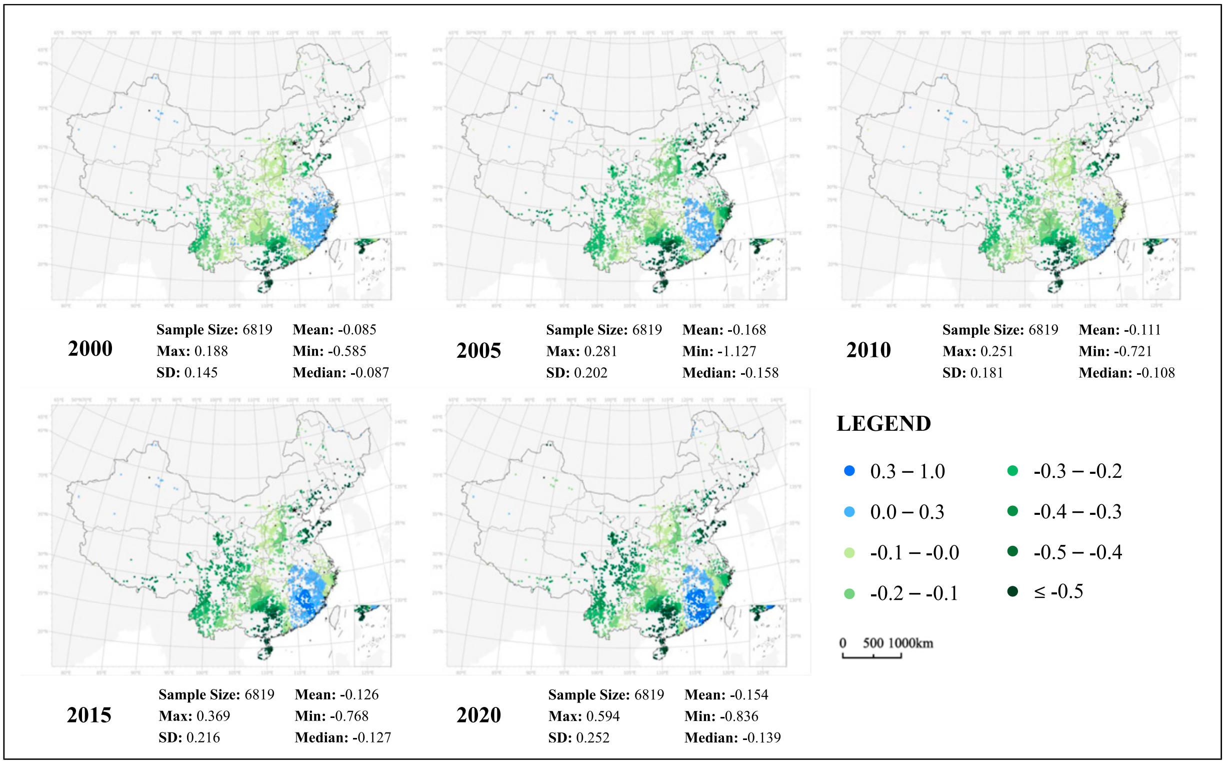


Figure 8. Geographically weighted regression coefficient for resilience–locality.

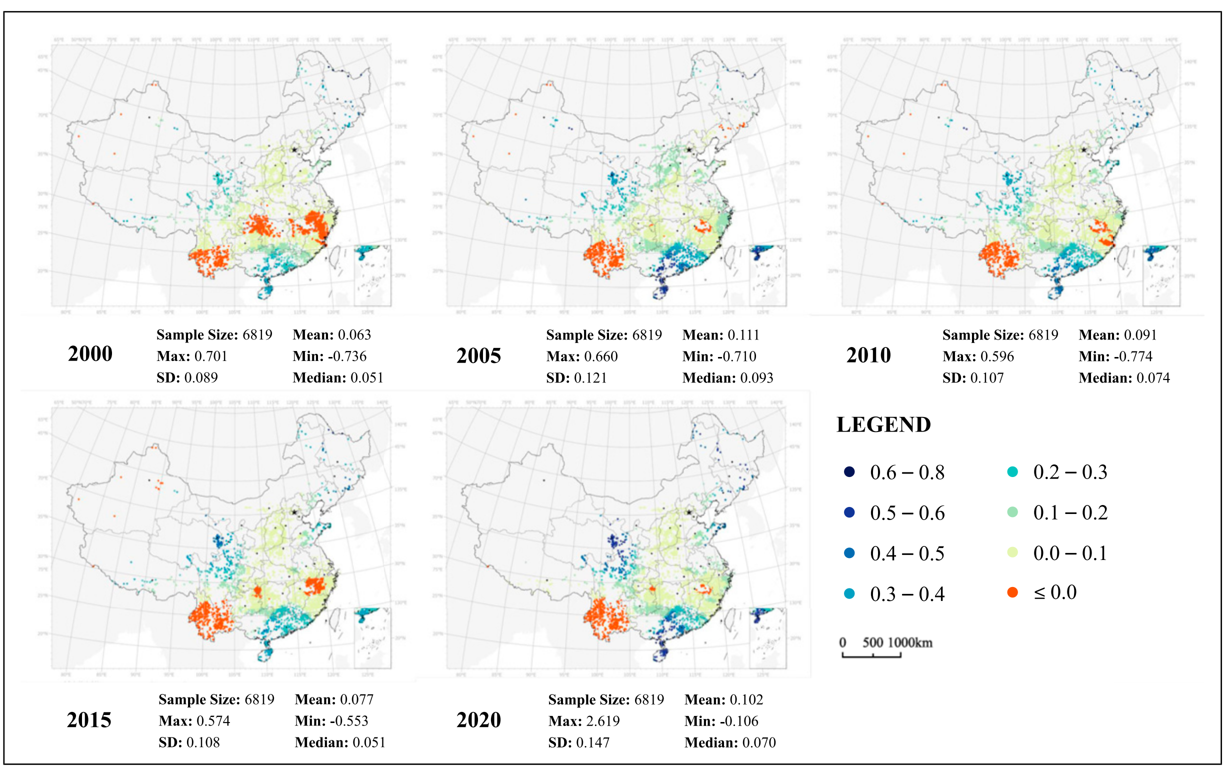


Figure 9. Geographically weighted regression coefficient for resilience–mobility.

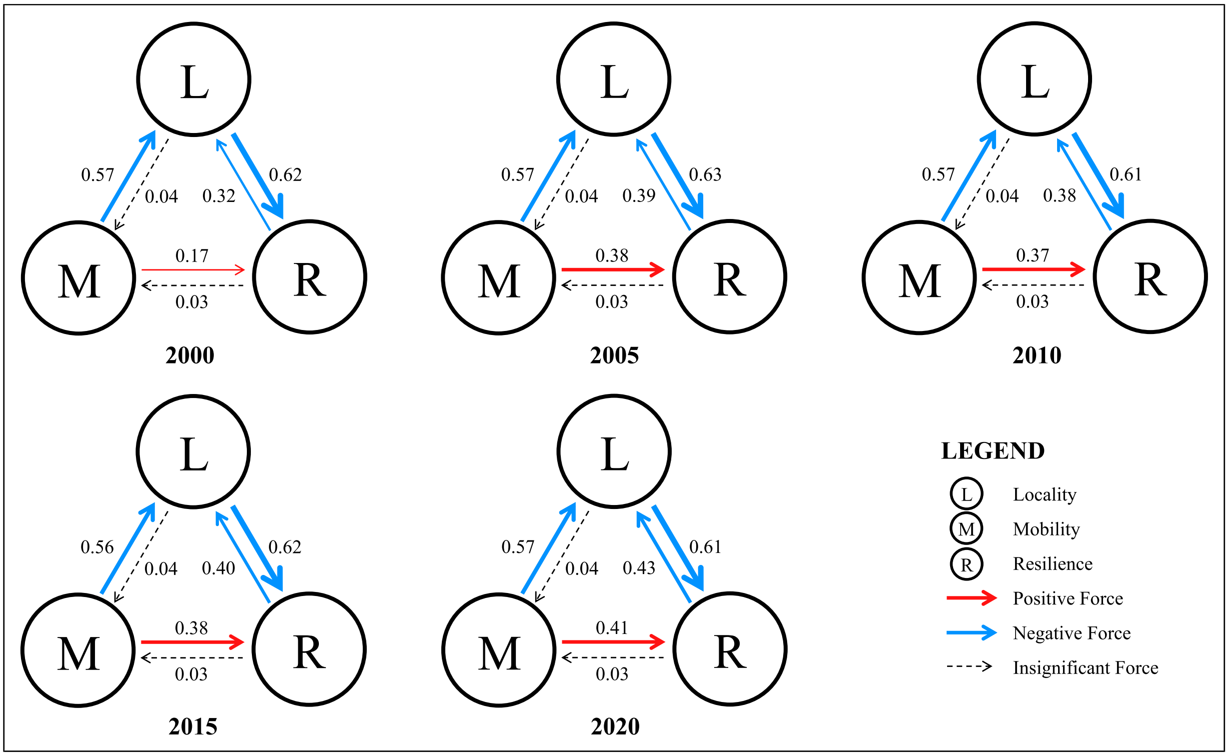


Figure 10. Adaptive mechanisms of traditional villages (the numbers on the arrows represent the geographically weighted regression R^2 for the two segments of the arrow, while the thickness of the lines represents the magnitude of R^2).

caused by this process. For example, in the Lijiang Dayan Ancient Town, over 90% of the original residents rented out their old houses and purchased new homes in newly built residential areas. In contrast, traditional villages in the CQ-HB and AH-ZJ-JX-FJ clusters gradually offset the underlying costs as the total benefits obtained from increased mobility increase. In 2000, high-value areas of regression coefficients were distributed in the GD-GX region. By 2020, one additional high-value cluster, QH-SC-GS, had emerged, indicating that increasing mobility continuously enhanced the resilience of these regions.

Using mobility as the dependent variable and resilience as the independent variable, the R^2 over 5 years remained at approximately 0.03 (Table 4), indicating a very low value. This further confirms that changes in mobility in traditional Chinese villages are mainly the result of exogenous factors such as government-led infrastructure construction.

Adaptive mechanisms of traditional villages. Overall, of the six sets of regression results for mobility and locality, locality and mobility, resilience and locality, locality and resilience, mobility and resilience, and resilience and mobility, significant regression relationships were observed for four sets: mobility and locality, resilience and locality, locality and resilience, and mobility and resilience. Moreover, the regression coefficients for locality and resilience and mobility and resilience were increased positively every year, indicating that these two systems were in a rapid development stage, whereas the relationships between mobility and locality and resilience and locality have matured (Figure 10). Amongst the four sets of results showing significant regression relationships, only the impact of mobility on resilience was globally positive; the other three sets exhibited globally negative effects. In the future, an increasing number of traditional villages are likely to fall into a lock-in trap state (low locality, high mobility, high resilience).

Conclusion

This study took 6819 traditional villages in China (in five batches) as the research objects and drew and quantified the spatiotemporal dynamic evolution maps of the locality, mobility, resilience and adaptability of these traditional villages over the past 20 years. Based on the Adaptive Cycle Theory, we constructed a research theory using the 'Locality–Mobility–Resilience' model for the adaptability of traditional villages. We depicted the spatiotemporal changes, spatial differentiation and clustering characteristics of the locality, mobility and resilience of traditional villages, revealing the stage characteristics and transition rules of their adaptive cycle. Furthermore, we constructed regression models for the pair-wise correlations of the locality, mobility and resilience of traditional villages, describing the direction and degree of interaction between the elements and explaining the underlying influencing mechanisms.

Addressing the dual research queries concerning adaptability patterns and system operations within traditional Chinese villages over the past two decades, this study reveals several key insights. Firstly, adaptability has been characterised by prevalent states of poverty, exploitation and gambling, with a notable transition primarily between poverty and exploitation phases. Adaptive cycles have largely solidified, with significant shifts affecting only a minority of villages, often entrapped in a pathological state. Spatially, locality patterns have solidified, exhibiting higher levels in western regions and lower in the eastern region, while resilience has declined unevenly from southeastern to northwestern region, with the highest values clustering in eastern and southern parts. Secondly, the study underscores the operational dynamics of adaptability systems, highlighting that mobility has a predominantly negative yet stabilised impact on locality, with the exception of diminishing positive effects in remote provinces. Resilience's influence on locality, initially negative, has waned over time. Conversely, locality and resilience exert negligible direct influence on mobility, which is instead driven by infrastructural development, primarily government-led, underscoring the overriding role of external factors in shaping mobility trends within these traditional settlements.

Innovatively, this study advances a novel 'locality–mobility–resilience' theoretical framework for adaptive cycles in traditional Chinese villages, enriching measurement methodologies and providing empirical quantitative support for the adaptive mechanisms at play. Through meticulous analysis of spatial heterogeneity and temporal evolution in adaptability across 6819 villages over two decades, it uncovers disrupted natural lifecycles and regional disparities, while delineating phase transition laws within adaptive cycles, crucial for conservation and development strategies. Moreover, it elucidates the detrimental impact of enhanced mobility and resilience on locality, advocating for innovative preservation approaches. However, limitations exist, primarily in the absence of first-hand field data, discrepancies in data standards. Future research aims to refine theoretical constructs, improve data collection methods, and employ sophisticated analytical tools to decipher the intricate adaptive mechanisms, addressing the complex challenge of balancing natural disturbances, human activities, conservation and development to enhance the sustainability of traditional villages, which is a critical imperative for national revitalisation and cultural heritage preservation.

Author contributions

Pengcheng Xue was primarily responsible for writing and revising process. Jiayin Zhang was involved in the writing and revising process. Fang Wang provided research inspiration for the research design and organised the entire research through the process. Leye Wang offered valuable research ideas and involved in the revising process.

Declaration of conflicting interests

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