Spatiotemporal Differentiation Pattern Analysis of Land Consolidation Projects in Sichuan Province (Postprint)

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Abstract

Analyzing the distribution characteristics of land consolidation projects during specific periods from different spatial scales can provide decision-making references for formulating subsequent land consolidation planning and optimizing spatial layouts. Based on land consolidation project data from 2011–2015, with county-level units as evaluation units, and employing the coefficient of variation method, gravity center model method, and spatial autocorrelation model method, this study explores the distribution characteristics of land consolidation projects in Sichuan Province at different spatial scales and analyzes the characteristics of gravity center shifts and spatial pattern evolution. The research indicates: From a temporal perspective, the total number of land consolidation projects in Sichuan Province exhibits a downward trend, while the differences in absolute and relative project scales gradually decrease, demonstrating a trend toward equilibrium. Land consolidation projects display distinct features at different spatial scales. At the regional level, projects are concentrated in the Basin Hilly Agricultural Land Consolidation Zone; at the municipal level, they are primarily concentrated in Chengdu City and Yibin City, while being sparsely distributed in Ganzi Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, and Panzhihua City. All gravity center points in the movement trajectory fall within the Basin Hilly Agricultural Land Consolidation Zone, indicating a certain degree of regional equilibrium in spatial distribution. The distribution of land consolidation projects at the county scale exhibits significant agglomeration. High-high agglomeration areas are mainly concentrated in the northeastern part of the Basin Hilly Agricultural Land Consolidation Zone, while low-low agglomeration areas are primarily distributed in the Northwest Sichuan Alpine Plateau Ecological Consolidation Zone. Due to influences from socio-economic conditions, population, terrain, and policies in the project areas, the spatiotemporal pattern equilibrium of land consolidation projects in Sichuan Province requires further improvement. This study clarifies that the focus of land consolidation planning in Sichuan Province lies in the Basin Hilly Agricultural Land Consolidation Zone, and the future development direction involves timely and moderate implementation of land consolidation in the Southwest Sichuan Mountain Valley Agricultural Land Consolidation Zone and the Northwest Sichuan Alpine Plateau Ecological Consolidation Zone, which will facilitate optimization of the spatial development and utilization pattern of land in Sichuan Province.

Full Text

Spatio-temporal Variation of Land Consolidation Projects in Sichuan Province

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Abstract

Analyzing the distribution characteristics of land consolidation projects across different spatial scales during specific periods provides a decision-making reference for developing subsequent land consolidation plans and optimizing spatial layouts. Based on land consolidation project data from 2011–2015 and using counties as evaluation units, this study employs coefficient of variation analysis, gravity center modeling, and spatial autocorrelation modeling to explore the distribution characteristics of land consolidation projects in Sichuan Province across different spatial scales, analyzing gravity center shifts and spatial pattern evolution. The findings reveal: (1) From a temporal perspective, the total number of land consolidation projects in Sichuan Province shows a declining trend, with both absolute and relative scale differences among projects gradually decreasing, indicating a trend toward equilibrium. (2) Land consolidation projects exhibit distinct characteristics at different spatial scales. At the regional scale, projects are concentrated in the hilly agricultural land consolidation area of the basin; at the municipal scale, they are mainly concentrated in Chengdu and Yibin, with fewer projects in Ganzi Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, and Panzhihua. (3) All gravity center points fall within the hilly agricultural land consolidation area of the basin, indicating certain regional equilibrium in spatial distribution. (4) Land consolidation projects show significant clustering at the county scale. High-high clustering areas are concentrated in the northeastern part of the hilly agricultural land consolidation area, while low-low clustering areas are mainly distributed in the alpine plateau ecological restoration area of northwestern Sichuan. Influenced by socio-economic conditions, population, terrain, and policies in project areas, the spatio-temporal pattern equilibrium of land consolidation projects in Sichuan Province needs further improvement. This study clarifies that the focus of land consolidation planning in Sichuan Province lies in the hilly agricultural land consolidation area of the basin, and that future development should involve timely and appropriate consolidation in the mountainous valley agricultural land area of southwestern Sichuan and the alpine plateau ecological restoration area of northwestern Sichuan, which will help optimize the spatial development and utilization pattern of land resources in the province.

Keywords: Land consolidation; Gravity movement; Spatio-temporal variation; Equilibrium trend; Geographical balance; Sichuan Province

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Introduction

Land consolidation work in China began with the "Notice of the CPC Central Committee and the State Council on Further Strengthening Land Management and Effectively Protecting Cultivated Land" (Zhongfa [1997] No. 11) [1]. In March 2012, the State Council approved the "National Land Consolidation Plan (2011-2015)," elevating land consolidation to a national strategic deployment. After nearly two decades of development, land consolidation has evolved from land development and rearrangement to comprehensive consolidation, with its connotation deepening from quantity management to quality management and then to ecological stewardship. Its extension has transformed from natural engineering to comprehensive social engineering, becoming an important tool and foundational platform for "protecting development, safeguarding red lines, promoting transformation, and benefiting people' s livelihoods." Land consolidation plays a crucial supporting role in national strategies for food security, new socialist rural construction, urban-rural integrated development, and conservation priority [2]. Currently, Sichuan Province faces prominent contradictions between human activities and land resources, significant regional differences in land use, generally low overall land quality, and urgent needs for ecological environment improvement. Summarizing the achievements and problems of land consolidation can provide important references for innovating land consolidation planning in Sichuan. Therefore, how to use scientific methods to timely clarify future development trends and key areas of land consolidation, thereby rationally guiding investment, effectively arranging tasks and project layouts, and constructing a new-era land consolidation pattern, deserves in-depth research.

Recent domestic research on land consolidation has mainly focused on theoretical strategies [1,3–5], consolidation models [6,7], benefit evaluation [8,9], and rural comprehensive land consolidation [10,11]. Regarding research scales, studies have primarily concentrated on small-scale county and municipal levels [10,12] and single or multiple project scales [13,14], with fewer analyses from larger scales. Guan et al. [15] analyzed the coordination between farmland consolidation project arrangements and spatio-temporal distribution of cultivated land resources at the national level. In terms of scale types, administrative-scale studies are more common, while regional-scale and parcel-scale studies are relatively scarce. Wang et al. [16] found that multi-scale land consolidation research accounts for only 1% of all literature after analyzing nearly 30 years of land consolidation publications. Constrained by basic data, studies on the spatio-temporal variation of municipal- and county-level land consolidation distribution characteristics within specific periods remain rare. Therefore, based on 2011–2015 land consolidation project data in Sichuan Province, this paper conducts mathematical statistical analysis of project "inputs and outputs" from temporal and spatial dimensions, combining gravity center modeling and spatial autocorrelation modeling at administrative and regional scales to analyze the spatio-temporal patterns of land consolidation projects in Sichuan from 2011 to 2015.

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1. Study Area Overview

Sichuan Province is located in southwestern China along the upper reaches of the Yangtze River, bordering Chongqing Municipality to the east, Yunnan and Guizhou provinces to the south, the Tibet Autonomous Region to the west, and Qinghai, Gansu, and Shaanxi provinces to the north. The province spans 1,075 km east-west and 921 km north-south, covering a total area of 486,100 km^2. Geographical coordinates range from 97°21 to 108°31 E and 26°03 to 34°19 N, with significant elevation differences and a pronounced west-high, east-low topography. Based on regional landforms, climate, soil, and land use characteristics, Sichuan is divided into five consolidation zones: Chengdu Plain Comprehensive Improvement Zone, Basin Hilly Agricultural Land Consolidation Zone, Southwestern Sichuan Mountain Valley Agricultural Land Consolidation Zone, Basin Peripheral Mountain Ecological Restoration Zone, and Northwestern Sichuan Alpine Plateau Ecological Restoration Zone [17]. The province governs 21 prefecture-level cities (autonomous prefectures) and 182 counties (cities, districts), making it a major southwestern province characterized by large population, weak foundation, unbalanced development, and underdevelopment. At the end of 2015, the permanent population reached 82.04 million, an increase of 638,000 from the previous year, including 39.125 million urban residents and 42.915 million rural residents, with an urbanization rate of 47.69%. The registered population totaled 91.326 million. Per capita disposable income was 26,205 yuan for urban residents and 10,247 yuan for rural residents.

During 2011–2015, Sichuan Province comprehensively promoted full-coverage land consolidation, constructed high-standard farmland on a large scale, focused on agricultural land comprehensive consolidation projects, and vigorously advanced urban-rural construction land increase-decrease linkage, post-disaster reconstruction, and targeted poverty alleviation. Land consolidation projects supplemented 1.28$\times10^{5}$ hm^2 of cultivated land, averaging 2.56$\times10^{4}$ hm^2 annually, exceeding the planned target by 5.04$\times10^{4}$ hm^2. Specifically, land rearrangement supplemented 1.16$\times10^{5}$ hm^2 (90.62%), land development supplemented 1.14$\times10^{4}$ hm^2 (8.91%), and land reclamation supplemented 6.00$\times10^{2}$ hm^2 (0.47%). High-standard farmland construction reached 1.74$\times10^{6}$ hm^2, surpassing the planned target of 1.66$\times10^{6}$ hm^2 by 1.72$\times10^{4}$ hm^2.

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2. Materials and Methods

2.1 Data Sources and Processing Attribute data were obtained from the final acceptance data of all land consolidation projects in Sichuan Province from 2011–2015 in the Ministry of Land and Resources' Rural Land Consolidation Monitoring and Supervision System. This includes projects funded by national, provincial, county governments, and self-raised funds, covering land consolidation, wasteland development, disaster-damaged cultivated land reclamation, homestead reclamation, industrial and mining wasteland reclamation, and high-standard farmland renovation. By December 31, 2015, a total of 2,644 land consolidation projects had been accepted. For spatial analysis convenience, the 2015 Sichuan administrative divisions were used as the standard, with 182 counties (cities, districts) as research units. After processing, an attribute database was established using statistical data from 182 counties (cities, districts) for 2011–2015. Many projects belong to comprehensive land consolidation, making it difficult to define specific project types. Considering that some districts and counties have relatively single consolidation types and existing data cannot meet research needs if classified by consolidation type, this paper selected four indicators that comprehensively reflect macro-level land consolidation effectiveness: investment scale, construction scale, newly-added cultivated land scale, and project number. The first three indicators are basic statistical parameters of land consolidation projects, while project number reflects overall project frequency across regions. These four indicators intuitively represent the comprehensive "input-output" level of land consolidation across regions, with newly-added cultivated land scale as the "output indicator" and the other three as "input indicators." Using these four indicators to characterize the spatial differentiation pattern of land consolidation in Sichuan Province holds certain significance.

2.2 Research Methods The main methods employed include mathematical statistics, gravity center modeling, and spatial autocorrelation modeling. Mathematical statistics methods are common in statistical analysis; this paper uses standard deviation index (S) and coefficient of variation (Cv) for analysis, which will not be elaborated here. The following sections focus on gravity center modeling and spatial autocorrelation analysis.

2.2.1 Gravity Center Model The concept of gravity center in physics applies to mechanical studies, referring to the point where the resultant force of gravity acts on all parts of an object [18]. Applied to geography, the land consolidation gravity center concept means: for a large project area consisting of n sub-regions, the gravity center of a certain attribute is calculated from each sub-region' s attribute value and geographic coordinates, where the attribute is analogous to physical weight. Let $D(x\ ,\ y\ )$ be the geographic coordinates of sub-region i' s gravity center, and A be the quantified value of a certain attribute. Then the geographic coordinates of the large project area' s attribute gravity center $G(X\ ,\ Y\ )$ are calculated as:

$$X = \frac{\sum_{i=1}^{n} A_i x_i}{\sum_{i=1}^{n} A_i}, \quad Y = \frac{\sum_{i=1}^{n} A_i y_i}{\sum_{i=1}^{n} A_i}$$

Obviously, when attribute values change, the gravity center position of the large project area will shift accordingly. When a region' s geometric center coincides with its attribute gravity center, it indicates balanced development of that attribute. When the attribute gravity center significantly differs from the geometric center, it signals unbalanced distribution of the attribute, or "gravity center deviation." The deviation direction indicates the development direction and key areas of land consolidation projects, while the deviation distance indicates the degree of equilibrium [19].

For quantitative analysis of equilibrium degree, the gravity center shift distance d is calculated using spatial distance formulas to represent the shift magnitude [20]. For two consecutive years ($T\ ,\ T\ $) with gravity center coordinates ($X\ ,\ Y\ $) and ($X\ ,\ Y\ $), the formula is:

$$d_{lk} = C \times \sqrt{(X_k - X_l)^2 + (Y_k - Y_l)^2}$$

where C is a constant equal to 111.11, the conversion coefficient from geographic coordinates to planar distance on Earth' s surface [21].

2.2.2 Spatial Autocorrelation Analysis Spatial autocorrelation is a spatial statistical analysis method commonly used to measure the diffusion benefits and clustering characteristics of indicators such as regional economy and urbanization levels [22]. It is typically divided into global and local spatial autocorrelation. The global spatial autocorrelation coefficient measures the overall correlation degree of an attribute' s observed values within a study area, determining whether spatial variable values are related to adjacent spaces. The most commonly used index is Moran’ s I [21]. The local spatial association index identifies specific locations of spatial clustering and determines similarity degrees among adjacent units within the same study area, useful for identifying “hotspot areas” and examining data heterogeneity. The common indicator is Local Moran’ s I (local indicators of spatial association, LISA). Spatial autocorrelation calculation first involves constructing a spatial weight matrix, then computing values to determine attribute clustering degrees. The formulas are:

Global Moran’ s *I*:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

Local Moran’ s *I*:

$$I_i = \frac{(x_i - \bar{x})}{S^2} \sum_{j=1}^{n} W_{ij}(x_j - \bar{x})$$

where I is the Moran’ s I index; I is the Local Moran’ s I index; n is the number of study units; x and x are attribute values of spatial units i and j; W is the spatial weight matrix value based on adjacency criteria (1 if two spatial units share a common boundary, 0 otherwise).

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3. Results

3.1.1 Overall Distribution Characteristics of Land Consolidation Projects from a Temporal Perspective The total number of land consolidation projects in Sichuan Province shows a declining trend over time (Table 1), consistent with Yang et al.’ s [20] conclusion that project numbers began decreasing annually after 2010 based on national data from 2006–2012. This decline stems from two main factors. First, land consolidation projects exhibit time lags due to separated bidding processes for different stages, asynchrony among planning, approval, design, implementation, and acceptance phases, and variations in institutional management and personnel qualifications. Second, project planning is influenced by location conditions, terrain, modern agricultural development directions, ecological civilization construction, and policy guidance [23].

The scale of newly-added cultivated land also decreases annually, reflecting current policy requirements that emphasize ecological land consolidation over simply increasing cultivated land rates. The newly-added cultivated land rate reached its lowest point in 2014 because post- “4.20” Lushan earthquake projects focused primarily on disaster-damaged cultivated land reclamation. Average construction scale experienced a slight decrease in 2013 (3.75% reduction), as wasteland development projects accounted for a larger proportion that year with relatively small construction scales. Using standard deviation index (S) and coefficient of variation (Cv) formulas, we calculated these indices for investment scale, construction scale, newly-added cultivated land scale, and project numbers across county-level units from 2011–2015 (Figure 1 [Figure 1: see original paper]).

The results show: (1) The standard deviation indices for project number, construction scale, newly-added cultivated land scale, and investment scale generally exhibit a wave-like decreasing trend, indicating gradually diminishing absolute scale differences among districts and counties. The coefficient of variation for project number shows a yearly decline, while those for construction and investment scales show wave-like decreases, and the coefficient for newly-added cultivated land scale first increases then decreases. This demonstrates a decreasing trend in relative scale differences among districts and counties. (2) Comparative analysis reveals synchronous variation patterns between investment and construction scales' standard deviation indices and coefficients of variation, indicating strong correlation between these two indicators. Their standard deviation indices show significant wave-like decreases, while coefficients of variation show wave-like decreasing characteristics, with the most dramatic fluctuation occurring in 2014, indicating the greatest variation change that year—attributable to post-disaster reconstruction affecting task arrangements and project layouts. Newly-added cultivated land scale shows similar variation characteristics, though its coefficient of variation did not decrease in 2014. Project numbers show wave-like decreases in standard deviation index and gradual decreases in coefficient of variation, though the decline rate slows, indicating decreasing absolute scale and diminishing relative differences among districts and counties.

3.1.2 Overall Spatial Distribution of Land Consolidation Projects

(1) Regional Scale Perspective. Land consolidation projects from 2011–2015 show obvious regional differences, with 49.47% concentrated in the Basin Hilly Agricultural Land Consolidation Zone. The Basin Peripheral Mountain Ecological Restoration Zone and Chengdu Plain Comprehensive Improvement Zone have relatively similar distributions, accounting for 22.39% and 20.35% of total projects respectively. In contrast, the Southwestern Sichuan Mountain Valley Agricultural Land Consolidation Zone and Northwestern Sichuan Alpine Plateau Ecological Restoration Zone account for only 4.12% and 3.67% of projects (Figure 2a [Figure 2: see original paper]). Over 60% of Sichuan' s available land resources are concentrated in the basin hilly area, and achieving macro-objectives of land consolidation must consider regional natural conditions as the background—this distribution of available land resources constitutes the main reason for spatial distribution differences. The Basin Hilly Agricultural Land Consolidation Zone is a traditional cultivated land concentration area, a major agricultural product production region, and the most concentrated distribution area of purple soil in the province, thus possessing large consolidation potential and high cultivation intensity. Although the Southwestern Sichuan

Mountain Valley and Northwestern Sichuan Alpine Plateau zones have abundant per capita land resources, their high altitude, steep slopes, and status as key areas for the Grain for Green Program limit development and utilization, resulting in fewer land consolidation projects.

(2) Municipal Scale Perspective. From 2011-2015, land consolidation projects were mainly concentrated in Chengdu and Yibin cities, with fewer in Ganzi Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, and Panzhihua City. Eight cities including Chengdu, Yibin, Guangyuan, Mianyang, Nanchong, Suining, Luzhou, and Bazhong each had more than 135 projects. Eight other prefecture-level cities had project totals between 60-135, while five cities (Ganzi Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, Zigong, Panzhihua, and Ziyang) had fewer than 60 projects, with Ganzi having the fewest at only 11 projects (Figure 2b [Figure 2: see original paper]). Compared with Hu et al.' s [24] statistics for 2003-2008, Luzhou and Chengdu remain at high levels provincially. Chengdu has dense population, the province' s lowest per capita cultivated land area, and acute human-land contradictions, but its developed economy yields the province' s highest GDP per unit land area and agricultural output value per unit cultivated land area, leading to more land consolidation projects. Regions with large numbers of municipal-scale projects basically concentrate in population agglomeration areas, demonstrating that land consolidation is important for resolving human-land contradictions. In contrast, Ganzi Prefecture has the highest per capita land resource possession but is constrained by geographic conditions, ecological fragility, frequent natural and geological disasters, and prominent grassland desertification and degradation issues, resulting in tightening resource and environmental constraints.

3.2 Gravity Center Movement Trajectory of Land Consolidation Projects The gravity center model has been widely applied in geography, and recent scholars have used it for spatio-temporal analysis of land consolidation investments [20]. This study focuses on "input and output" indicators, using ArcGIS 10.2 software to analyze gravity center movement trajectories.

3.2.1 Project Number Gravity Center Movement The overall movement trend of project number gravity centers from 2011-2015 (Figure 3 [Figure 3: see original paper]) shows north-south fluctuations. In terms of direction and distance: the 2011-2012 gravity center shifted southwestward by 57.77 km; during 2012-2013 and 2014-2015, investment gravity centers moved northwestward by 42.33 km and 29.04 km respectively, with greater north-south movement amplitude; the 2013-2014 period showed the largest movement distance (75.32 km) toward the southeast. Convergence relative to the reference point indicates improved overall spatial distribution equilibrium in Sichuan Province, with key consolidation areas and directions becoming increasingly stable and clear.

3.2.2 Construction Scale Gravity Center Movement Construction scale gravity centers show overall east-west fluctuation trends (Figure 4 [Figure 4: see original paper]), indicating that regional differences in project scale are more significant in the east-west direction. Regarding direction and distance: during 2011-2012 and 2014-2015, construction scale gravity centers shifted southwestward by 43.63 km and 40.31 km respectively; the 2012-2013 center moved northeastward by 59.81 km, and the 2013-2014 center moved southeastward by 27.99 km, showing large lateral movement amplitude. This occurs because terrain undulates significantly in the east-west direction with high west and low east topography, making construction scale closely related to location and terrain conditions.

3.2.3 Investment Scale Gravity Center Movement Investment scale gravity center movement shows primarily lateral shifts (Figure 5 [Figure 5: see original paper]), with consistency in movement direction between investment and construction scales. During 2011-2012 and 2014-2015, construction scale gravity centers shifted southwestward by 40.92 km and 55.09 km respectively; during 2012-2013 and 2013-2014, investment gravity centers moved northeastward, with greater eastward lateral movement amplitude, shifting 51.58 km and 42.13 km respectively. This reflects large east-west differences in provincial economic and social development levels but smaller north-south differences.

3.2.4 Newly-Added Cultivated Land Scale Gravity Center Movement The gravity center movement trajectory for newly-added cultivated land scale (Figure 6 [Figure 6: see original paper]) converges with investment scale gravity center movement, showing certain synchrony. The directional characteristics of newly-added cultivated land gravity center movement in each stage are consistent with construction scale gravity center movement. Movement distances for 2011-2012, 2012-2013, 2013-2014, and 2014-2015 were 52.50 km, 62.01 km, 50.25 km, and 68.22 km respectively. This indicates certain correlation between the two, confirming Wei et al.' s [22] argument about the relationship between newly-added cultivated land scale and investment scale—newly-added cultivated land scale is influenced by investment scale to some extent.

The most obvious common feature of all indicator gravity center movement trajectories is that all gravity center points fall within the Basin Hilly Agricultural Land Consolidation Zone. All annual gravity centers shift eastward relative to the benchmark gravity center (102°41 29.92 E, 30°37 44.83 N), moving to central Sichuan, with the easternmost point reaching Chuanshan District of Suining City. According to the "Sichuan Province Land Consolidation Plan (2011-2015)," the Chengdu Plain Comprehensive Improvement Zone, Basin Hilly Agricultural Land Consolidation Zone, Southwestern Sichuan Mountain Valley Agricultural Land Consolidation Zone, and Basin Peripheral Mountain Ecological Restoration Zone are designated as provincial-level key agricultural land consolidation areas. The eastward deviation of consolidation gravity centers indicates that eastern Sichuan remains the key consolidation area. During 2011-2015, the most major land consolidation projects in Sichuan were distributed in the basin hilly area, demonstrating that project spatial distribution is influenced by policy factors—consistent with Fan et al.' s [23] conclusion that policy is the guarantee for land consolidation implementation. Overall, the four indicators show poor consistency in longitudinal and latitudinal changes with fluctuating variations. In 2014, all indicator gravity centers were farthest from the geographic gravity center, indicating the most significant spatial distribution differences that year.

3.3.1 Global Clustering Characteristics GeoDA is commonly used software for calculating spatial autocorrelation coefficients. This study uses GeoDA to calculate Moran' s I for the five-year total "input" and "output" levels of counties (cities, districts) in Sichuan Province (Table 2), with all results passing Z-tests. The results indicate significant clustering in land consolidation distribution at the county scale, consistent with the spatial distribution patterns shown in Figure 2. The positive correlation effect of construction scale is higher than other indicators, and the bivariate distribution of investment scale and newly-added cultivated land scale also shows significant positive correlation.

3.3.2 Spatial Heterogeneity Analysis The most important aspect of spatial association analysis is identifying spatial clustering points or sub-regions. LISA (Local Indicators of Spatial Association) cluster maps generated from local autocorrelation analysis effectively indicate the spatial correlation degree between each region and its surroundings. Using GeoDA and ArcGIS software, LISA cluster maps visualize the spatial heterogeneity of land consolidation project "input" and "output" levels at the county scale (Figure 7 [Figure 7: see original paper]). In the maps, "high-high" indicates counties (cities, districts) with high land consolidation "input" and "output" values and high surrounding values—these adjacent sub-regions are "hotspot areas." "Low-low" represents "coldspot areas" with the opposite meaning. Units falling in these two zones show strong positive spatial correlation (homogeneity). "High-low" indicates counties with high values but low surrounding values, while "low-high" indicates the opposite—units in these zones show strong negative spatial correlation (heterogeneity). The analysis reveals:

(1) Overall, the LISA cluster patterns of all indicators from 2011–2015 are basically consistent with land consolidation potential but differ somewhat from cultivated land resource distribution, contrasting with previous studies concluding that land consolidation patterns align with cultivated land distribution in Chongqing [23] and Hubei [22]. This difference arises from Sichuan' s large topographic variations and significant location condition differences.

(2) From the perspective of clustering locations, high-high areas for project numbers do not show obvious contiguous clustering characteristics due to diversified project investment types and varying investment and construction scales across project types. High-high areas for other indica-

tors are mainly concentrated in the northeastern part of the Basin Hilly Agricultural Land Consolidation Zone. This region features hilly topography with some low mountains and valley plains, representing the main distribution area of purple soil in China, with abundant cultivated land resources, large areas of prime farmland, and concentration of the "Rebuilding a Dujiangyan Irrigation System through Grain Production Area Land Consolidation Major Project (Phase I)." It is also a key area for agricultural land consolidation and reclamation in Sichuan. During 2011–2015, this region strengthened agricultural infrastructure construction and actively transformed medium-low yield farmland, becoming a hotspot area for land consolidation. Low-low areas are mainly distributed in the Northwestern Sichuan Alpine Plateau Ecological Restoration Zone, which has large grassland areas and abundant cultivated land reserves but suffers from high elevation, steep slopes, limited cultivated land resources, harsh natural environments, strong ecological constraints, poor economic and technical conditions, and difficult land development and utilization. Low-high areas mainly surround high-high areas, with low-high areas for all indicators except newly-added cultivated land scale also distributed in some plain areas, indicating large construction land demand in these low-high areas and exploring "off-site compensation" for cultivated land reserves [25]. Among the four indicators, only newly-added cultivated land scale and investment-scale-influenced newly-added cultivated land scale have high-low areas, appearing only in Renhe District and Meigu County. Renhe District in Panzhihua City is located in the heart of the Sichuan-Yunnan-Guizhou resource golden triangle, with abundant land resources, sufficient light and heat, and high-quality cultivated land, thus possessing rich cultivated land reserves. Through comprehensive reclamation of land damaged by production, construction, and natural disasters, Renhe District has improved its ecological environment, ensured sustainable land resource utilization, and served as a demonstration for land reclamation in other districts and counties under Panzhihua' s jurisdiction.

(3) Regarding the number of counties (cities, districts) in each clustering type, the hotspot prefecture-level cities for land consolidation from 2011–2015 are mainly Bazhong, Nanchong, Mianyang, and Guangyuan in the Basin Hilly Agricultural Land Consolidation Zone, extending to the Chengdu Plain Comprehensive Improvement Zone and Basin Peripheral Mountain Ecological Restoration Zone. There are 19 high-high areas and 42 low-low areas for construction scale; 17 high-high and 35 low-low areas for investment scale; 20 high-high and 30 low-low areas for newly-added cultivated land scale; and 15 high-high and 37 low-low areas for investment-scale-influenced newly-added cultivated land scale. Thirteen counties are high-high areas for all four indicators: Yilong, Langzhong, Bazhou District, Pingchang, Tongjiang, Nanjiang, Cangxi, Jiange, Zitong, Yanting, Xichong District, Guanghan, and Shehong. All hotspot cities are located in northeastern Sichuan, a concentrated distribution area for population

and industry, which basically aligns with the higher coordination degree of the rural population-land-economy system in northeastern Sichuan [26]. Among these, Bazhou District, Pingchang, Yilong, and Shehong each have populations exceeding one million, again verifying the positive correlation between key land consolidation areas and population agglomeration.

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4. Conclusions and Recommendations

Based on 2011–2015 land consolidation monitoring and supervision data, this study employs gravity center modeling, spatial autocorrelation modeling, ArcGIS, GeoDA software, and mathematical statistics to investigate the spatio-temporal differentiation characteristics and gravity center shifts of land consolidation projects in Sichuan Province. The findings help deeply determine the regional characteristics and directionality of land consolidation in Sichuan and facilitate overall arrangement of future land consolidation work.

4.1 Main Conclusions

(1) From a temporal perspective, the total number of land consolidation projects in Sichuan Province shows a declining trend. This results from two factors. First, land consolidation projects have time lags. The separated bidding processes for different stages, asynchrony among planning, approval, design, implementation, and acceptance phases, and variations in institutional management and personnel quality cause project delays. An integrated implementation mechanism combining project planning, approval, design, implementation, and acceptance should be explored. Second, project planning and layout are influenced by location conditions, terrain, and national policies (such as two post-disaster reconstruction programs).

(2) Land consolidation project patterns in Sichuan show different characteristics across spatial scales. At the regional scale, projects concentrate in the Basin Hilly Agricultural Land Consolidation Zone, indicating that achieving macro-objectives of land consolidation must consider regional natural conditions as the background. At the municipal scale, projects mainly concentrate in Chengdu and Yibin, with fewer in Ganzi Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, and Panzhihua City, showing positive correlation between municipal-scale project numbers and population agglomeration.

(3) All indicator gravity center points fall within the Basin Hilly Agricultural Land Consolidation Zone. Consolidation gravity centers shift eastward relative to the geographic gravity center, showing certain regional equilibrium in spatial distribution. Land consolidation project spatial distribution is influenced by policy factors.

(4) Land consolidation projects show significant clustering at the county scale. High-high clustering areas concentrate in the northeastern part of the Basin Hilly Agricultural Land Consolidation Zone, while low-low clustering areas mainly distribute in the Northwestern Sichuan Alpine Plateau Ecological Restoration Zone. Rural population agglomeration, land consolidation layout, and economic development levels are interrelated and interact with each other.

4.2 Policy Recommendations

(1) Appropriately strengthen land consolidation investment in the Tibetan areas of northwestern Sichuan Plateau and the Yi areas of Greater Liangshan to improve spatial distribution equilibrium. The concepts of respecting, accommodating to, and protecting nature should be upheld. Scientific evaluation of ecological environment problems and spatial distribution characteristics should be conducted to optimize land consolidation project layouts, increase ecological land consolidation investment, and scientifically plan and implement demonstration projects in ecological protection areas.

(2) Integrate land consolidation work with targeted poverty alleviation efforts, synchronizing their frequencies and resonating their objectives. Focus on developing characteristic industrial economies, constructing ecological barriers, and assisting precise poverty alleviation and elimination. For example, Bazhong City closely integrates land consolidation projects with "Bashan New Residence"construction, linking project implementation with poverty elimination and infrastructure improvement to promote economic development in project areas.

(3) Strengthen top-level design and continue promoting "full-area coordinated" comprehensive land consolidation and "differentiated" regional land consolidation. Overall arrangements for production, living, and ecological land uses should be made to achieve coordinated development of the "three lives," integrate urban-rural land resources, and promote coordinated sustainable development. Based on regional differences and connections, comparative advantages of each region should be fully utilized to establish regionally focused distribution patterns, coordinate land consolidation across regions, and promote coordinated development between regional economies and land use.

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Note: Figure translations are in progress. See original paper for figures.