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Locational Drivers of Non-Cultivated Land Use in Heterogeneous Topographies: A Case Study of Sichuan Basin, China

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Abstract:	Food security remains a pressing concern for nations worldwide. A significant challenge arises from the non-cultivated use (NCU) of previously cultivated land, potentially reducing food production capacity. This study investigates the driving forces behind NCU in China's Sichuan Basin, a crucial agricultural zone. A sliding window method was employed to extract the NCU patches between 1991-2018, furthermore, the driving effects and pattern of NCU was explored by conducting multi-scale geographically weighted regression (MGWR) model across different regions. Our research reveals a critical finding: (1) The cumulative NCU area in the Sichuan Basin grew continuously from 1991 to 2018, with a notable net increase after 2005, peaking in 2015 before declining. This phenomenon expanded from peripheral mountainous areas to the basin interior and from urban centers to outskirts, showing a recent leapfrog-like aggregation trend. (2) The Heterogeneous impacts of locational factors across different regions were revealed: in mountainous areas, improvements in transportation and market accessibility would slow down NCU, whereas in plain areas, the opposite would be true. These findings highlight the need for differentiated policy measures to address NCU effectively, including increasing infrastructure investment and market capacity in mountainous areas to reduce transportation costs and incentivize land protection, while providing grain subsidies, technical support, and farm machinery rentals in plain areas to encourage sustainable land use and organizing the uniform planting of advantageous crops like fruits and tea to increase efficiency. By elucidating the spatial heterogeneity of NCU drivers, this study provides valuable insights for policymakers aiming to optimize land-use strategies and ensure long-term food security.
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Dear Editor of *Journal of Rural Studies*,

I am pleased to submit our manuscript titled "Locational Drivers of Non-Cultivated Land Use in Heterogeneous Topographies: A Case Study of Sichuan Basin, China" for consideration for publication in *Journal of Rural Studies*.

This study addresses a crucial issue in the context of global food security by exploring the drivers behind the non-cultivated use (NCU) of previously cultivated land in the Sichuan Basin, one of China's key agricultural regions. By applying a multi-scale geographically weighted regression (MGWR) model and using a sliding window method to analyze NCU patches from 1991 to 2018, our research reveals significant spatial heterogeneity in the factors influencing NCU across different regions within the basin.

The key findings of our study include the identification of a leapfrog-like aggregation trend in NCU expansion from peripheral mountainous areas to the basin's interior and from urban centers to their outskirts. Additionally, we uncover that locational factors such as transportation and market accessibility have opposing effects on NCU in mountainous versus plain areas. These insights underscore the necessity for tailored policy interventions to mitigate the adverse impacts of NCU and promote sustainable land use.

We believe that this research makes a valuable contribution to the field by providing a nuanced understanding of the spatial heterogeneity of NCU drivers, which can inform more effective land-use policies. The findings have practical implications for policymakers seeking to optimize land-use strategies and ensure long-term food security, not only in China but also in other regions facing similar challenges.

The manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have approved the manuscript and its submission to *Journal of Rural Studies*. We have adhered to ethical guidelines in conducting and presenting this research.

We hope that you will find our manuscript suitable for publication in *Journal of Rural Studies*. We look forward to your feedback and would be happy to address any questions or concerns you may have.

Thank you for considering our submission.

Sincerely,

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Highlights

- Applies sliding window to extract the NCU patches between 1991-2018 in Sichuan Basin
- Reveals the heterogeneous locational drivers of NCU by MGWR model
- Cumulative NCU area grew from 1991 to 2018, surged after 2005, peaked in 2015, then declined
- In mountainous areas, improvements in transportation and market accessibility would slow down NCU

Title: Locational Drivers of Non-Cultivated Land Use in Heterogeneous Topographies: A Case Study of Sichuan Basin, China

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Locational Drivers of Non-Cultivated Land Use in Heterogeneous Topographies: A Case Study of Sichuan Basin, China

Abstract: Food security remains a pressing concern for nations worldwide. A significant challenge arises from the non-cultivated use (NCU) of previously cultivated land, potentially reducing food production capacity. This study investigates the driving forces behind NCU in China's Sichuan Basin, a crucial agricultural zone. A sliding window method was employed to extract the NCU patches between 1991-2018, furthermore, the driving effects and pattern of NCU was explored by conducting multi-scale geographically weighted regression (MGWR) model across different regions. Our research reveals a critical finding: (1) The cumulative NCU area in the Sichuan Basin grew continuously from 1991 to 2018, with a notable net increase after 2005, peaking in 2015 before declining. This phenomenon expanded from peripheral mountainous areas to the basin interior and from urban centers to outskirts, showing a recent leapfrog-like aggregation trend. (2) The Heterogeneous impacts of locational factors across different regions were revealed: in mountainous areas, improvements in transportation and market accessibility would slow down NCU, whereas in plain areas, the opposite would be true. These findings highlight the need for differentiated policy measures to address NCU effectively, including increasing infrastructure investment and market capacity in mountainous areas to reduce transportation costs and incentivize land protection, while providing grain subsidies, technical support, and farm machinery rentals in plain areas to encourage sustainable land use and organizing the uniform planting of advantageous crops like fruits and tea to increase efficiency. By elucidating the spatial heterogeneity of NCU drivers, this study provides valuable insights for policymakers aiming to optimize land-use strategies and ensure long-term food security.

Keywords: Food security; Non-cultivated use; Multi-scale geographically weighted regression; Land use; Spatial analysis

1. Introduction

Food security is a critical issue facing nations globally today. Amidst the compounded risks of climate change, the COVID-19 pandemic, and geopolitical conflicts, the cost of nutritious food has soared, exacerbating inequalities and tightening global food security (Ziervogel and Ericksen, 2010; Paudel et al., 2023). Unsustainable farming practices, the exodus of agricultural populations, and the challenges faced by smallholder farmers have become prevalent worldwide (Veeck et al., 2020), with future global agriculture and food systems predicted to be even more vulnerable (Kapari et al., 2023).

As a prevalent phenomenon in global agricultural transformation, non-cultivated use (NCU) of cultivated land is currently an important factor affecting food security. Major regions and countries around the world are employing various policy measures to prevent the intensification of NCU phenomena. For example, China has implemented the Permanent Basic Farmland Policy (Wang et al., 2023), and the United States has established minimum scale requirements for major crops (Chaifetz and Jagger, 2014).

Other than non-agriculturalization, which refers to transforming agricultural land into construction land (Chen et al., 2022), NCU happens when forests, orchards, grassland, fishponds, or barren land replace cultivated land (Ansari et al., 2021). Although NCU won't lessen the absolute amount of agricultural land sources, it disrupts the existing soil structure to varying degrees, leading to a deterioration in soil quality and farming conditions, thus posing a hidden threat to food production (Su et al., 2014; Su et al., 2020). Currently, the identification and measurement of NCU are primarily based on economic statistics (Devi & Prasher, 2018), household survey data (Fraval et al, 2018), and national land survey data. These methods are typically limited in scale of study and are difficult to standardize across different years. Methods based on remote sensing and land use change data increasingly attract researchers' attention due to their lower costs and larger scale (Weiss et al., 2020; Zhang et al., 2022). However, studies based on land use classification over different time periods may have the issue of error accumulation.（Mueller-Warrant et al, 2016）.In contrast, some researchers have employed the sliding window method at the temporal or spatial level, making studies at the plot scale more detailed and continuous, and reducing errors through certain logical checks.(Goodwin et al., 2022; Pan et al., 2022).

There are many factors contributing to NCU, including natural conditions, socio-economic conditions, and population characteristics, whereas NCU is essentially a behavior aimed at maximizing benefits. It is generally accepted that that comparative economic advantages drive the phenomenon of NCU (Ito, 2020). Traditional field crops, such as rice and wheat, usually have price constraints that do not satisfy farmers' pursuit of high economic benefits (Brett, 2010). As the structure of residents' agricultural product consumption becomes diverse, the market demand also shows a trend of diversification (Chegere and Stage, 2020). Some policy factors also act as catalysts behind the NCU phenomenon. For instance, in China, the liberalization of land transfer, and the government's long-standing efforts to eradicate rural poverty and restore the ecological environment have, to some extent, led to diverse agricultural production (Yang and Zhang, 2021). In the United States, the Conservation Reserve Program (CRP) encourages farmers to remove environmentally sensitive land from agricultural production, thus reducing the amount of farmland（Hendricks & Er, 2018). In Ghana, neoliberal economic policies and urban expansion have significantly impacted agricultural land use. The Structural Adjustment Program and the oil industry's development have driven land use changes, resulting in reduced agricultural lands and increased urban areas. (Acheampong et al., 2018).

In addition, NCU is associated with regional resource endowments, long-term agricultural production habits, economic development levels, and the agricultural labor force (Liang et al., 2021). Existing research has explored how topographical conditions, farmland quality, and farmland size affect agricultural production decisions. Generally, the proportion of NCU is higher in mountainous areas than in plains(Zhang et al., 2023; Han et al., 2022), with decreases in farmland quality (Wang et al., 2019), worsening water resource conditions (Zhang et al., 2021), and excessively large or small farm sizes(Chen and Kong, 2016) all contributing to the trend of NCU. Since NCU is labor-intensive while traditional farming is land-intensive, the out-migration of rural labor and aging of the workforce lead to a decrease in labor input, thereby weakening the diversification of production(Luo & Qiu, 2018; Qian et al., 2016; Zhong et al., 2016), but this also leads to the possibility of cultivated land abandonment (Liu, 2022; Xu et al., 2019). Existing studies have also examined how factors such as the gender of farmers (Gebre et al., 2019), their education levels (He et al., 2019), health conditions (Kamdem, 2020), the average operational size of family labor (Al-Amin et al., 2019), and the structure of income sources (Chang et al., 2022) affect farmers' production decisions. However, some critical factors may still influence NCU, such as geographic location, which have not been adequately discussed in previous studies due to insufficient theoretical attention or existing controversies. In fact, locational factors not only help explain the reasons for the formation of NCUs in different regions but also facilitate the implementation of policies, such as improving transportation and market accessibility. Therefore, this factor requires more detailed exploration in the study of NCU, Even though this factor is difficult to quantify as clearly as socio-economic or demographic elements.

To fill the existing knowledge gap in the literature, this study analyzes the impact of geographic location on non-cultivated use (NCU) of cultivated land using multi-source socioeconomic and remote sensing data from 1981 to 2018. The research employs a sliding window approach and multi-scale geographically weighted regression (MGWR) methods, with the Sichuan Basin, a region characterized by complex terrain, serving as a case study. We seek to address the following research questions: (1) What are the temporal and spatial patterns of NCU in the Sichuan Basin over the past 30 years? (2) How did locational factors impact on NCU spatial heterogeneously? (3) How can differentiated intervention policies be formulated?

2. Theoretical framework

2.1 The concept of non-cultivated use (NCU)

Non-cultivated use refers to transforming original cultivated land into other agricultural land types such as forests, orchards, grasslands, and wastelands. In China, the commonly used concept of non-grain use among scholars shares similarities with NCU, referring to the transition of farmland from planting food crops to cultivating cash crops, forest fruits, or breeding (Su et al., 2016). The distinction between them is that NCU focuses only on macro changes in land use types without concerning the micro-level changes in crop planting (Liang et al., 2021), whereas non-grain use encompasses both macro and micro-level meanings. Both concepts fall within the scope of agricultural adjustment behaviors, closely tied to farmers' interests(Makate et al., 2016; Meraner et al., 2018). They reveal the inherent conflict between land operators' rights to use land for agricultural production for maximum profit and the national goals of cultivated land protection.

Another concept frequently used in academia is "cropland abandonment," which refers to the cessation of farming on a given cultivated land, typically followed by natural revegetation (Lasanta et al., 2020). Cropland abandonment is considered likely to occur on marginalized lands with a loss of agricultural labor or poor agricultural conditions (Wang & Song, 2021; Han & Song, 2019). Unlike cropland abandonment, non-cultivated use does not differentiate the reasons for the transformation of farmland into other natural land classes and can include situations of cropland abandonment and scenarios where farmers actively adjust their agricultural practices.

2.2 The heterogeneous impact of geographic location on NCU

Geographic location largely determines the most suitable use of farmland. Rational farmers choose to maximize output by deciding whether to engage in non-cultivated use. From the perspective of land rent, areas with higher land productivity near urban suburbs often prioritize planting fruits, precious seedlings, and flowers instead of field crops to meet urban market demands (Barlowe，1978; Pribadi & Pauleit，2015; Ghosh, 2021). As the distance from the farmland to the city increases and land rent decreases, the land will continue to be used for planting field crops such as grains (Wang et al., 2024). Studies also indicate that when farmland is sufficiently distant from urban areas, local farmers might plant forests to alleviate poverty or opt for land abandonment to reduce labor input, thus leading to NCU again (Ge et al., 2019; Vongvisouk et al.，2014).

The perspective of land rent provides a basic explanation for the distribution of NCU, while the situation becomes more complex in specific empirical contexts. Many scholars have discussed NCU with convenient transportation and developed market accessibility, but no consensus has been reached yet. Most scholars believe that convenient transportation and developed markets facilitate the transition of farmland to diversified agricultural production, making it more likely to see manufactured transformations into woodlands, grasslands, or even fishponds (Balogun et al., 2023; Li et al., 2021). However, some scholars argue that improved transportation and road conditions help reduce farmers' agricultural production vulnerability, thus eliminating the need for diversified production methods to cope with climate change and livelihood risks (Nguyen et al., 2016). In socio-economically less developed mountainous areas with small per capita farmland, many farmers continue to engage in agricultural production to earn a basic income, and conveniently located quality farmland is used sustainably (Yang et al., 2022). The impact of transportation and market location conditions on NCU must be understood in the context of the specific location of the land plots. Agricultural decision-making by farmers is a complex and comprehensive process. As mentioned in the introduction, considering natural endowments, the proportion of NCU in mountainous farmlands is generally higher than in plains. However, considering effective labor supply and comparative profits, the conclusion is not singular. Hence, we propose a theoretical hypothesis: **In mountainous areas, the improvement of transportation infrastructure and market conditions predominates in mitigating farmland abandonment, thus reducing the incidence of NCU; in plain areas, the improvement of locational conditions leads to the pursuit of economic profits from NCU, therefore increasing the incidence of NCU**.

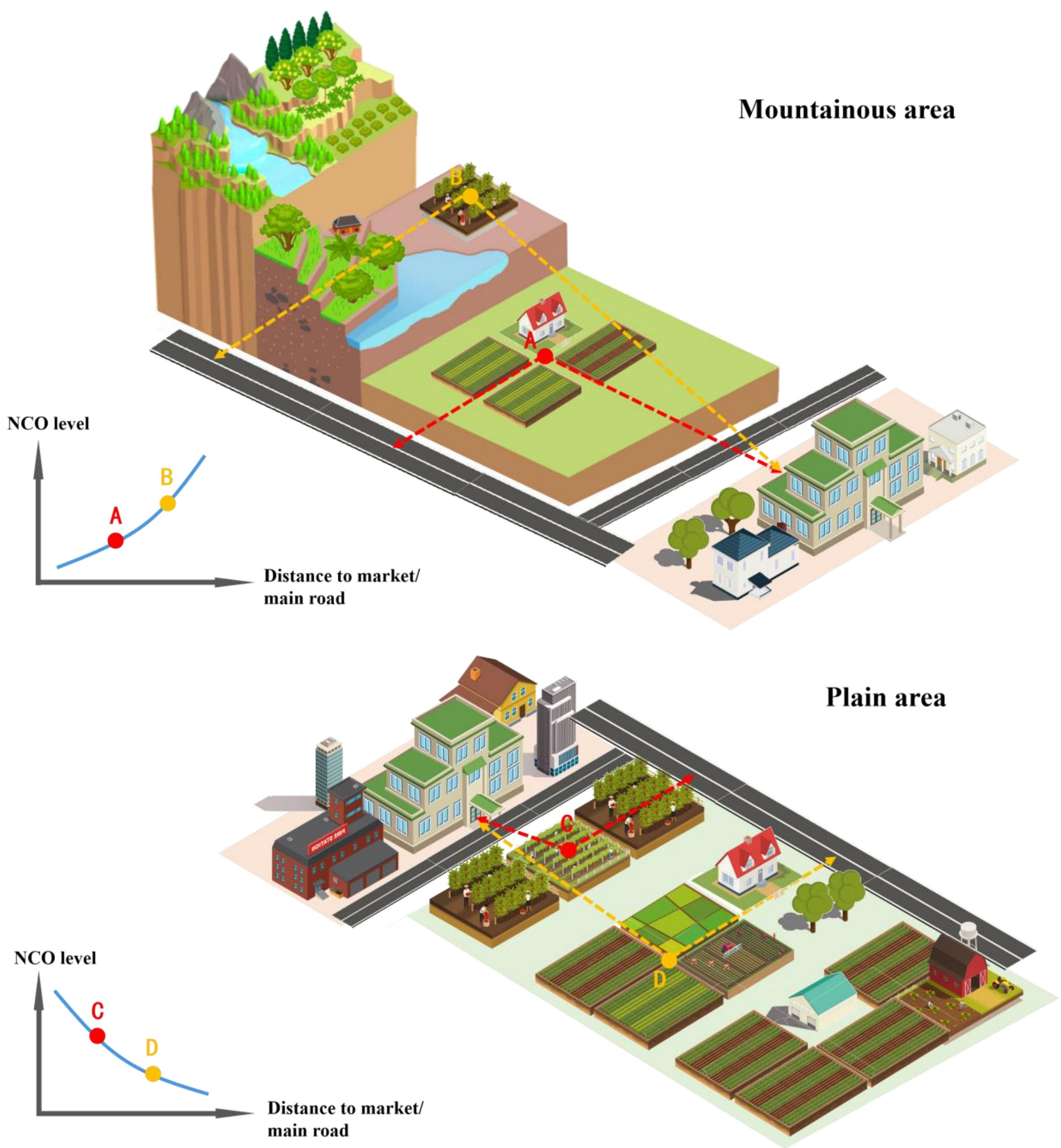

Figure 1 Conceptual framework of the impact of locational factors on NCU

3. Study area and data sources

3.1 Study area

The study area, as shown in figure 2, located in the Sichuan Basin in central-eastern Sichuan Province, is encircled by highlands and mountains, including the Tibetan Plateau, Yunnan-Guizhou Plateau, Daba Mountains, and the Three Gorges of the Yangtze River. The basin is structured west to east from the Chengdu Plain, central hills, to the eastern gorges, with hill and mountain areas in the north and south, encompassing seventeen province-level cities. In 2020, the region generated a gross domestic product of 4,500.243 billion yuan, with a permanent population of 72.71 million, accounting for 93% and 90.4% of the province's total, respectively. The value-added output ratios for the primary, secondary, and tertiary sectors were 11%, 36%, and 53% respectively.

Over time, the complex natural conditions have shaped a distinct agricultural production landscape in the Sichuan Basin. It is China's most extensive base for medicinal materials and aromatic oils and is renowned for its citrus fruits and kiwifruits. The basin houses over 85% of the province's cultivated land and some orchards, with the surrounding mountainous areas predominantly used for forestry and pasture. Among these, the Chengdu Plain in the west, being early developed, has a high land utilization rate, producing crops like rice, wheat, and rapeseed, and is one of the most suitable areas for tea and kiwifruit; cultivated lands in the hilly areas are planted with mulberry, tea, citrus, and tung trees; gentle slopes and village areas are commonly planted with citrus, apples, and bamboo; tobacco and wild medicinal herbs are primarily grown in the peripheral mountain areas.

Under the combined influence of historical planting practices, agricultural structural adjustments, and the influx of industrial and commercial capital to rural areas, the NCU trend in the Sichuan Basin has become increasingly prominent in recent years. From the perspective of agricultural industrial structure, according to the third national land survey, the total area of cultivated land in Sichuan decreased by approximately 1.4928 million hectares (about 22.2%) compared to the second survey. In comparison, orchard areas increased by 436,200 hectares (about 56.9%), and forest areas increased by 3.2176 million hectares (about 14.5%). Additionally, the devastating Wenchuan earthquake on May 12, 2008, severely affected the western and northern parts of the Sichuan Basin, exacerbating soil erosion and loss. The post-disaster reconstruction efforts focused on converting farmland back to forest and soil conservation, further promoting the trend towards NCU.

Overall, the Sichuan Basin, as a study subject for NCU, has the following typical characteristics. First, the basin's diverse natural conditions, terrain, and climate can provide a reference model for NCU management across China's topographical and climatic regions. Second, it has a generally solid agricultural foundation with a long history of diversified agricultural production, and there is significant spatial differentiation in types of agricultural land. Third, it has historically experienced major natural disasters and enjoys a positive economic development trend. The rapid expansion of NCU necessitates a balance among agricultural, ecological, and economic sectors, making it suitable for exploring driving mechanisms and policy analysis.

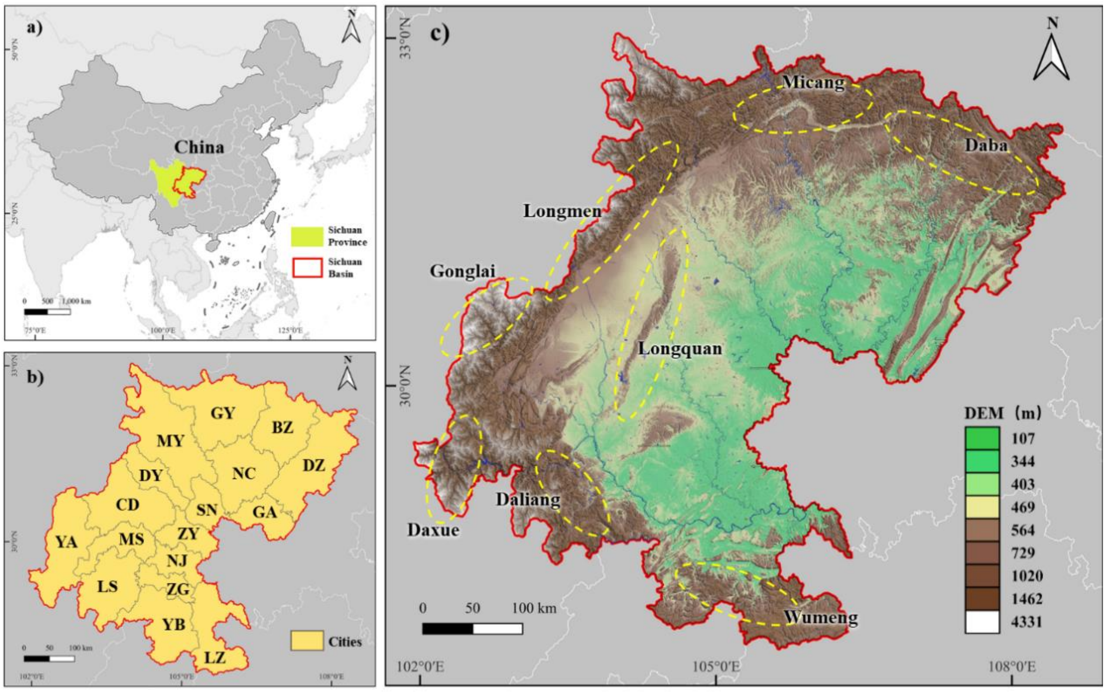

Figure 2 Overview map of the study area

Note: a) Location of Sichuan Province and Sichuan Basin; b) Cities included in Sichuan Basin (BZ: Bazhong, CD: Chengdu, DY: Deyang, DZ: Dazhou, GA: Guang'an, GY: Guangyuan, LS: Leshan, LZ: Luzhou, MS: Meishan, MY: Mianyang, NC: Nanchong, NJ: Neijiang, SN: Suining, YA: Ya'an, YB: Yibin, ZG: Zigong, ZY: Ziyang); c) The topography of Sichuan Basin and the names of the main mountain ranges.

3.2 Data sources

The spatial data used in this article includes Land Use and Cover Change, Digital Elevation Model, Soil Organic Matter, Meteorological Data, socioeconomic data, and Demographic Data, as detailed in Table 1. We processed all collected data using the Geographic Information System software platform ArcGIS 10.8, standardized to the "WGS_1984_UTM_Zone_48N" coordinate projection system, and used the vector boundary of the Sichuan Basin as a mask to extract and clip the data.

Table 1 Data descriptions and sources

Data Type	**Data Name**	**Attribute**	**Temporal Resolution**	**Spatial Resolution**	**Sources**
Land Use and Cover Change	CLCD	grid	1990-2021	30m	https://doi.org/10.5281/zenodo.5816591
Digital Elevation Model	GDEMV3-30M	grid	-	30m	https://www.gscloud.cn/
Soil Organic Matter	HiHydroSoil（v2.0）-ORMC	grid	2020	250m	https://www.futurewater.nl/publicaties/
Meteorological Data	GPRChina Temp	grid	2018	1000m	http://doi.org/10.5281/zenodo.5111989
	Monthly precipitation data set with 1 km resolution in China from 1960 to 2020	grid	2018	1000m	https://doi.org/10.11922/sciencedb.01607
Socioeconomic Data	POI of the administration center	shapefile	-	-	https://lbs.amap.com/

	Main road	shapefile			https://www.openstreetmap.org/
	NPP-VIIRS 2018	grid	2018	0.004 degree	(http://www.resdc.cn/DOI),2022.DOI:10.12078/2022090902
Demographic Data	The spatial distribution of population in 2018, China	grid	2018	1000m	https://dx.doi.org/10.5258/SOTON/WP00645
	China 100m Age Structures in 2018	grid	2018	1000m	https://dx.doi.org/10.5258/SOTON/WP00646

4. Methods

4.1 Detecting NCU by sliding window

China Land Cover Annual Dataset (CLCD) (Yang and Huang, 2022)was employed as the baseline data for extracting temporal changes in land cover patches. By selecting sampling points of different land use types from various years within the study area, we conducted an accuracy validation for this dataset. The Overall Accuracy reached 86.0%, meeting the requirements for proceeding with the next steps of our analysis. Initially, the dataset underwent temporal filtering and logical reasoning checks to generate a sequence of cultivated land patches from 1991 to 2021. Subsequently, a sliding window method was applied to inspect cultivated land patches annually to enhance data continuity (Tian et al., 2021; Kulanuwatl et al., 2021) . The specific approach was as follows, referencing the approach raised by Zhang et al.(2023): all cultivated land classes in the dataset were labeled as 1, and all other land classes as 0. For each pixel unit, the land class values from the previous year and the following year of each inspected year between the second and penultimate years were collected, setting the sliding window length to three years. For each sliding window, if the average value across three years was not less than two-thirds, the inspected year was marked as 1; if the average value did not exceed one-third, the inspected year was marked as 0. Consequently, all pixel units assigned a value of 1 were designated as cultivated land, and those assigned a value of 0 as non-cultivated land for that particular year.

Building on this inspection, non-cultivated land was further classified into impervious surfaces and other agricultural lands, including forest, shrub, grassland, water, snow/ice, barren and wetland, with pixels that had ever been impervious surfaces during the study period excluded from the analysis. Subsequently, a four-year sliding window was used to detect transitions from cultivated land to other agricultural land types. If a pixel's assignment changed from 1 to 0 and continued to be 0 for the following three consecutive years, it indicated a transition to NCU, and the year of change was marked as the occurrence year of the NCU. This process yielded annual additions of NCU land pixels from 1991 to 2018. Using historical satellite images provided by Google Earth Pro and time-series NDVI data from Google Earth Engine APPs, we verified the accuracy of the occurrence years of these NCU land pixels. The results indicate that the years of NCU occurrence calculated using the sliding window method are 88.0% completely accurate, and 91.3% of the years have an error margin controlled within one year before or after the actual occurrence.

In further analysis, to exclude the recultivation of NCU patches during the study period and to determine the extant NCU pixels at the end of the period in 2018, the study extracted the cultivated land patches for 2018 and compared them with the annually added NCU pixels. If a NCU pixel had reverted to a cultivated land patch by the end of the study period, it was marked as "recultivated" and deducted from the cumulative NCU patches at the end.

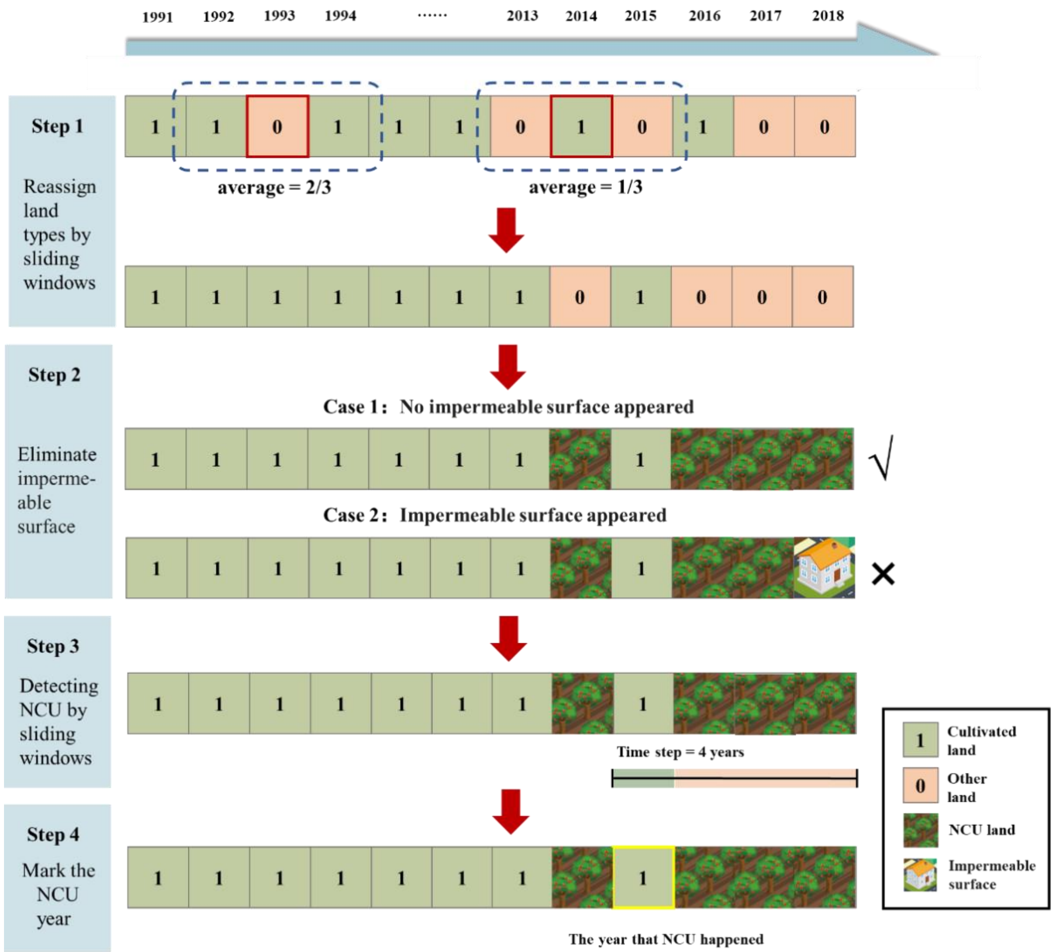

Figure 3 The process of sliding window method

4.2 Multi-scale Geographically Weighted Regression (MGWR)

The MGWR model is an improvement on the traditional classical GWR model, allowing the exploration of spatial relationships between explained variables and explanatory variables at different scales by adaptive adjustments of bandwidth distinct for each explanatory variable. A wider bandwidth indicates a wider spatial influence and more universal driving forces, while a narrower bandwidth links with more significant heterogeneity in local influence. The formula for the MGWR model is as follows:

$$y_i = \beta_{bwo}(u_i, v_i) + \sum_{j=1}^{m} \beta_{bwj}(u_i, v_i) x_{ij} + \varepsilon_i \tag{1}$$

In Equation(1), (u_i, v_i) represents the spatial coordinates of the sample point i. bwj represents the bandwidths utilized to calibrate the j th conditional relationship (Fotheringham et al., 2017). $\beta_{bw0}(u_i, v_i)$ represents the estimated intercept coefficient at (u_i, v_i). $\beta_{bwj}(u_i, v_i)$ is the regression coefficient at (u_i, v_i) for the jth explanatory variable. ε_i is the random disturbance term. The MGWR model used in this study was constructed using the MGWR 2.2 software developed by Oshan et al. (2019). The adaptive bi-square was selected as the kernel function for computing the weight matrix, AICc as the criterion for optimal bandwidth determination, and SOC-f as the convergence criterion.

4.3 Spatial Sampling and Variable Selection

Using the absolute level of NCU, such as the area of NCU or its proportion within the study units, as the dependent variable may present unfair levels of NCU among study units with significant disparities in basic cultivated land amount, thus introducing biases in the driving analysis. Therefore, based on the NCU temporal patches extracted in Section 3.2 for the year 2018, we calculate the NCU area and cultivated land in each study unit. The following formula is used to compute the relative level of NCU, which is the dependent variable of the driving analysis.

$$\text{the level of NCU} = \frac{area\ of\ NCU}{area\ of\ NCU + area\ of\ cultivated\ land} \tag{2}$$

We focus on the impact of locational factors on NCU, selecting "Distance to the nearest administrative center (county level)" and "Minimum distance to the main road" as independent variables, as discussed in the theoretical framework section. Additionally, given the complex and diverse topography of the study area, ranging from the periphery to the basin's interior with significant terrain undulations and varying soil development, the unique basin structure and windward slope topography lead to local differentiation in temperature and precipitation patterns. These factors influence agricultural production decisions, making controlling for topographic, soil, and meteorological factors necessary. Moreover, demographic factors, including gender ratio and dependency ratio, reflect the structural characteristics of the agricultural labor force, which indirectly affects the choice of agricultural structure. These are also considered as control variables in this study. The description of variables is shown in Table 2.

Table 2 Definition and descriptive statistics for variables

Variable type	Dimension	Variable Name	Abbreviation	Mean	STD	Min	Max
Dependent variable	-	NCU level	nongrain	17.27	16.75	0.08	97.22
Independent variable	Location factors	Distance to the nearest administrative center	min_center	16622.42	8584.55	524.44	46757.07
		Minimum distance to the main road	min_road	1863.95	2126.07	0.30	17152.19
Control variable	Topographic and soil factors	Soil organic matter content	soil_organ	19792.18	5925.26	11008.00	62264.00
		Slope	slope	10.54	7.28	0.33	57.67
	Meteorological factors	Annual average temperature	temper	17.44	1.03	10.87	19.22
		Annual precipitation	total_pre	1209.56	198.62	849.13	2031.83
	Economic factors	Nighttime light index	npp	0.88	2.71	0.11	81.70
	Demographic factors	Labor force gender ratio	gender	100.53	3.95	91.00	118.04

	Population dependency ratio	dependency	67.19	11.37	32.78	88.84
	Total population number	demo_count	2.82	5.07	0.00	184.62

The driving analysis in this article uses 5km x 5km plots as research units, with the center point of each unit serving as the sampling point. Subsequently, the cultivated land patches and impervious surface patches from the CLCD data spanning 1991 to 2018 were overlaid to define the total cultivated and impervious surface areas, respectively. Sampling points within plot units that had no cultivated land patches or that fell exactly on impervious surfaces were then eliminated. The spatial attributes of dependent and independent variables were assigned to the remaining sampling points. Sampling points with missing or anomalous spatial values were removed, ultimately retaining 3,219 sampling points for the driving analysis.

5. Results

5.1 Spatiotemporal Characteristics of NGU

As depicted in Figure 4, the spatial distribution of newly added NCU patches in the early 1990s predominantly clustered in the western parts of Chengdu, western Meishan, and eastern Ya'an within the Chengdu Plain. These areas, influenced by the trends of the Gonglai Mountains, Longmen Mountains, and Longquan Mountains, showed a narrow distribution pattern. Scattered distributions were also noted in the southern hilly regions of Yibin and Luzhou, the southeastern parts of Mianyang, and the southern hills of Bazhong.

Towards the late 1990s and the beginning of the new century, new NCU patches mainly spread across the northern and southeastern hilly areas of the basin, as well as along the eastern mountain ranges parallel to the basin, focusing primarily around the cities of Guangyuan, Dazhou, Bazhong, Yibin, and Luzhou. Additionally, a significant aggregation of NCU land emerged around the outskirts of central Chengdu, expanding radially over time. Over the past decade, NCU phenomena have predominantly manifested in dotted clusters around the central urban areas of Meishan, Ziyang, Suining, and Nanchong, as well as near secondary centers in the greater Chengdu area, with distributions being relatively dispersed and distant from the original NCU zones. Overall, the trend of NCU land over the past thirty years can be summarized as an expansion from the peripheral mountainous and hilly areas into the interior of the basin and from the Chengdu Plain and urban centers outward, with a noticeable recent leapfrogging pattern of dotted clustering.

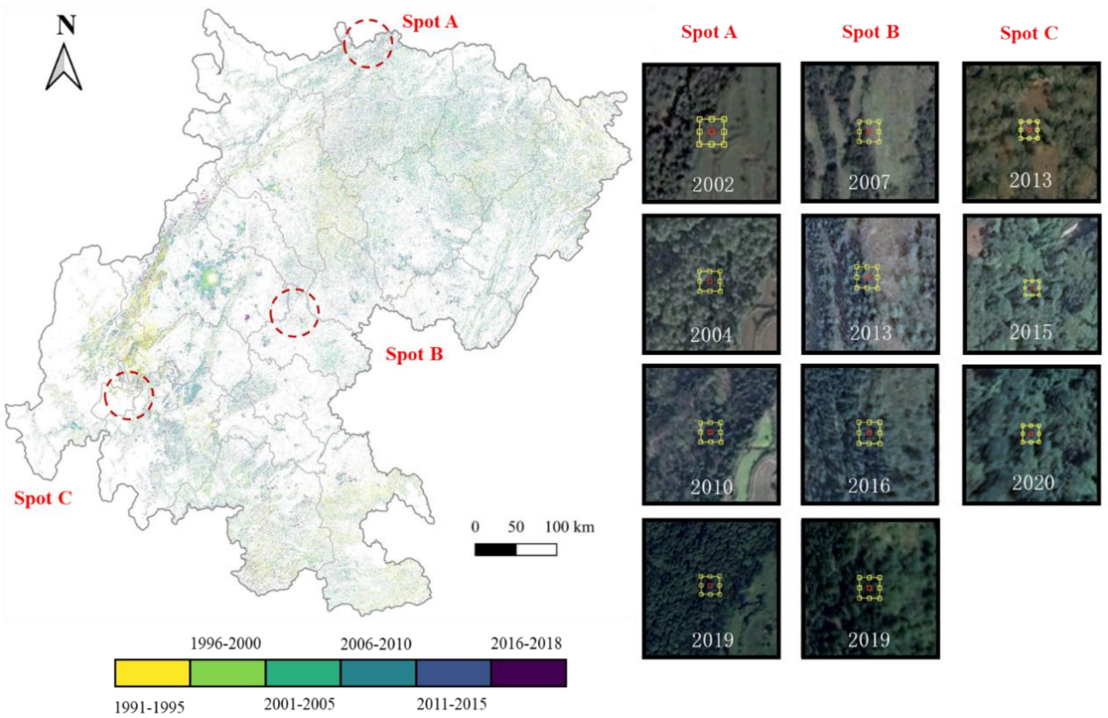

Figure 4 Spatiotemporal dynamics of NCU in the Sichuan Basin

As shown in Figure 5, from 1991 to 2018, the cumulative area of NCU land in the study area continued to grow. The growth rate was relatively stable before 2005, after which there was a noticeable increase in the net additional area. The annual increase in NCU land displayed a fluctuating growth trend, from 1995 to 1997 experiencing a low point, followed by a rebound. The peak years for NCU growth were 1991, 1993, 2007, 2012, and 2015, with the highest increase in NCU area reaching 2,631 square kilometers in 2015, before rapidly declining. By 2018, the increase in NCU area had fallen back to 677 square kilometers. The recultivated farmland is predominantly found along the Longmen Mountains, Longquan Mountains, the northern hilly regions, and the southern Wumeng Mountains. Most of these reclaimed plots were subjected to NCU in the late 1990s and early 2000s.

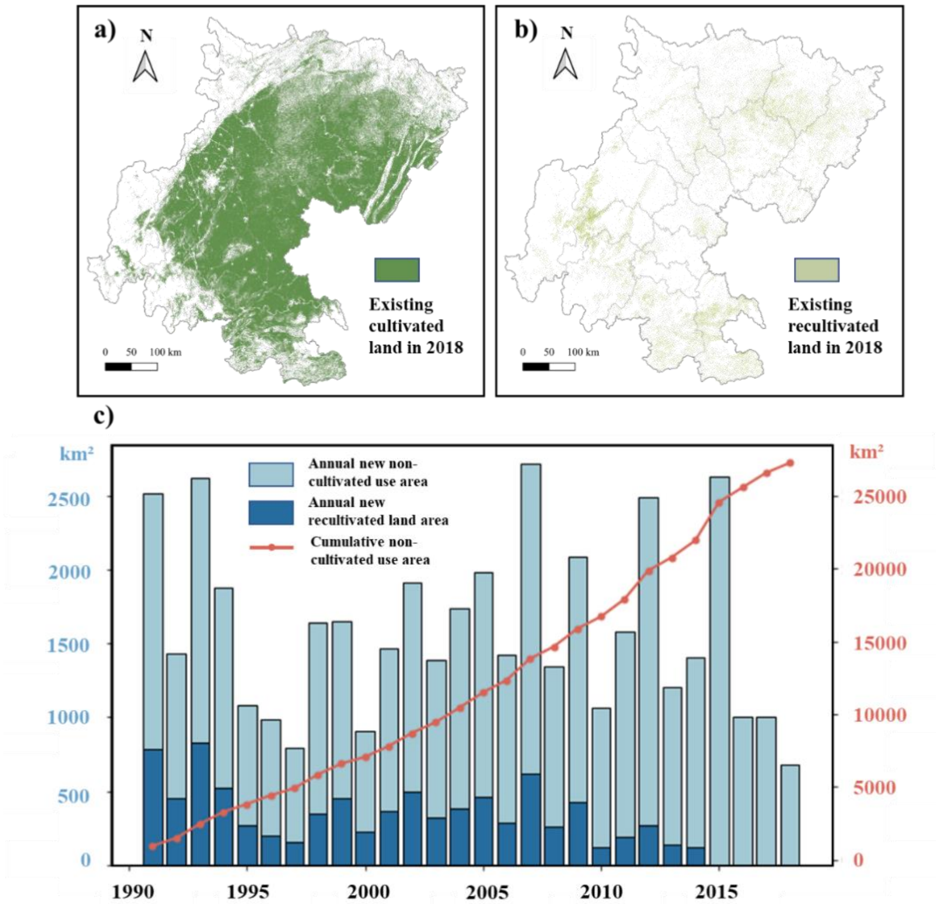

Figure 5 Cultivated land, recultivated land and annual changes of NCU Area in the Sichuan Basin

5.2 Investigation of NCU Driving Factors

5.2.1 Spatial Scale Effects of the MGWR Model

The adjusted R-squared of our MGWR model is 0.857, indicating that the overall model fit is quite good. The Table 3 shows the statistical characteristics and significance of the regression coefficients for each variable. Generally, natural factors have many significant samples, with those significant at the 95% level exceeding 50% and the significant samples for annual precipitation reaching 100%. Economic and population factors generally have a lower proportion of significant samples, except for the Nighttime light index, where more than half of the samples are significant at 95%, while other indicators do not exceed half. The samples significant at the 95% level for the variables we focused on, Distance to the nearest administrative center and Minimum distance to the main road, are 26.47% and 51.97%, respectively, and at the 90% significance level, the proportions are 35.88% and 63.75%, respectively. Regarding the regression coefficients, apart from the coefficients for precipitation, slope, and soil organic matter being positive, the impact of other variables on NCU exhibits multi-directionality across the entire study area. The mean coefficients for distance to the nearest administrative center, minimum distance to the main road, labor force gender ratio, population dependency ratio, and total population number are close to zero. This indicates that the global impact direction of these factors on NCU cannot be determined and they exhibit significant locality.

Table 3 Descriptive Statistics of MGWR Model Regression Results

Variable	**Coefficient**			**Percentage of Sample Points by Significance of t-Test （%）**	
	Min	**Mean**	**Max**	**P≤0.05**	**P≤0.1**
Intercept	-1.67	0.02	1.14	68.38	73.47
min_center	-0.74	-0.03	1.02	26.47	35.88
min_road	-0.13	0.04	0.12	51.97	63.75
NPP	-0.50	0.17	0.57	54.49	65.80
gender	-0.29	0.01	0.37	35.45	44.86

dependency	-2.19	0.03	4.24	25.29	32.18
demo_count	-0.47	-0.03	0.23	15.81	22.65
total_pre	0.17	0.21	0.28	100.00	100.00
slope	0.02	0.07	0.16	90.87	94.16
temper	-3.22	-0.61	0.34	77.76	80.80
soil_organ	0.02	0.03	0.04	57.56	76.79

The MGWR (Multi-scale Geographically Weighted Regression) model allows for spatial variation in parameter estimation and generates unique optimal bandwidths for the relationship between the dependent and independent variables. The figure illustrates the optimal bandwidths and the standard deviations of the regression coefficients for different variables. The results indicate significant differences in optimal bandwidths across variables. The bandwidth for the variable "Distance to the nearest administrative center" is very small, indicating a minor scale of impact on NCU with pronounced regional heterogeneity. In contrast, "Minimum distance to the main road" has a slightly larger bandwidth but is still below average. For natural factors, except for temperature, other elements exhibit larger bandwidths, especially soil organic matter, which shows its global impact on NCU. The bandwidths for economic and demographic factors are smaller than the average, indicating that variables characterized by settlements exhibit significant locality. Overall, the MGWR model in this study helps reveal the spatial non-stationarity of influencing factors and explain the scale effects of different independent variables.

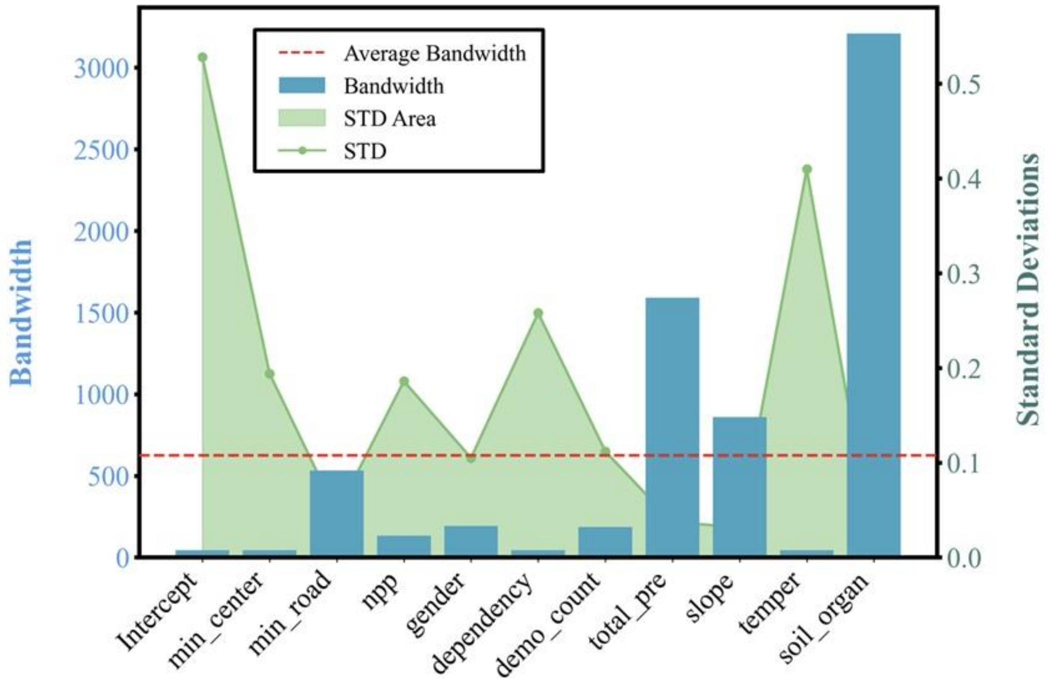

Figure 6 Bandwidths and standard deviations of variables in MGWR model

5.2.2 Spatial variation characteristics of MGWR model coefficients

As depicted in the Figure 7, in the Chengdu Plain area and the interior plains of the basin, the "Distance to the nearest administrative center" shows a negative correlation with the NCU level, meaning that the closer it is to the administrative center, the more likely it is to transform from cultivated to non-cultivated land. In the northern mountainous regions of the basin and the southwest Daliang Mountains area, the farther from the administrative center, the more likely the NCU phenomenon occurs. Similarly, in the Chengdu Plain area between Longquan Mountain and Longmen Mountain, proximity to the main roads increases the likelihood of NCU, whereas in the southern mountainous and hilly areas, northern mountains, and the eastern parallel mountain ranges, the farther from the main roads, the more likely NCU occurs. In the MGWR model, the intercept represents the impact on the dependent variable due solely to spatial context after all other variables are constant. In this study, the intercept exhibits negative values in the central plain area and positive values in the northern and southern mountainous and hilly areas, indicating that, after controlling for other factors, the central plains are more inclined to maintain existing cultivated land use, while there is still a strong tendency for NCU in the mountainous and hilly areas.

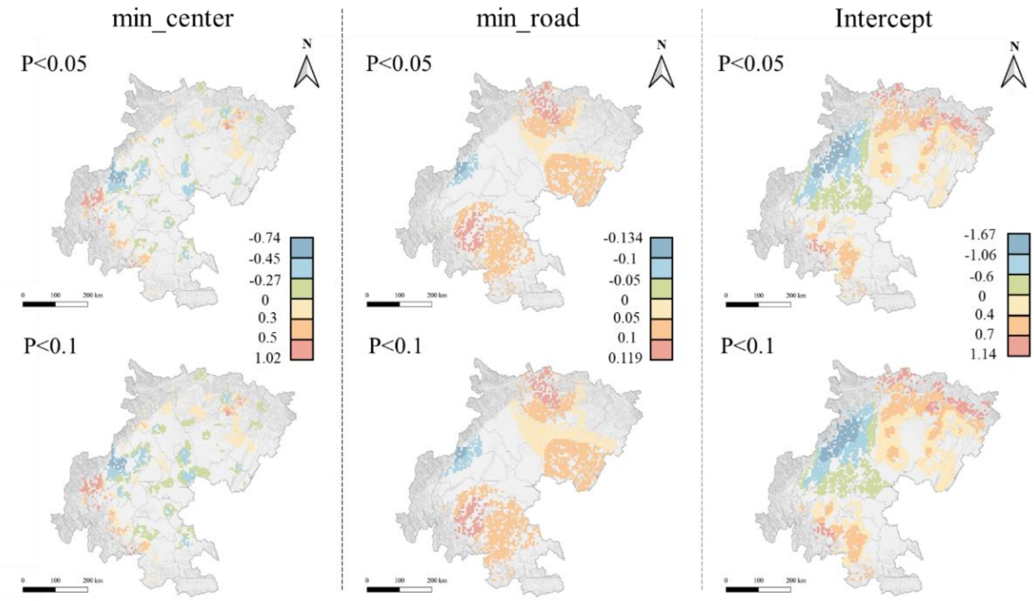

Figure 7 Spatial Distribution of MGWR Regression Coefficients at 95% ($p < 0.05$) and 90% ($p < 0.1$) Significance Levels

To further substantiate our findings, we have plotted scatter diagrams (Figure 8) depicting the differential historical recultivation patterns in mountainous and plain areas. For plain areas, we applied selection criteria of terrain undulation less than 100 meters, elevation less than 500 meters, and slope less than 10 degrees. Conversely, for mountainous areas, the criteria included terrain undulation greater than or equal to 200 meters, elevation greater than or equal to 500 meters, and slope greater than or equal to 20 degrees. As illustrated in Figure 8, historically, the extent of recultivation in mountainous regions has generally been higher than that in plain areas. This disparity is attributed to the pronounced marginalization characteristics of land in mountainous regions, where the instability of land use structures is more evident (Exner et al., 2015). With increasing distance from the nearest administrative center and the main road, the trend of recultivation of NCU (non-cultivated units) plots in mountainous areas demonstrates a significant decline. In contrast, plain areas exhibit a slight upward trend. This indicates that in mountainous regions, plots with locational advantages are not only less prone to NCU phenomena but are also more readily recultivated into arable land if they do occur. For plain areas, only relatively remote regions are more susceptible to reverting from high-value land use back to arable land; however, the recultivation trend remains subtle and the proportion is minimal.

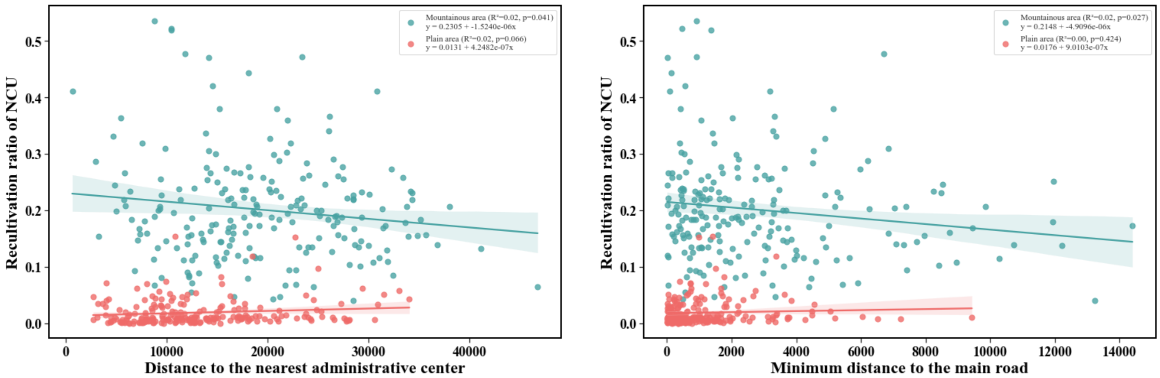

Figure 8 Impact of Locational Factors on Recultivation Ratio

6. Discussion

6.1 Possible Explanation of the Temporal and Spatial Changes in NCU

To understand the spatio-temporal patterns of NCU, it is necessary to comprehend the historical agricultural structural adjustments, which are potential drivers of NCU. In the early 1990s, China underwent its first agricultural restructuring to improve the dietary structure of its residents, aiming to alter the heavy proportion of grain crops in Chinese agriculture. However, this adjustment also prohibited private activities such as digging fish ponds, planting fruit trees, or afforestation on cultivated land. This restructuring was a major shock to the existing agricultural industrial structure, but planting habits were not completely reversed. As a result, new types of NCU plots showed an unstable fluctuating trend. The second agricultural adjustment in 1998 targeted issues such as the overall low quality and lack of competitiveness of agricultural products. Oriented by both domestic and international markets, zonal cultivation of advantageous agricultural products gradually took shape. During this period, the Sichuan Basin was tasked with developing industries like citrus, tea, medicinal materials, and large-scale herbivorous livestock. Thus, during the ten years of this second restructuring, there was a fluctuating increase in NCU.

The "5·12" Wenchuan earthquake in 2008 and the subsequent reconstruction efforts temporarily affected the trends of NCU. The earthquake damaged 112,533.4 hectares of cultivated land in Sichuan Province, with some fields taking 2-3 years to recover; it also severely affected natural forest conservation and reforestation projects and grassland areas, leading to significant livestock losses and fish pond damages. This explains why, after reaching a peak in NCU increments in 2007, there was a sharp decline in 2008. Over the next three years of post-disaster reconstruction, significant funds were invested in specialty agricultural industries and resource restoration in the hardest-hit areas, such as encouraging the construction of standardized bases for kiwi and tea, which led to a slight rebound in NCU levels in 2009 and 2011. By 2012, NCU increments had returned to their previous levels, surpassing those of 2007, marking another peak.

The central and local government's attention to NCU issues and a series of farmland protection measures are the main reasons for the sharp decrease in NCU increments after the peak in 2015. During this period, despite the ongoing third agricultural restructuring and rural revitalization strategies, protecting farmland and maintaining grain production capacity remained the bottom line in agricultural policies. In March 2021, the "Sichuan Province Food Security Guarantee Regulations" emphasized that permanent basic farmland should be used primarily for grain production, prohibiting the abandonment and wastage of farmland. In March 2022, a notice on "Preventing Nongrain Use of Farmland to Stabilize Grain Production in the Aquaculture Industry" stipulated the prohibition of using permanent basic farmland for pond aquaculture. Thus, during this phase, the increase in NCU was well-controlled.

6.2 Revealing heterogeneous driving patterns of locational factors

The impact of transportation accessibility and market proximity on NCU has long been a central topic of research in academia and a focus for agricultural policymakers. This paper proposes a novel spatial heterogeneity analysis framework to explain this issue. NCU is a comprehensive decision made by farmers considering natural land endowments, planting habits, market demand, policy direction, and labor conditions. For farmers, even deciding to leave cultivated land fallow is the most rational choice based on their own considerations. Therefore, if transportation accessibility and market proximity are improved, farmers in different regions will have different interests, such as obtaining higher economic benefits or simply improving previously unsustainable farming practices. Some studies have concluded that favorable transportation and market locations promote the expansion of NCU. These study areas include the Central Plains of Thailand (Patarasuk and Binford, 2012), the Northern Plains of Zhejiang Province, China (Su et al., 2014; Xiao et al., 2015), and the North China Plain (Yu et al., 2017). However, other scholars have found that transportation and market location improvements are negatively correlated with NCU, primarily in mountainous areas (Ahrends et al., 2015; Mtaturu, 2024; Gatto et al., 2015; Zeng et al., 2022). This aligns with our research conclusions. Our study cleverly selected the geographically diverse Sichuan Basin, utilizing a simple theoretical framework to unify these two seemingly contradictory but actually coexisting viewpoints, providing a new perspective for future agricultural transformation research.

In our study, the Sichuan Basin is characterized by its open eastern boundary and its surrounding mountainous terrain, with hilly regions to the north and south. Due to these topographical constraints, sloping farmlands are widespread and highly fragmented, with traditional smallholder farming being the predominant mode of agricultural production. These areas are prime candidates for reforestation policies and natural forest protection projects. Furthermore, as the proportion of rural labor migrating for work and engaging in non-agricultural employment continues to rise, the phenomenon of land abandonment on sloping farms is likely to accelerate (Hong et al., 2024). The proximity of transportation infrastructure and markets plays a mitigating role in this NCU (non-cultivated utilization) phenomenon, with farmland located in these areas more likely to be preserved compared to more remote farmland. Even if NCU occurs, such lands are more readily re-cultivated. In contrast, the Chengdu Plain and the extensive flatlands in the basin's interior have favorable agricultural conditions, making intentional land abandonment due to natural constraints virtually nonexistent. Farmers in these regions are primarily concerned with maximizing the profitability of their land. Consequently, areas closer to markets and major roads are more likely to be designated as demonstration zones for the cultivation of high-value crops or for the development of ecological and agritourism farming, often manifesting in the form of orchards or shrubs. These economically driven NCU phenomena are challenging to reverse to their original farming state without strong administrative intervention, as reflected in the Chinese proverb, "It is difficult to revert from luxury to frugality"（You she ru jian nan）.

In fact, China, as a vast country with complex and diverse terrain ranging from the northeastern plains to the southeastern hills and the western mountains and plateaus, offers farmers a variety of NCU options. For example, tea and fruit planting are suitable for hills and gentle slopes, while mulberry orchards and nurseries may develop in low-altitude flat areas (Su et al., 2016). Therefore, when exploring the impact of specific factors on NCU, it is necessary to comprehensively consider the terrain of the study area.

6.3 Application of the MGWR model in NCU drivers analysis

This study pioneers the application of the MGWR model to analyze the drivers of NCU issues, enabling a more nuanced understanding of the heterogeneity in these influences. Compared to previous methods that used spatially invariant models (Hong et al., 2024) or the classical GWR (Pourmohammadi et al., 2021) to analyze NCU drivers, the MGWR model offers a crucial enhancement. The classical GWR, though accounting for spatial heterogeneity, assumes that all explanatory variables impact NCU at the same spatial scale. In contrast, the MGWR model allows for variable-specific spatial scales, enabling a more detailed examination of the heterogeneity in NCU influences. This approach uncovers complex spatial patterns that are critical for understanding NCU dynamics and formulating more effective policy interventions. The MGWR model is particularly well-suited to this research for two key reasons: first, the influence of various locational factors on NCU exhibits spatial variability, which aligns with the complex topography of the Sichuan Basin. More importantly, this study incorporates both socioeconomic and natural variables, and it is evident that these different types of variables are likely to impact NCU at distinct spatial scales. To demonstrate these differences and the advancements offered by the MGWR model, Table 4 provides diagnostic comparisons among the OLS, classical GWR, and MGWR models using the same variables.

Table 4 The comparison of diagnostic information of OLS, GWR and MGWR models

Model	RSS	Log-likelihood	AIC	AICc	R2	Adj. R2	Bandwidth
OLS	1492.506	-3330.478	6682.957	6685.054	0.536	0.535	3219
GWR	465.325	-1454.645	4168.420	4475.155	0.855	0.820	114
MGWR	379.230	-1125.355	3398.614	3648.227	0.882	0.857	See Fig.6

The results indicate that the MGWR model outperforms the OLS and classical GWR models in terms of model fit, as reflected by indicators such as Residual sum of square, log-likelihood, AIC, AICc, R^2, and adjusted R^2. The greater improvement of the GWR model over OLS highlights that spatial heterogeneity in the influence of various driving factors on the explanatory variables is a primary source of previous estimation bias. Additionally, the variation in bandwidths across variables—which reflect their spatial influence scales—is significant. The GWR model's single bandwidth often resembles the median of the MGWR model's variable-specific bandwidths, leading to local coefficients that can be difficult to interpret. Furthermore, as shown in Figures 6 and 7, the spatial heterogeneity in driving factors and the bandwidth information provided by the MGWR model offer valuable insights for developing tailored NCU management policies.

6.4 Policy implications and limitations

This paper analyzes the impact patterns of locational factors on NCU using the Sichuan Basin as a case study. These factors are often the primary concerns of regional development policymakers and are relatively more straightforward to implement. Although the conclusions are based on a specific region, we believe that, supported by rigorous theoretical analysis and comparison with existing literature, these findings are also applicable to agricultural areas worldwide, especially those with complex terrain similar to the Sichuan Basin. In mountainous areas with relatively poor transportation and market conditions, local governments should increase investment in infrastructure, including the construction of primary road networks between urban and rural areas and the enhancement of market capabilities, to reduce the comparative cost of transporting field crops versus forestry and fruit crops, thereby boosting farmers' motivation to protect cultivated land. In plain areas, suburban zones near cities are hotspots for NCU. Measures such as grain subsidies, technical support services, and farm machinery rentals can encourage surrounding farmers to sustainably use farmland and reduce NCU. Advantageous agricultural products like fruits and tea should be uniformly planted in designated bases to appropriately increase planting efficiency.

The main limitations of this study are as follows. Firstly, the impact patterns of geographic location on active adjustment and passive abandonment leading to NCU might differ. However, due to the lack of household interviews and field survey data, we did not differentiate between these two types of NCU. In future research, a more in-depth and detailed understanding of farmers' decision-making motivations will help improve our theoretical framework. Secondly, the impact of geographic location on NCU may exhibit scale effects. With the support of high spatiotemporal resolution cultivated land monitoring data, conducting multi-scale analyses of NCU phenomena will still be significant for safeguarding food security.

7. Conclusion

In this study, we first proposed a hypothesis: in mountainous areas, improvements in transportation and market accessibility would slow down NCU, whereas in plain areas, the opposite would be true. Based on this hypothesis, we used the sliding window method to extract NCU plots in the Sichuan Basin from 1991 to 2018 and employed MGWR to explore the driving effects of locational factors on NCU. The main findings of this study are as follows. During the study period, the cumulative NCU area in the study region continued to grow, with a significant increase in net growth after 2005. The newly added NCU area peaked in 2015 and then rapidly declined. The NCU phenomenon expanded from the peripheral mountainous and hilly areas to the interior of the basin and from the Chengdu Plain and urban centers to the outskirts. In recent years, a leapfrog-like punctiform aggregation trend has become apparent. In mountainous areas, the closer to the main roads and administrative centers, the less likely NCU is to occur; conversely, in plain areas, NCU is more likely to occur in areas close to main roads and administrative centers. This heterogeneous driving mechanism reflects the different demands of farmers for agricultural production conditions in mountainous and plain areas, leading to different production decisions. This research conclusion validates our hypothesis and systematically supplements existing research findings. Based on our understanding of the NCU phenomenon, we propose policy recommendations to improve agricultural infrastructure investment in mountainous areas, encourage sustainable farming practices in plain areas, and concentrate the cultivation of advantageous crops.

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Conflict of Interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.