Spatiotemporal evolution and driving factors of the rural settlements in the mountain-plain transitional zone

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Abstract: Identifying the spatiotemporal evolution characteristics of rural settlements and their driving factors is of great significance to layout optimization of rural settlements, intensive and economical use of rural land, and preparation of land space planning. Focusing on the mountain–plain transitional zone of Dujiangyan City, China, as the study area, this paper employs methods including landscape pattern index, kernel density estimation, average nearest neighbor index, and Geodetector to quantitatively analyze the spatiotemporal layout evolution characteristics of rural settlements and relevant driving factors in Dujiangyan City over the last decade. The four main findings are as follows. First, land use area of rural settlements and the quantity of patches in Dujiangyan exhibited synchronous changes during 2005-2015. Total class area (CA) increased from 6161.43 to 7265.43 hm^2, then declined to 7043.01 hm^2, and the number of patches (NP) increased from 16 543 to 26 018, and then declined to 25 890. Second, the maximum kernel density estimation values in the east and southeast of Dujiangyan City increased remarkably from 48.34 to 74.69 per hm^2 during 2005-2010. Third, the average nearest neighbor index of rural settlements continually decreased in the foregoing 10 years, indicating a higher concentration of rural settlements. Finally, production and living conditions are the main driving factors of dynamic change in land use in rural settlements, while the impact of socio-economic factors is relatively smaller. Among others, the *p*-value of road accessibility is 0.057, and the impact *p*-value of land slope is 0.035.

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1 Introduction

Rural settlements can be defined as locations where rural residents reside and engage in production. The spatial distribution and evolution of these settlements are the result of interaction phenomena and processes of rural residents with their surrounding natural, social, economic, and cultural environments as well as a core embodiment of rural human-earth relationships[1-3]. In light of China's continuously accelerated urbanization process, the non-agricultural transfer of the rural population is continuing to increase. Statistical data show that China's rural population declined from 896 000 000 in 1990 to 603 000 000 in 2015. However, despite this rural population decline, the land use area of settlements exhibited continued year-by-year growth[4]. Additionally, because vast areas of rural land have lacked planning and guidance for a long time, a large number of "rural problems" have emerged, e.g., disorderly spatial layout of settlements, per capita land use area exceeding standards, rural hollowing-out, and housing sites left unused, all of which have aggravated land use conflicts in China, seriously impeded agricultural industrialization and urban-rural integration, and posed severe challenges to new rural construction and revitalization. Therefore, carrying out a study on the spatiotemporal layout evolution of rural settlements and the underlying driving factors will be of great theoretical and realistic significance to revealing the fusion mechanism between human activities and the surroundings, thereby shedding light on policies and practices to bring about reasonable rural land use and optimizing settlement layouts.

In recent years, driven by a series of major strategies like new rural construction and rural revitalization in China, rural settlements have become a key research field in rural geography and related disciplines, and abundant research results have been reported. Numerous scholars have carried out a large quantity of related analytical research on the spatiotemporal layout evolution of settlements[5-9], driving factors[10-13] and spatial layout optimization[14-17] at scales ranging from villages[18], towns[19] up to districts and counties[20] and even cities[21]. However, in general, existing studies mostly concentrated on plains, mountainous areas, and hills, and few have considered mountain-plain transitional zones with a fragile ecological environment.

Secondly, linear regression is usually used to analyze the driving factors of rural settlements' spatiotemporal layout evolution. Spatial positional relationships and spatial variation laws of rural settlements can easily be overlooked in daily operation processes. On this basis, a mountain-plain transitional zone—Dujiangyan City is taken as the study area. First, a landscape pattern index, kernel

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density estimation, and average nearest neighbor index were used to reveal spatiotemporal layout evolution features of rural settlements, and then a geographical detector was used to analyze the driving factors of land use change in rural settlements. The results of this study are expected to provide a theoretical basis for dynamic evolution monitoring and optimization of rural settlements' spatial layout so as to promote optimal urban–rural land resource allocation.

2 Material and methods

2.1 Study area

Dujiangyan, connected to Chengdu City, Sichuan Province, is located at northwest edge of Chengdu Plain (Figure 1). Situated where the Minjiang River flows out of the mountain, Dujiangyan lies between 31°02'09"-31°44'54"N and 103°25'42"-103°47'0"E. Featuring a subtropical seasonal humid climate, its average annual precipitation is 1243.80 mm. The area of this city totaled 1208 km^2 in 2015. It contains 1 subdistrict office, 17 towns, and 2 villages, a registered population of 620 500, and permanent resident population of 680 200.

Crossing the Longmen Mountain area in western Sichuan and situated at the alluvial fan top of the Minjiang River on the Chengdu Plain, Dujiangyan lies at the eastern edge of the first of three steps divided by the China Mega-geomorphology, namely a typical mountain-plain transitional zone starting at the first step of Qinghai-Tibet Plateau and stretching to the Chengdu Plain located in the second step[22,23]. East-west elevation change is drastic, the terrain presents a steplike distribution from the northwest to southeast from high mountains, middle mountains, low mountains, hills, and plains successively, with an altitude range of 571-4658 m and maximum relative altitude height of 4087 m. Mountains and hills account for 65.79% of the territory, and plain dams account for 34.21%, in line with the local saying that "six mountains, one river and three pieces of field."

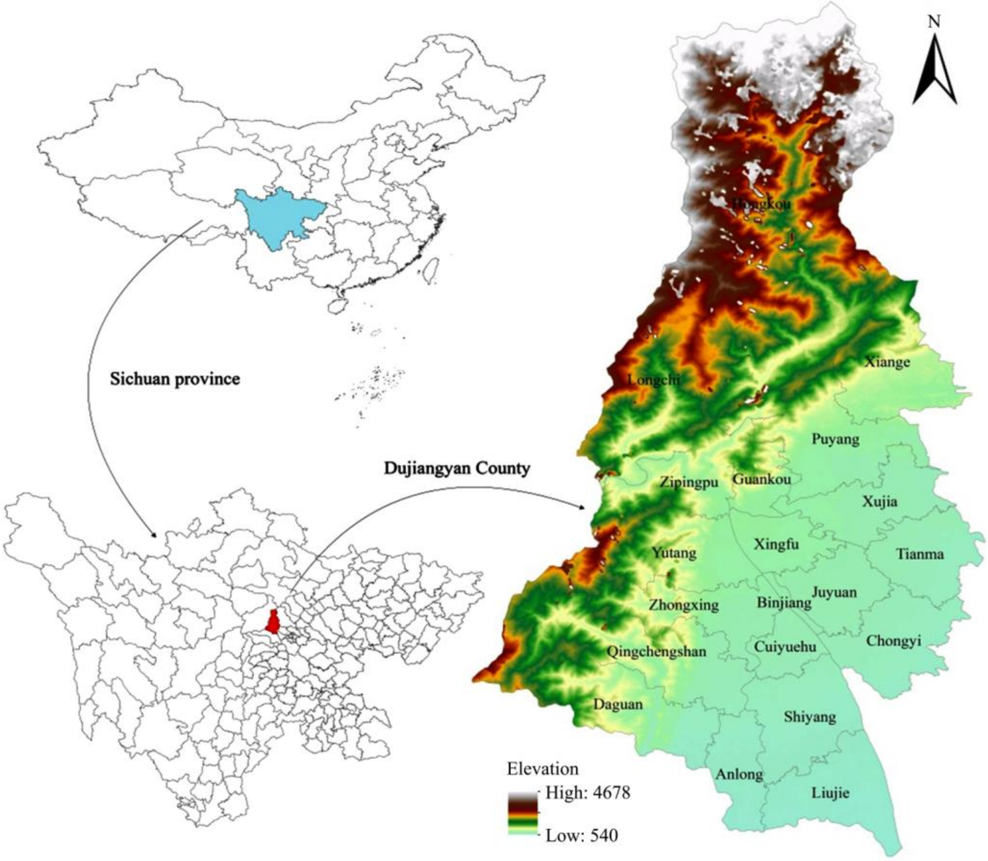


Figure 1 Location map of Dujiangyan

2.2 Data sources and preprocessing

The main data used in this study include 2005, 2010, and 2015 land use databases for Dujiangyan derived from the Dujiangyan Land and Resources Bureau. In ArcGIS 10.2, the spatial analysis tool was used to extract vector data from land use databases, e.g., rural settlements, organic towns, central city areas, water systems, and roads. Then, area data on settlements were converted into point data. The 30 m resolution DEM data of Dujiangyan were derived from Geospatial Data Cloud Platform of Computer Network Information Center, CAS (http://www.gscloud.cn), and raster data of elevation and slope of the study area were acquired through DEM data. The 1 km×1 km spatial distribution data of population and 1 km×1 km GDP kilometer grid data were derived from the resource and environmental data cloud platform (http://www.resdc.cn/Default.aspx). After the projection transformation of the above data, geographical coordinates and projection coordinates were merged.

2.3 Methods

2.3.1 Landscape pattern index

A landscape pattern index can reflect highly concentrated landscape pattern information and scale features through simple quantitative indicators[24]. Rural settlements are an important constituent of the rural landscape. In this study, four indicators—total class area (CA), number of patches (NP), mean patch size (MPS), and patch size standard deviation (PSSD), are used to quantitatively characterize scale evolution features of rural settlements in Dujiangyan in 2005-2015. The above indicators were calculated using the path analyst plugin in ArcGIS 10.2. The meaning and computational formulas of these indicators are given in Table 1.

Table 1 Definition of landscape pattern indicators

Indicator	Abbreviation	Computational formula	Description of indicator
Total class area	CA	$CA=\sum_{i=1}^{n} a_i$	CA represents the aggregate area of patches in rural settlements and reflects the size of land use in rural settlements
Number of patches	NP	$NP=n$	NP represents the aggregate number of patches in rural settlements and reflects the fragmentation of patches in rural settlements
Mean patch size	MPS	$MPS=\frac{CA}{NP}$	MPS represents the average land use size of patches in rural settlements and reflects the fragmentation of patches in rural settlements
Patch size standard deviation	PSSD	$PSSD=\sqrt{\frac{\sum_{i=1}^{n}(a_i-\frac{CA}{NP})}{NP}}$	PSSD represents the difference between land use size of rural settlements and mean patch size and measures the dispersity of patch size in rural settlements

2.3.2 Kernel density estimation

Kernel density estimation (KDE) is a nonparametric method used to estimate probability density functions. It can perform data aggregation for an entire area according to input factor data to generate a continuous high-density surface[25,26]. The kernel density estimation value can well reflect the spatial distribution density and spatial structural features of rural settlements. The computational equation is as follows:

$$f(x,y)=\frac{1}{nh^2}\sum_{i=1}^{n}k\left(\frac{d_i}{n}\right) \tag{1}$$

where, $f(x, y)$ is density estimation located at (x, y), a/hm^2; n is the number of observations; h is bandwidth, km; k is the kernel function; and d_i is the distance from (x, y) to the i-th observing locations, km.

2.3.3 Average nearest neighbor index

After being proposed by Clark and Evans in 1954, the average nearest neighbor index was introduced by King into the spatial distribution analysis of urban settlements[27]. By measuring the distance from the centroid of each element to the centroid of its nearest neighbor element, this method allows the average value of distances between these nearest neighbors to be calculated. The average value is then compared with the average distance in an assumed random distribution in order to measure the overall spatial distribution pattern of elements. The computational formulas are as follows:

$$D_o=\sum_{i=1}^{n}d_i/n \tag{2}$$

$$D_e=0.5\sqrt{\frac{A}{n}} \tag{3}$$

$$ANN=\frac{D_o}{D_e} \tag{4}$$

where, D_o is the observed average distance from the centroid of each rural settlement patch to the centroid of its nearest neighbor patch, m; D_e is the expected average distance of nearest neighbor points of each rural settlement patch in the theoretical model, m; d_i is the distance of nearest neighbor points of rural settlement I, m; n is the total number of rural settlements; A is the area of study area, m^2.

If ANN<1, the observational model is more aggregated than the random model. However, if ANN >1, the observational model is more disperse than the random model. In order to quantitatively analyze the aggregation or dispersity between observed and expected average distance values, the difference between observed and expected values is compared with their standard deviation[28]. The computational formulas are as follows:

$$SE_r=0.26136\sqrt{\frac{A}{n^2}} \tag{5}$$

$$Z=\frac{r_o-r_e}{SE_r} \tag{6}$$

where, SE_r is the standard deviation of the average distance of nearest neighbor points; Z is the standardized Z value. When the significance level is α=0.05, if Z>1.96 or Z<−1.96, the difference value between the observational model and random model has statistical significance. On the contrary, if −1.96<Z<1.96, it can be deemed that even though the observational model seems more aggregated or disperse, it has no significant difference from a random model.

2.3.4 Geographical detector

A geographical detector is a group of statistical methods that detects spatial differentiation and reveals the underlying causal mechanisms. The core idea is that an independent variable has an important effect on a dependent variable, and the spatial distribution of independent variables should be similar to that of dependent variables[29]. The model formula is as follows:

$$P_{D,U}=1-\frac{1}{n\sigma_U{}^2}\sum_{i=1}^{m}n_{D,i}\sigma_{U_{D,i}}^2 \tag{7}$$

where, $P_{D,U}$ is the detectability index of impact factor D on dynamic land use change of rural settlements; $n_{D,I}$ is the number of samples in the secondary area; m is the number of secondary areas; σ_U^2 is the variance of rural settlement scale in the whole area; $\sigma_{U_{D,i}}^2$ is the variance of the secondary area. Assume $\sigma_{U_{D,i}}^2\neq 0$, and the model holds. The value of $P_{D,U}$ is in the range [0, 1], and the greater the $P_{D,U}$ value, the higher the impact degree of factor D on dynamic land use change of rural settlements in the town.

3 Results and analysis

3.1 Evolution features of land use scale in rural settlements

In ArcGIS 10.2, the patch analyst tool was used to calculate related landscape pattern indexes of rural settlements in Dujiangyan, and results are shown in Table 2. The land use area of rural settlements and quantity of patches in Dujiangyan presented synchronous changes during 2005-2015, namely, they first increased rapidly and then slowly decreased. After the total class area (CA) increased from 6161.43 to 7265.43 hm^2, it declined to 7043.01 hm^2, and the number of patches (NP) first rose to 11 290, then declined to 25 890. It should be pointed out that Dujiangyan was strongly affected by the 2008 Wenchuan Earthquake (magnitude Ms8). Most residential houses suffered varying degrees of damage, with some collapsing completely. In the subsequent repair and reconstruction phase, the increasing quantity of temporary houses and shelters resulted in the highest quantity of settlements and land use area to occur in 2010.

In contrast, while the total area and number of settlement patches were synchronously changing, the average patch area

(MPS) continuously reduced. This indicates that settlements tended to become increasingly fragmented during the 2005-2015 period, and intensive use degree continuously declined, but the change rate slowed down. The patch size standard deviation was greater in 2010 than in 2005, indicating that the difference between rural settlements in terms of land use area was most significant in 2010.

Table 2 Changes of landscape pattern indexes in rural settlements in Dujiangyan during 2005-2015

Year	CA/hm^2	NP	MPS/hm^2	PSSD/%
2005	6161.43	16 543	0.372	53.41
2010	7265.43	26 018	0.279	57.81
2015	7043.01	25 890	0.272	56.27

3.2 Spatial evolution features of rural settlements

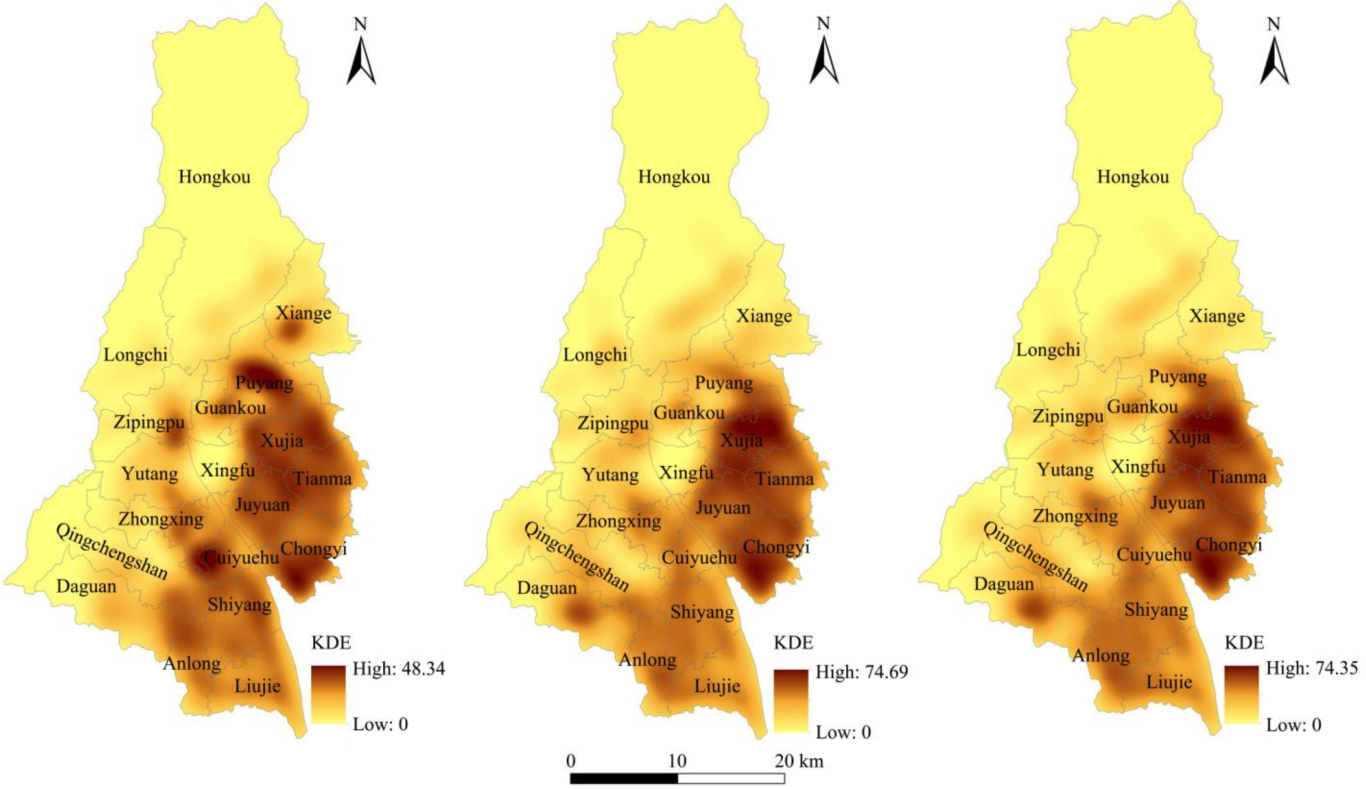
The average nearest neighbor index is able to reveal overall aggregation features of rural settlements very well, and a kernel density distribution graph can characterize local spatial aggregation tendencies of rural settlements in different years in greater detail and resolution.

In ArcGIS 10.2, vector data of rural settlements were converted into point data, and average nearest neighbor indexes were calculated according to Equations (2)-(6) as shown in Table 3. *ANN* values of rural settlements in Dujiangyan during 2005-2015 were all below 1, indicating that in terms of spatial distribution in 2005 compared with 2015, rural settlements were more aggregated than the random model. All standardized Z-values were smaller than −2.58, and based on the significance level α=0.01 test, the aggregation tendency of rural settlements in Dujiangyan was very significant. Comparatively speaking, *ANN* values continuously decreased during 2005-2015, indicating that rural settlements in Dujiangyan became increasingly aggregated.

Table 3 Average nearest neighbor indexes of rural settlements in Dujiangyan in 2005 and 2015

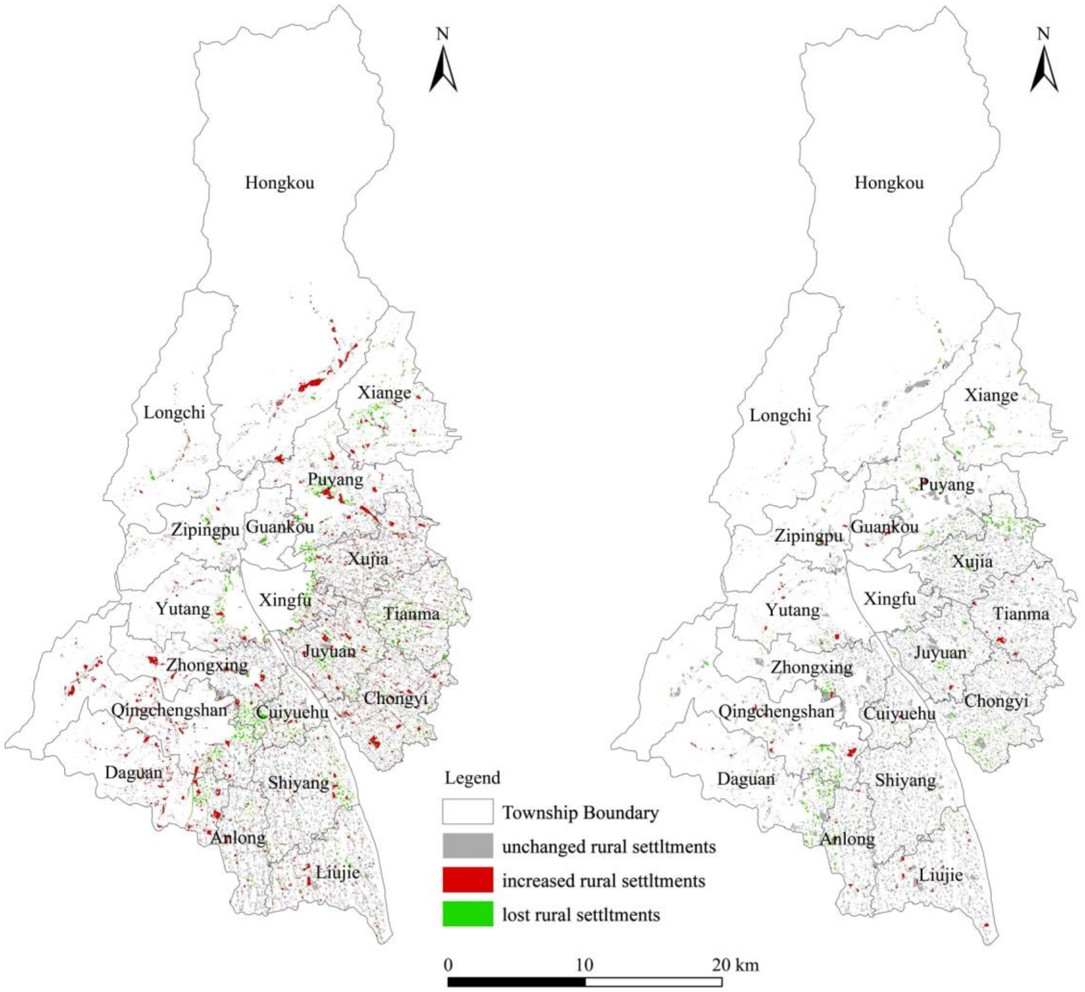
Year	Observed average distance/m	Expected average distance/m	*ANN*	Z-score	*p*-value
2005	89.802	138.987	0.644	–87.08	0.000
2010	70.487	111.896	0.630	–114.19	0.000
2015	68.963	112.172	0.615	–118.57	0.000

In ArcGIS 10.2, when using the Kernel Density tool to analyze the spatial distribution laws of rural settlements in the study area, the search radius *h* had a major effect on the final calculation result. If *h* was too small, the change of spatial point density might be uneven, and the simulation effect was unsatisfactory. When *h* was too large, although the smoothing effect was good, it would conceal spatial structures and authenticity of settlement density[30]. Based on research results in the literature[31], a 2.5 km search radius was finally confirmed through repeated tests as sufficient for carrying out kernel density estimation of rural settlements' spatial distribution. The kernel density distribution graph of rural settlements in Dujiangyan generated using this approach had better accuracy. The calculation results are shown in Figure 2. In addition, in order to clearly show the spatial evolution characteristics of rural settlements in the two periods, this paper overlays the rural settlements patches in each period. The results are shown in Figure 3. The following points can be observed in the figure. First, the maximum kernel density estimation values at three time points were 48.34, 74.69, and 74.35 per hm^2, respectively, indicating that the number of rural settlements rapidly increased within the unit area during 2005-2010, whereas the change during 2010-2015 was minor. In other words, rural settlements showed an abrupt change in the first time period but changed little in the second.



a. 2005 b. 2010 c. 2015

Figure 2 Kernel density distribution graphs of rural settlements in Dujiangyan in 2005 and 2015



a. 2005-2010 b. 2010-2015

Figure 3 Spatial variations of rural settlements for Dujiangyan during 2005-2015

It can also be clearly observed that areas with high kernel densities (deep color) were gradually aggregated; they changed greatly in the first time period from a multikernel spatial distribution (2005) to a centralized clustering development (2010 and 2015). Comparatively speaking, between 2005 and 2015, the number of rural settlements increased rapidly in the east and southeast and the developed from a multi-kernel low-value spatial distribution into high-value clustering distribution, mainly because the east and southeast are part of the Minjiang River alluvial plains, with fertile soil and abundant cultivated land resources. They are typical traditional farming areas with large settlement density, and both also served as portals to open Dujiangyan to the outside world due to their convenient transportation and complete infrastructure. Therefore, rural settlements were densely distributed and increased rapidly in the east and southeast of Dujiangyan.

3.3 Driving factors behind dynamic land use change of rural settlements

Rural settlement change is usually influenced by the natural environment, production needs and pressures, and lifestyles and the social economy, among others. Such changes can therefore be considered as reflecting the aggregate influences of rural production, socioeconomic, and environmental factors. According to data availability and scientific principles as well as the practical situation in Dujiangyan, altitude (X_1), slope (X_2), cultivated land area (X_3), garden plot area (X_4), road accessibility (X_5), distance from a water source (X_6), distance from organic town (X_7), distance from the central city area (X_8), population density (X_9) and per km^2 GDP (X_{10}) were selected as potential driving factors in this study. Mean values of elevation and slope as well as road accessibility in each km grid were calculated using locational condition indexes obtained via Euclidean Distance in ArcGIS. The natural breaking point method was used to divide the above indexes into five grades to detect impact *P*-values of various factors on dynamic land use change in rural settlements. The calculation results are shown in Table 4.

Table 4 Detected influence values of various factors on dynamic land use change in rural settlements

Index	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
P-value	0.025	0.035	0.03	0.03	0.057	0.028	0.024	0.008	0.023	0.02

According to Table 4, three main points should be elaborated. First, production and living conditions are the main driving factors of dynamic change in rural settlements. The impact *p*-values of road accessibility, cultivated land area, garden plot area, and distance from a water source are 0.057, 0.03, 0.03, and 0.028, respectively. On the one hand, in order to reduce travel time, meet the demand for production and domestic water, and improve the convenience of production and daily life, settlements show a certain road orientation and hydrophilicity. On the other hand, the production conditions of cultivated land and garden resources are relatively good, but due to the low incomes offered by the primary industry, many peasant households can be considered to follow a pattern of “drifting between urban and rural areas”. Although farmers have seen their property incomes increase, they still find it difficult to settle in the city. However, their increased incomes have boosted the demand and ability of farmers to build houses.

Second, it can be seen from the table that an area's natural slope and elevation can also exert great effects on rural settlements. Slope has a greater effect than altitude, with respective impact *P*-values of 0.035 and 0.025. This result can be explained as follows. Firstly, topographic conditions are a key element influencing peasant households in terms of house-building behavior and have a bearing on housing site selection. For instance, a higher altitude and steeper slope will certainly add to the construction cost. Additionally, Dujiangyan is located in the mountain–plain transitional zone and contains complicated landforms, such that slope and altitude are important factors underlying the triggering of natural disasters like debris flow and landslide. Therefore, in order to avoid natural disasters, the government has guided peasant households to translocate toward areas with a gentler terrain slope.

The third result that can be seen in the table is that in addition to distance from an urban area, other influential socio-economic factors also have a certain effect on dynamic change of rural settlements. However, their influence scope is relatively small, with impact values of distance from organic town, population density, per km^2 GDP, and distance from the central city area calculated as 0.024, 0.023, 0.02, and 0.008 respectively. Among the socioeconomic factors, population density and GDP per capita help reveal the demand for housing construction and the strength of housing demand, which exert a certain influence on change patterns of rural settlements but serve less as a driving force. In addition, with the development of the social economy, towns and central cities are expanding outward, and built-up areas are becoming larger. In this process, the closer a settlement is to an expanding area, the greater the change it will undergo.

4 Discussion

This study adopted three methodologies, including landscape pattern index, kernel density estimation, and average nearest neighbor index, to study the spatiotemporal evolution features of rural settlements within a county-level administrative region. The landscape pattern index is mainly intended to explore the evolution features of rural settlements in the time sequence, whereas kernel density estimation index and average nearest neighbor index allow for better understanding of the evolution pathway of rural settlements in terms of spatial distribution and thus supplement the evolution features in the time sequence. The comprehensive application of these three methods therefore helps reveal the spatiotemporal evolution features of rural settlements effectively and lays the foundation for analysis of the driving factors underlying rural settlements' evolution.

Geographical Detector (Geog-Detector) exploration was used to study the driving factors behind land use change in rural settlements because rural settlements exhibit both socio-economic and geospatial attributes. Geog-Detector is a set of statistical methods to explore spatial differentiation and reveal relevant driving forces, and is able to effectively analyze the driving forces behind the evolution of rural settlements. According to Geog-Detector's exploration results, the factors influencing the evolution of rural settlements in Dujiangyan City can be ranked as follows: road accessibility (0.057) > slope (0.035) > cultivated land area (0.03) = garden plot area (0.03) > distance from water source (0.028) > altitude (0.025) > distance from organic town (0.024) > population density (0.023) > per km^2 GDP (0.02) > distance from central city area (0.008). This order of influence suggests that rural settlements in Dujiangyan City are largely influenced by production, living, and natural conditions.

First of all, Dujiangyan City is a mountain-plain transitional zone starting from the first step of the Qinghai-Tibet Plateau and stretching to the Chengdu Plain, located in the second step, and its topography features large terrain undulations. More than 90% of rural settlements in Dujiangyan City are distributed in areas with an altitude <1000 m, and over 70% of rural settlements are distributed in areas whose slope is <5°. Thus, strong directivity of low altitude and low slope is apparent. Meanwhile, the spatial distribution pattern is high-density and large-scale in eastern and southeastern plain regions but low-density and small-scale in northwest and northwestern mountainous regions. This indicates that in mountain-plain transitional zones with large terrain undulations, natural environment factors exert large constraining and restricting influences on the evolution of settlement spatial patterns, which corresponds to existing research results[32,33].

Rapid socio-economic development decreases the natural environment's impact on the evolution of settlements, to be overtaken by the impact of production, daily living, and socioeconomic factors, which gradually come to play a leading role. For instance, population growth and movement as well as the growth of rural disposable incomes have become endogenous factors behind the growth of rural settlements. Traffic and other infrastructure plus distance from organic towns shape the direction and speed of settlements' evolution. For Dujiangyan City, the impact *P*-value of road accessibility (0.057) is much greater than the *P*-value of any other impact factor. During 2005-2015 in Dujiangyan City, 4 886 more rural settlements were added within a 500 m radius of roads, and patch area increased by 566.67 hm^2, which shows a strong traffic directivity. In addition, Dujiangyan City was hit hard in the 2008 Wenchuan Earthquake. Due to unanticipated nature of this disaster, the evolution of settlements was heavily influenced by support policies put in place after the earthquake, which became an external factor shaping settlements' evolution. For instance, Dujiangyan City's "Golden Land Project" and "Linking with Increase and Decrease in Urban and Rural Construction Land" led to Xiang'e Township and Puyang Town both enjoying policy dividends, raised large amounts of construction funds, and guided farmer households to move to safer settlement points in good order. Specifically, after the Wenchuan Earthquake, Xiang'e Township raised hundreds of millions of RMB in construction funds and built 16 centralized settlement points capable of withstanding a M8 earthquake and having capacity to hold 12 000 people.

5 Conclusions

In this study, a landscape pattern index, kernel density and average nearest neighbor index were utilized to analyze spatiotemporal evolution features of rural settlements in Dujiangyan during 2005-2015. On this basis, a geographical detector model was used to quantitatively identify driving factors of land use change in rural settlements in Dujiangyan. The following conclusions were drawn.

In general, land use quantities and areas of rural settlements during 2005-2015 presented identical change tendencies. Settlement landscapes presented a fragmented growth tendency, and intensive land use degree was gradually reduced.

In terms of spatial distribution, the kernel density value presented progressive increase from the northwest to the southeast. Kernel density estimation values exhibited clear changes during 2005-2010. The highest value increased from 48.37 to 74.69 per hm^2, gradually developing toward the high-value clustering direction, namely growth rate and aggregation features of rural settlements on plains were significant, with relatively complete supporting infrastructure and dense population distribution.

Land use in settlements was affected by a range of factors encompassing production and living conditions, the natural environment, and the social economy. Specifically, the effect of production and living conditions is great, and settlements tend to be distributed at locations with favorable traffic conditions and more convenient production and living conditions. Perfecting rural land use planning and completing a rural land use system are effective pathways to solving the disorderly spatial arrangement of rural settlements and their extensive land use forms.

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