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Spatial–Temporal Differentiation and Driving Factors of Cultivated Land Use Transition in Sino–Vietnamese Border Areas

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Abstract: Understanding the transformation of cultivated land use is crucial for advancing sustainable development goals related to food security. However, in mountainous regions, there is a lack of comprehensive studies that fully account for the diverse factors influencing cultivated land use transformation. This study aims to elucidate the temporal and spatial dynamics of cultivated land resource transformation in the mountainous Sino–Vietnam border area, uncover its underlying driving mechanisms, and offer insights for safeguarding cultivated land, promoting economic development, ensuring homeland security, enhancing ecological security, and bolstering border stability and prosperity. To investigate the cultivated land use transformation pattern in the Sino–Vietnam border area from 2000 to 2020, we employed kernel density estimation and geo-information spectra. Additionally, we developed a comprehensive driving force system tailored to the unique characteristics of cultivated land use in the border region. We applied a spatial econometric model to dissect the driving mechanisms governing cultivated land use transformation. Our findings revealed several key insights: (1) The density of cultivated land in the Sino–Vietnam border area exhibited an initial increase followed by a decrease. Notably, the transformation of cultivated land was most prominent in the eastern plains, intensifying over time. (2) The predominant type of transformation in the Sino–Vietnamese border area revolved around the mutual conversion of cultivated land and woodland, with the mutual conversion of cultivated land and grassland ranking second. (3) Against the backdrop of urban–rural integration, the transformation of cultivated land use at the border progressed from a phase of rapid decline to a phase of slower decline. (4) The transformation of cultivated land was influenced by a complex interplay of socio-economic factors, natural environmental conditions, policy management, and transportation infrastructure. The relative importance of these factors in driving cultivated land use transformation varied significantly across different time periods. In light of these findings, we recommend promoting agricultural modernization and industrialization in the Sino–Vietnamese border areas. It is essential to consider the region's distinct cultivated land characteristics, implement tailored land policies, and develop diversified strategies for the utilization and management of cultivated land. Furthermore, harnessing land resources to stimulate economic development should be a focal point of future initiatives in the area.

Keywords: cultivated land use transition; spatio-temporal evolution; driving mechanism; spatial econometric model; Sino–Vietnamese border areas

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1. Introduction

Eradicating hunger and achieving food security is one of the key objectives of the 17 Sustainable Development Goals (SDGs) [1,2]. Scholars have made great efforts to increase agricultural food production and develop policy [3,4], but the recent report on the State of

Food Security and Nutrition in the World still indicates that the world is regressing in its efforts to eradicate hunger, food insecurity, and all forms of malnutrition [5,6]. Cultivated land (CUL) is an essential natural resource crucial for human survival, development, and agricultural activities. It also plays a vital role in upholding social stability and ensuring national food security [7]. Given that the transformation of cultivated land use (T-CUL) holds direct implications for global food security and the pursuit of sustainable development goals, it is imperative to gain a comprehensive understanding of the spatial and temporal dynamics of T-CUL, discern its driving mechanisms, and safeguard the essential role of CUL in food production [8,9]. In addition to the functions of food production, spatial carrying capacity, and ecological conservation [10,11], cultivated border land also has the functions of maintaining homeland security [12]. Currently, the Sino–Vietnamese border area is undergoing a critical phase of fostering bilateral cooperation and optimizing population distribution [13]. In this region, the T-CUL is influenced by a complex interplay of internal and external forces, including urban expansion, trade activities at ports, industrial restructuring, and efforts to enhance food quality and production [14,15]. Consequently, border villages and houses are transitioning into hollow communities with unoccupied households, resulting in sparsely populated open areas. This transformation raises concerns about non-grain-oriented land use and land extensification [16–18]. Many nations recognize the need to protect and enhance the quality of CUL while imposing strict controls on its conversion into non-CUL [19]. Therefore, it is of great significance to conduct comprehensive research on T-CUL in border areas, to optimize the integration of border development and cultivated land use within the context of expanding urbanization.

Land use transition was originally evolved by Grainger based on the study of forest transition, which refers to the spatial pattern of land use types affected by the regional economy to form a general pattern of expansion or contraction [20]. Since then, Defries and Lambin have explored and deepened the meaning of land use transformation, driving research progress in this area [21,22]. T-CUL is an important part of land use transition research, specifically for continuity of understanding. In recent years, research on T-CUL has mainly focused on the perspective of the apparent form and hidden function of CUL, with emphasis on the interaction mechanism and coupling mechanism with the phenomenon of marginal CUL abandonment [23], multifunctional conflict [24], landscape ecology [25], and eco-efficiency [26] to develop interaction and coupling mechanisms. The study of explicit forms mainly starts from the implication of the change in the quantity and spatial structure of CUL, and active research assesses the characteristics of the spatial and temporal dynamics of the CUL, the analysis of the paths, the driving force of the spatial and temporal changes, and the dominant causes of the changes [27]. The implicit functions are mainly changes in the functional aspects of products and services provided by CUL, with major breakthroughs in functional transformation [28,29], property rights attribution, soil quality [30], and inputs and outputs. Regarding the mechanism of T-CUL, Barlowe Raleigh argues that any land use activity occurred within the framework of the triple interconnection and interaction of natural, economic, and institutional systems [31]. As most scholars believe, changes in socio-economic factors were the main drivers of changes in the nature of CUL, such as urbanization and industrialization, changes in market demand, and adjustments in agricultural policies [32]. Hence, did the T-CUL in the backward border mountainous areas also follow these laws?

Currently, the science focusing on the T-CUL is rich and provides much important support for our research, but some shortcomings remain and some questions need additional answers. Firstly, it is noteworthy that most current studies are primarily engaged in qualitative analysis and explanations, which, while informative, fall short of establishing the definitive laws and spatial patterns governing T-CUL. To address this limitation, our research endeavors to delve into the specific factors influencing various types of transitions involving cultivated land.

Secondly, T-CUL represents a complex outcome resulting from the interplay of multiple scales and factors. The intricate nature of its influencing elements gives rise to

diverse responses of cultivated land across different regions. Presently, numerous studies have focused on a national level, single provinces, economically thriving urban clusters, reclaimed plains, coastal regions, and other localized areas, thereby forming a "multi-perspective, multi-scale" research paradigm [33]. Unfortunately, relatively less attention has been directed toward remote mountainous areas. Situated within a karst zone, the Sino–Vietnamese border area predominantly features sloping cultivated land with a high degree of fragmentation. Its strategic significance and the burgeoning cross-border trade fundamentally shape its unique pattern of cultivated land utilization and development, distinguishing it from other regions. While the existing literature has been instrumental in shedding light on the T-CUL mechanism, it has not yet provided a definitive answer to the driving forces behind T-CUL in remote mountainous areas.

To achieve this, we systematically examine the evolution of CUL in the Sino–Vietnamese border area over the past two decades. Leveraging land use data and socio-economic statistics from different periods and employing kernel density analysis and geomorphological mapping analysis methods, we elucidate the spatial morphology of CUL. Furthermore, we employ a spatial econometric regression analysis model to dissect the driving mechanisms behind T-CUL in the border area spanning from 2000 to 2020. In doing so, our research lays the foundation for augmenting our understanding of T-CUL in mountainous regions, fostering the judicious utilization and sustainable development of CUL in border areas, reconciling the delicate balance between high-quality economic development and ecological preservation, and optimizing spatial planning and governance strategies in the border area for the future.

2. Materials and Methods

2.1. Study Area

The study area includes the Guangxi section and the Yunnan section, which are bounded between 20°36′–24°09′ N and 101°14–108°36′ E (Figure 1). This extensive region boasts a border length of approximately 2373 km and covers an expansive land area of approximately 40,000 km^2. In 2020, the total population of the study area is about 3,948,400 people. The area of CUL is about 6017 km^2, that of woodland (WL) is about 27,011 km^2, that of grassland (GL) is about 6058 km^2, the water area (WA) is about 296 km^2, the construction land (COL) area is about 417 km^2, and the unutilized land (UL) area is about 16 km^2. Notably, this border area is emblematic of its wide-ranging poverty levels and the coexistence of diverse ethnic groups. In this region, the terrain is predominantly characterized by mountains and hills, prominent karst landforms, and thin soil texture. There are geographical diversity and transition in climate, including humid subtropical climate and southern subtropical monsoon climate, resulting in greater differences in CUL resource endowment. Commencing in 1990, a policy of border area opening was implemented to provide support to the inhabitants of the border and western regions. This policy has played a pivotal role in propelling the prosperity and development of the region. In recent years, with the advancement of the "One Belt, One Road" initiative and the promotion of regional economic integration, coupled with the introduction of the "International Economic Corridor" strategy, the Sino–Vietnamese border area has become a critical land and sea access area in jointly building the Silk Road Economic Belt and 21st Century Maritime Silk Road [34]. As China and ASEAN countries continue to progress in their external opening-up, the impact of human economic activities on border farmland has gradually expanded. The conservation of farmland resources is facing formidable challenges. Historically, border populations have often found themselves on the "margins" of development, with young rural laborers increasingly migrating to urban centers in search of new opportunities. This trend has led to the abandonment of agricultural land, restrictions on land transfers, and a decline in the scale of agricultural production. A noteworthy consequence of these developments has been the occasional transfer or subletting of CUL to border populations in neighboring countries. This phenomenon has placed added pressure on regional food security. Moreover, the varying levels of economic

development across different areas have contributed to distinct degrees of T-CUL in different regions. Given these multifaceted challenges and transformations, our research focuses on the Sino–Vietnamese border area. Our primary objectives include uncovering the mechanisms underlying regional T-CUL, delineating the distinctive features of border T-CUL, and providing valuable insights to guide changes in CUL resource management, ultimately enhancing border governance in this dynamic region.

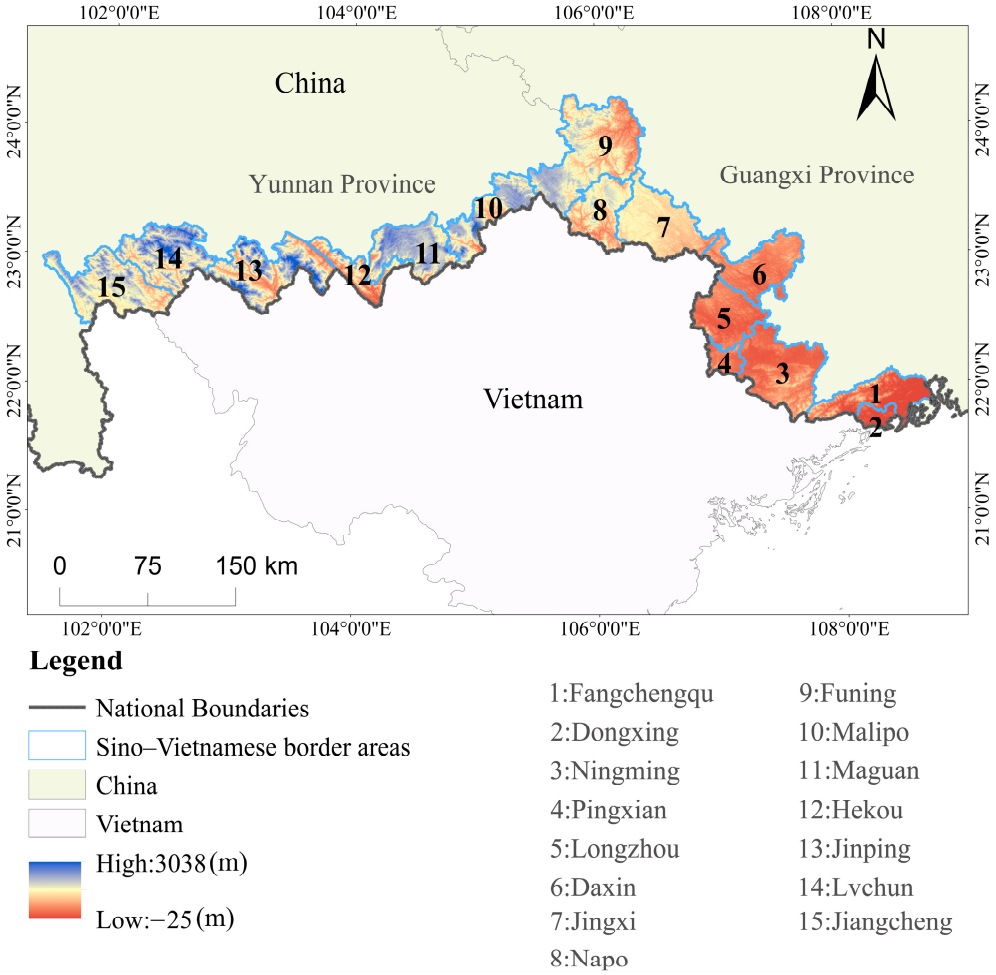


Figure 1. Location of the study area.

2.2. Data Source

Land use and socio-economic statistics were the primary data sources of this paper. Among them, the land use data were derived from the 30 m spatial resolution land use raster data provided by the Resource and Environment Science and Data Center of the Chinese Academy of Sciences, mainly for the years 2000, 2010, and 2020. In accordance with the study's requirements, the land was classified into several categories, including CUL, WL, GL, WA, COL, and UL. The classification standard is based on China's multi-period land use/land cover remote sensing monitoring data classification system, and the land use/cover classification system is based on strong temporal continuity and unified classification standards. Simultaneously, the land use/cover classification system is of great practical significance in terms of applicability, as it starts from the practical operation of land cover remote sensing monitoring, closely integrates with the national county-level land use status classification system, and facilitates the linkage between the results of land cover remote sensing monitoring and the results of ground-based conventional land use surveys as well as the additional processing of the data. It is well suited for conducting long-time series analysis of CUL evolution. These land use types were then recoded using

ArcGIS 10.2 for each period of data by assigning values ranging from 1 to 6, corresponding to their respective categories. The socio-economic data come from statistical yearbooks and statistical bulletins, such as 'Guangxi Statistical Yearbook' (2001–2021) and 'Yunnan Statistical Yearbook' (2001–2021). All maps were produced based on the Chinese standard map GS (2019)1822.

2.3. Kernel Density Estimation

Kernel density estimation is a type of non-parametric space detection density distribution. The peak or core is established based on the distance from each feature point to a reference position to shape a smooth continuous-density surface [35,36]. It is challenging to directly show the series and integrity of CUL from a geographical area when the characteristics of point density, wide area, and discreteness are integrated. Kernel density analysis depicts the regional heterogeneity of CUL density and the shrinkage of core points with distance through a smooth surface, which can better depict the characteristics of CUL agglomeration. The kernel density can be expressed by Equation (1):

$$f(a,b) = \frac{1}{nh^2}\sum_{i=1}^{n} k(\frac{d_i}{h}) \quad (1)$$

where $f(a,b)$ represents the CUL density estimation of point (a,b), n is the number of observations, h is the distance attenuation threshold, k is the spatial weight function, and di is the Euclidean distance from point (a,b) to i observation positions.

2.4. Geo-Information Spectra

The land use data of the study area in three periods were spatially superimposed in ArcGIS, and then geographic information fusion and visualization were realized. The transformation process and quantity change of T-CUL in two periods were formed, and the two synergistically revealed the dynamic evolution characteristics of CUL in the border area [37], as shown in Equations (2) and (3):

$$R_{ab} = P_{ab} \times 100\% / \sum_{a=1}^{n}\sum_{b=1}^{n} P_{ab} \quad (2)$$

$$D_{ab} = \frac{1}{2} \times \frac{\sqrt{L_{ab} / \sum_{a=1}^{n}\sum_{b=1}^{n} P_{ab}}}{P_{ab}\sum_{a=1}^{n}\sum_{b=1}^{n} P_{ab}} \quad (3)$$

where R_{ab} and D_{ab} refer to the change rate and separation degree, P_{ab} and L_{ab} represent the area and the number of map units of b land types from the initial t to the end $(t + \Delta t)$, and n is the number. R_{ab} is the proportion of the post-transformation land type to the total transformation land type; D_{ab} is the degree of dispersion in space, and the larger the value, the more discrete is the space.

2.5. Spatial Econometric Model

In this study, we employed various spatial econometric models (OLS), specifically the ordinary least squares regression model, spatial error model (SEM), and spatial lag model(SLM) [38,39]. Among these, the ordinary least squares model aims to find the best-fitting function by minimizing the sum of squared errors between the estimated values of all dependent variables and their actual values. This can be mathematically expressed by Equation (4):

$$y_i = \beta_0 + \sum_{j=1}^{k} \beta_j X_{ij} + \varepsilon_i \quad (4)$$

where y_i represents the dependent variable, and X_{ij} represents the independent variable. $i = 1, \ldots, n$ represents the number of observations; β_0 represents the constant term; β_j represents the j regression parameter; ε_i is the random error term.

The SLM is mainly applied to empirically analyze the spatial diffusivity of each factor variable with spatial correlation, with Equation (5):

$$y = pW_y + \beta X + \varepsilon \tag{5}$$

where y represents the vector of dependent variables, and p represents the spatial regression coefficient, reflecting the degree of spatial correlation between the values. X is the matrix of observations of the explanatory variables; W_y is the spatially lagged dependent variable; β reflects the effect of the independent variable on the dependent variable; ε is the vector of error terms.

The SEM measures the extent to which an error shock in a dependent variable in a neighboring region affects the dependent variable in this region through the interdependence among the randomly perturbed error terms, which is given by Equations (6) and (7):

$$\varepsilon = \lambda W\varepsilon + \mu \tag{6}$$

$$y = \beta X + \varepsilon \tag{7}$$

where y represents the dependent variable vectors, λ is the spatial error coefficient of the vector of dependent variables, X is the matrix of explanatory variables observations, ε is the error terms vector, β is the vector of regression residuals, W_ε is the matrix of spatial perturbation term weights, and μ is a normally distributed error vector.

2.6. Driving Factor Selection and Factor Parameterization

T-CUL is driven by the regional natural geographic environment base, the humanities, economic and social level of common interaction, and mutual constraints, and different factors in the T-CUL have a variable impact on the transformation [40] (Figure 2).

The natural geographical and environmental conditions of CUL serve as its foundation and significantly impact agricultural production and resource availability. Although the short-term influence of natural background factors on T-CUL may be relatively weak, the vast expanse of the Sino–Vietnamese border region, along with the evident spatial variability in precipitation from east to west and the critical role of water resources as a constraint to border agricultural [41] development, makes factors such as elevation, temperature, and rainfall essential considerations.

The driving force of social and economic factors on CUL use is more significant [42]. The transformation of the use of cultivated land usually corresponds to a certain stage of economic and social development, and the more intensive the economic activity and the more concentrated the population, the more likely it is to lead to the de-farming of cultivated land. The border area, serving as a gateway for foreign trade development, experiences more intensive land use due to the construction of ports, trade activities, and infrastructure development. This heightened activity has a profound impact on the utilization of CUL. Therefore, we have selected some indicators to characterize the economic and social development. For example: total population, proportion of secondary and tertiary industries, urbanization rate, per capita net income of farmers, and gross domestic product (GDP). Agricultural factors were represented by the total power of agricultural machinery and grain sown area. Measures such as the development of agricultural subsidy policies at the macro level by national and local governments play a critical role in changes in cultivated land. Agricultural expenditures were used to assess the influence of policy-related factors on agriculture and, by extension, CUL use. Additionally, the constraining effect of transportation location factors on the transformation of cultivated land use is fully reflected in the transformation of spatial patterns of regional cultivated land expansion or contraction resulting from the perspectives of economies of scale, diffusion of externalities,

and land price changes [43]. In this study, we included road mileage and distance from the port to characterize transport conditions.

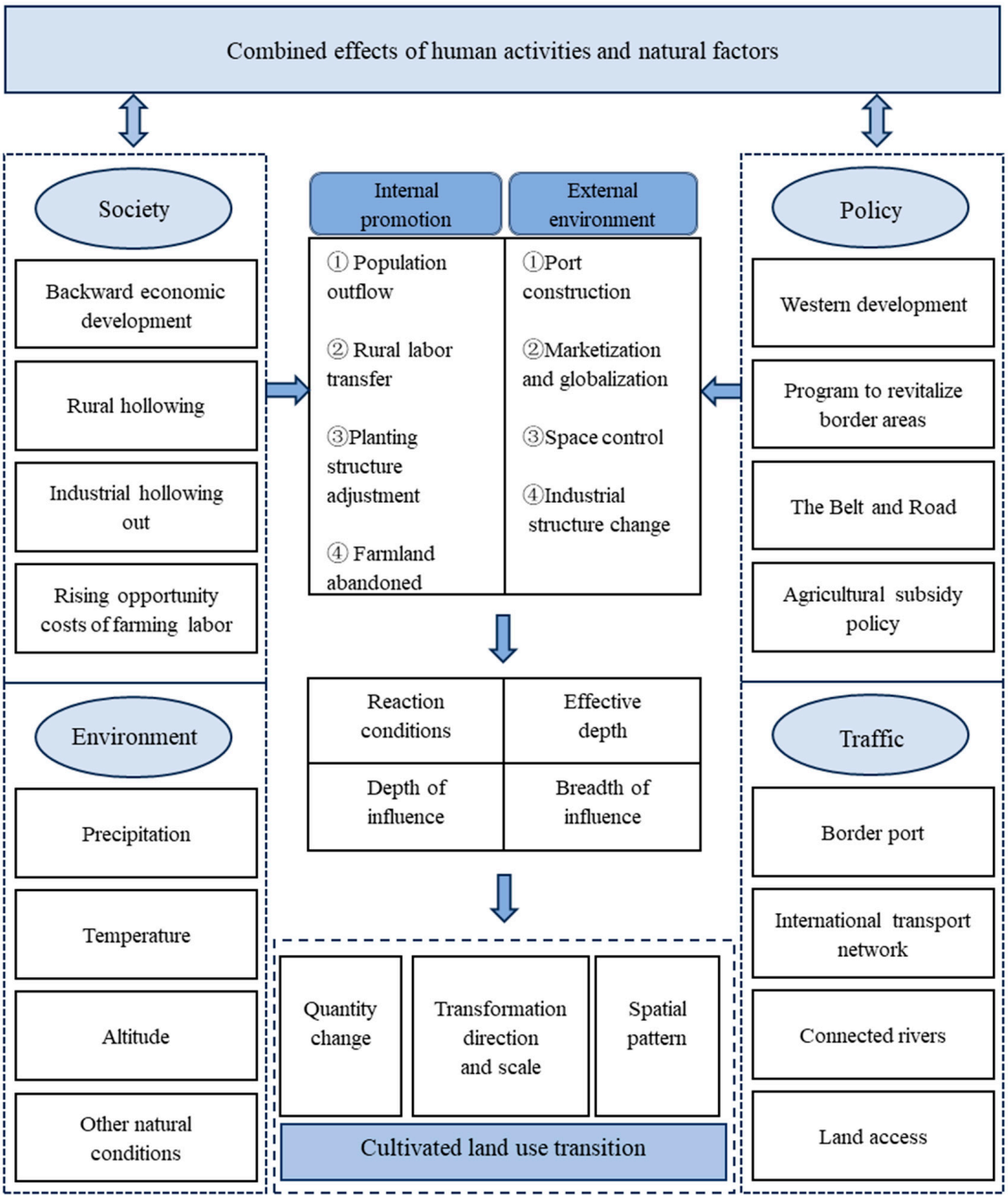


Figure 2. Influence framework of driving mechanism of T-CUL in the Sino–Vietnamese border region.

3. Results

3.1. Analysis of Spatial Agglomeration Characteristics of CUL

To gain a more lucid comprehension of the spatial agglomeration traits of cultivated land along the Sino–Vietnamese border, we configured the search radius for kernel density analysis at 6000 m using ArcGIS 10.8 software, while opting for default settings for other parameters. The density of CUL in the study area first increased and then decreased (Figure 3). CUL density in 2000, 2010, and 2020 was 14.94, 15.05, and 14.91 hm^2/km^2, respectively. Changes in cultivated land are mainly influenced by the natural farming

conditions of the region and the stage of social development. In terms of spatial distribution, CUL was predominantly concentrated in the eastern part of the study area, while the western region exhibited a more fragmented pattern. The distribution of CUL density appeared dispersed, particularly on the outskirts of cities within the border areas. From 2000 to 2020, the overall pattern of regional CUL nuclear density is basically consistent, with insignificant changes in the intensive areas at all levels (Figure 3). Specifically, high-density areas of CUL were mainly concentrated in Daxin, Longzhou, and Ningming counties on the border of Guangxi, and in Lvchun and Malipo counties on the border of Yunnan. This distribution pattern can be attributed to the fact that many of the region's towns and villages are situated in relatively flat areas, nestled on gentle slopes of low hills. These areas tend to exhibit modern agricultural practices and a higher proportion of CUL. In particular, the zones with medium-high and medium CUL density are concentrated around Jingxi City, Fangcheng District, and Jinping County. These areas are characterized by small mountain basins, resulting in a more contiguous and concentrated distribution of CUL. In contrast, low-density CUL zones are predominantly found in Maguan, Jiangcheng, Hekou, and Funing counties. This can be attributed to the challenging mountainous terrain, limited water resources, weak irrigation capacity, and unfavorable farming conditions, which hinder agricultural production in these regions.

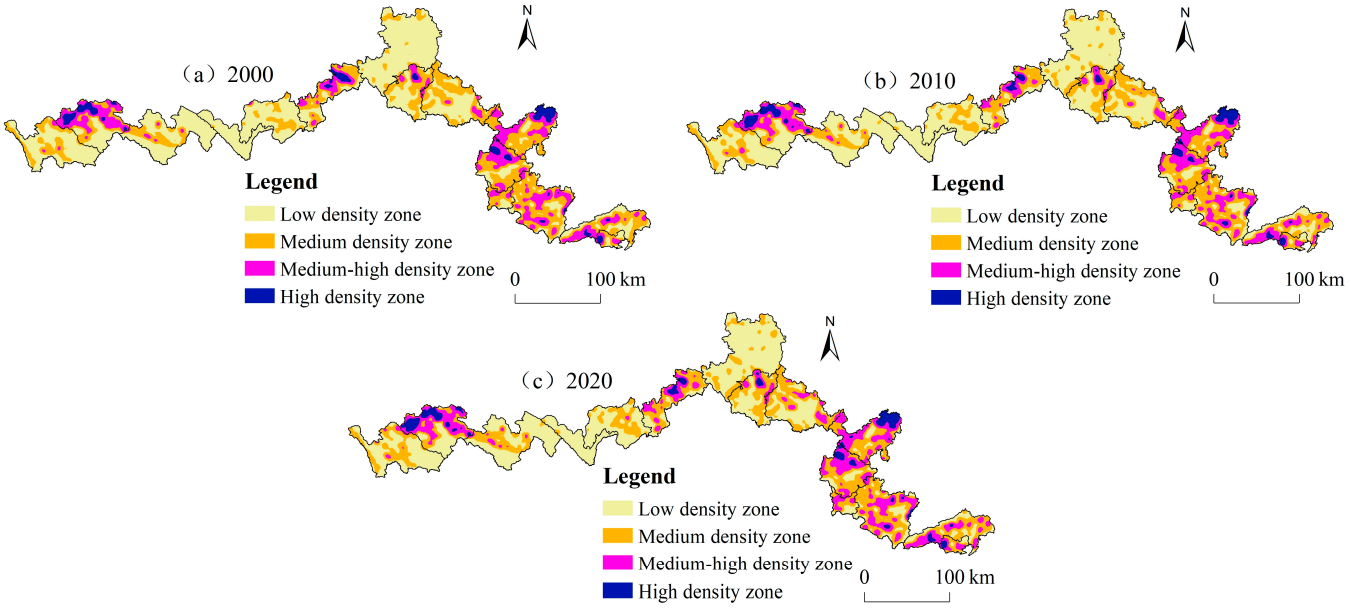


Figure 3. Kernel density distribution of CUL in Sino–Vietnamese border area from 2000 to 2020.

Between 2000 and 2010, we observed a decrease in the CUL area in the medium-density zones of Jiangcheng and Malipo counties in the Yunnan border areas. Specifically, the CUL area in Jiangcheng decreased by 9 km^2, while Malipo experienced a reduction of 13.62 km^2. These changes were primarily attributed to the reduction in agricultural land due to the de-farming and de-fooding practices in these regions. In contrast, counties like Jinping, Ningming, and Hekou transitioned from low-density areas to medium-high-density areas, resulting in a total increase in CUL area by 65.33 km^2. This shift indicated an agglomeration of cultivated land resources, driven by the region's concerted efforts to improve the quality of CUL and enhance the utilization rate of rural CUL through strict adherence to the principles of appropriation and replenishment. From 2010 to 2020, the spatial distribution of CUL exhibited more significant changes than that in the preceding decade. High-density CUL areas in various regions began to converge, although there were varying degrees of shrinkage observed in high-density areas of Malipo County, Jingxi City, Funing County, Daxin County, and Fangcheng District. This period was marked by rapid urbanization, industrial restructuring, unchecked urban expansion, and the less regulated

use of CUL resources, leading to the abandonment of farmland in the smallholder economy. These factors collectively contributed to a reduction in the overall CUL area in the region, posing a significant challenge to CUL protection and food security in the border areas.

3.2. Spatial Analysis of T-CUL

The significant regional variation in T-CUL in the study area is shown in Figure 4. Overall, the transformation of CUL resources around Jingxi City, Daxin County, Ningming County, and Longzhou County in the border areas of Guangxi was stronger, followed by that in Maguan, Funing, and Lvchun Counties in Yunnan, while the total amount of CUL resources in Hekou County, Fangcheng District, and Pingxiang City was less. T-CUL was distributed with more in the east and less in the west, which is basically consistent with the regional terrain characteristics.

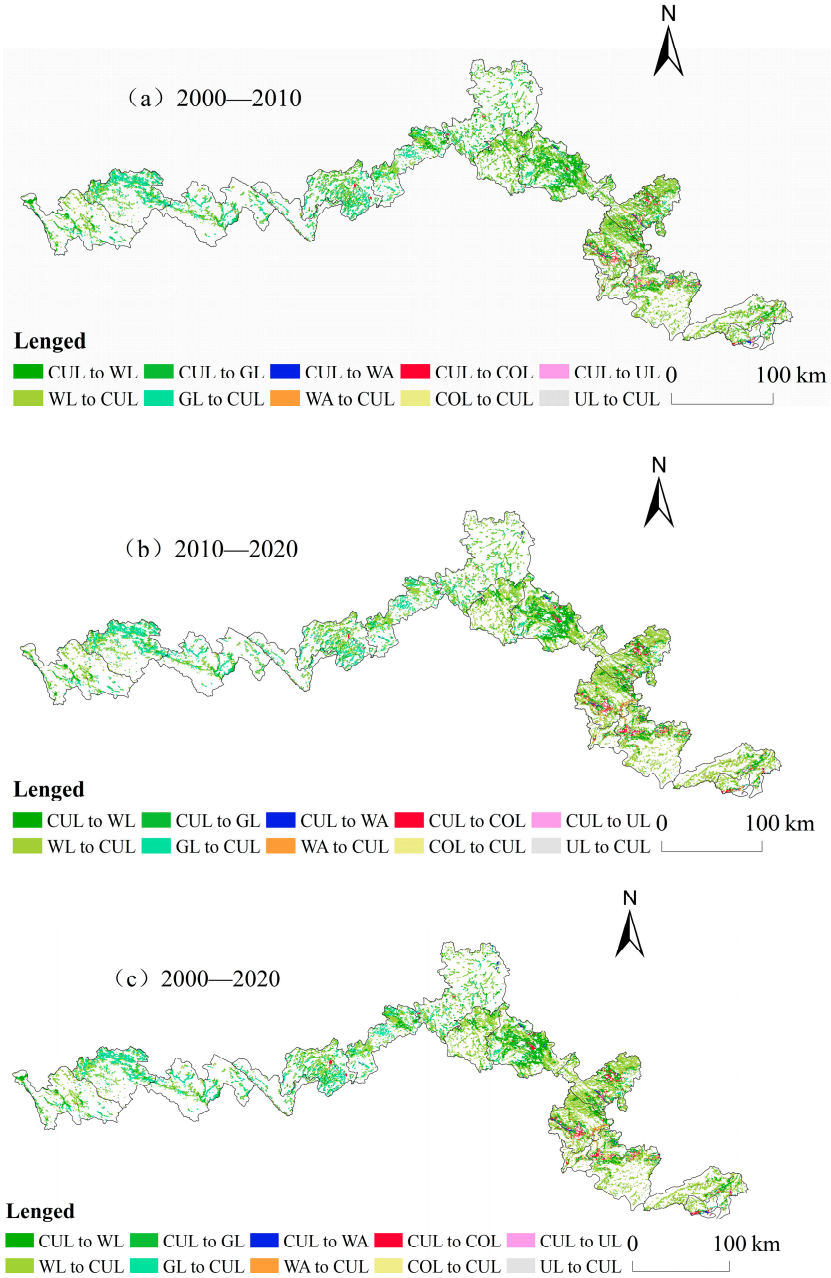


Figure 4. Spatial and temporal patterns of T-CUL in the Sino–Vietnamese border region. Spatio-temporal patterns from (**a**) 2000–2010a, (**b**) 2010–2020a, and (**c**) 2000–2020a.

From 2000 to 2010, the interchange between WL and CUL was more pronounced, with 198.83 km^2 of WL being converted into CUL, accounting for 28.61% of the total area converted (Table 1). This change was concentrated in the areas of Jingxi City, Longzhou County, and Daxin County, and was distributed in a flake pattern, reflecting the outward extension of CUL and the high level of agricultural development during this period. There was also a transition between GL and CUL, with 133.54 km^2 of GL being transferred to CUL, focused on Lvchun, Maguan, and Malipo counties, accounting for 19.22% of the total transformed area. Generally, the focus of land use transformation in the study area in 2000–2010 was represented by the mutual conversion of CUL and WL, and CUL and GL, with the former being widely distributed within the border areas of Guangxi and the latter being mainly distributed in the border areas of Yunnan.

Table 1. Unit ranking table of the T-CUL map in Sino–Vietnamese border areas from 2000 to 2020.

Year	Type	Code	Number of Spectral Units	Area/km^2	Rate of Change	Cumulative Change
2000–2010	WL to CUL	21	10,880	198.83	0.2861	0.2861
	CUL to WL	12	11,124	181.83	0.2617	0.5478
	GL to CUL	31	3633	133.54	0.1922	0.74
	CUL to GL	13	3657	100.15	0.1441	0.8841
	CUL to COL	15	1701	29.17	0.042	0.9261
	COL to CUL	51	1697	26.37	0.038	0.9641
	CUL to WA	14	537	13.39	0.0193	0.9834
	WA to CUL	41	462	8.28	0.0119	0.9953
2010–2020	WL to CUL	21	11,906	248.21	0.3381	0.3381
	CUL to WL	12	11,903	248.19	0.3381	0.6762
	GL to CUL	31	4038	66.68	0.0908	0.767
	CUL to GL	13	4094	67.46	0.0919	0.8589
	CUL to COL	15	2203	63.94	0.0871	0.946
	COL to CUL	51	1981	16.24	0.0221	0.9681
	CUL to WA	14	764	14.78	0.0201	0.9882
	WA to CUL	41	671	8.33	0.0114	0.9996

From 2010 to 2020, the T-CUL displayed increased activity compared to that in the previous period, with the transformation from CUL to WL remaining dominant. The mutual transfer between CUL and WL accounted for 67.62% of all transferred areas during this period. These changes were predominantly observed in Jingxi, Daxin, and Ningming counties. This could be attributed to the fact that agriculture continues to be the dominant industry in these areas, boasting favorable farming conditions that have led to the continuous reclamation of WL as CUL. The transition from CUL to WL was primarily concentrated in areas like Napo County, where poor CUL quality, high cultivation costs, and other unfavorable factors led to the abandonment of CUL as farmers shifted their livelihood strategies. Additionally, the policy of converting CUL back into forests has begun to yield results.

The conversion from CUL to COL expanded outward, increasing from 29.17 km^2 in the early period to 63.94 km^2 in the late period, weakening the stability of CUL resources. Geographically, the COL transition was primarily concentrated in the northern regions of Ningming and Daxin counties and Jingxi City. This reflects a more intense expansion of urban and rural COL in Guangxi than that in Yunnan during this period. Territorial spatial planning in the region showed a notable trend of converting CUL into COL, which, in turn, highlighted a spatial contraction where the area of CUL per capita and the area devoted to food crop cultivation significantly decreased. Changes in CUL were influenced by various factors, including regional economic improvements, border farmers' behaviors, industrial restructuring, ecological fragility as a natural constraint, and broader geographical factors such as the "One Belt, One Road" strategy and policy implementations.

3.3. Analysis of the T-CUL Stage and Trend

Defining the T-CUL should be based not only on the explicit form of CUL use, i.e., quantitative and spatial structure, but also include the invisible form, i.e., the multifunctional attributes of CUL. The dominant form of CUL use reflects the evolution of regional CUL quantity from the quantity and spatial structure, and then comprehensively and intuitively depicts the spatial and temporal pattern of T-CUL, which can more directly reflect the overall law of CUL change and spatial evolution trend at the macro level.

Large differences in the state of the development of CUL in the context of different rates of socio-economic development and locational conditions were observed (Figure 5). As a consequence of the strict system of CUL protection and the implementation of strict land use conservation, the amount of CUL has gone through four stages [44,45]. The first stage was marked by sustained increase (1949–2010). After the founding of China in 1949, China implemented land reform and land ownership policies that significantly boosted rural productivity. This resulted in the effective expansion of farmland and increased agricultural production through the mobilization of farm workers. Since 2000, the Sino-Vietnamese border areas have implemented major projects for the improvement of farmland and a comprehensive land improvement project for the prosperity of the border areas, increasing the amount of cultivated land and reaching a peak around 2010. The second stage witnessed rapid decline (2011–2015). This phase saw rapid urbanization and increasing demand for land for construction, which consumed some CUL. The third stage marked a slowdown in the rate of decline (2016–2020). During this period, in order to arrest the decline in the amount of cultivated land in the border areas, the governments of the border areas strengthened the policy protection system for cultivated land resources, and strict land use plans and protective measures for cultivated land were implemented. These efforts resulted in a noticeable reduction in the rate at which cultivated land area was decreasing. The fourth phase represented a period of smooth transformation followed by sustained increase (2021 to now). In this stage, there was a strengthening of land use planning and control measures. This led to the maintenance of a dynamic balance in the total cultivated land area. Additionally, a smooth transition and subsequent increase in CUL were achieved through a combination of replenishment, transformation, quality improvement, and renovation measures.

Combined with the process of T-CUL, there was a net increase in the area of CUL by 45.94 km^2 from 2000 to 2010. The Sino–Vietnamese border area has historically served as the gateway to the southwest of the country. To enhance the development conditions of border areas and maintain borderland security, significant projects such as farmland improvement and comprehensive land enhancement were implemented in the Sino–Vietnamese border areas. These initiatives aimed to optimize the rural ecological environment, increase the quantity of CUL, moderately enhance the quality of CUL, and bolster the capacity to ensure food security. The area of CUL decreased by 54.29 km^2 from 2010 to 2020, further exacerbating the contraction trend from the previous period. Border areas are affected by the combined effects of marginalization, politicization, and hollowing out, as well as the relatively low returns on CUL, which have led to the outward movement of border people from border villages, resulting in the abandonment of CUL and a lack of resource management; the situation of the current contraction in CUL use for transformational development remains grim. In 2020, it is in the stage of rapid decline in the change of cultivated land area in the border area between China and Vietnam to the stage of slow decline.

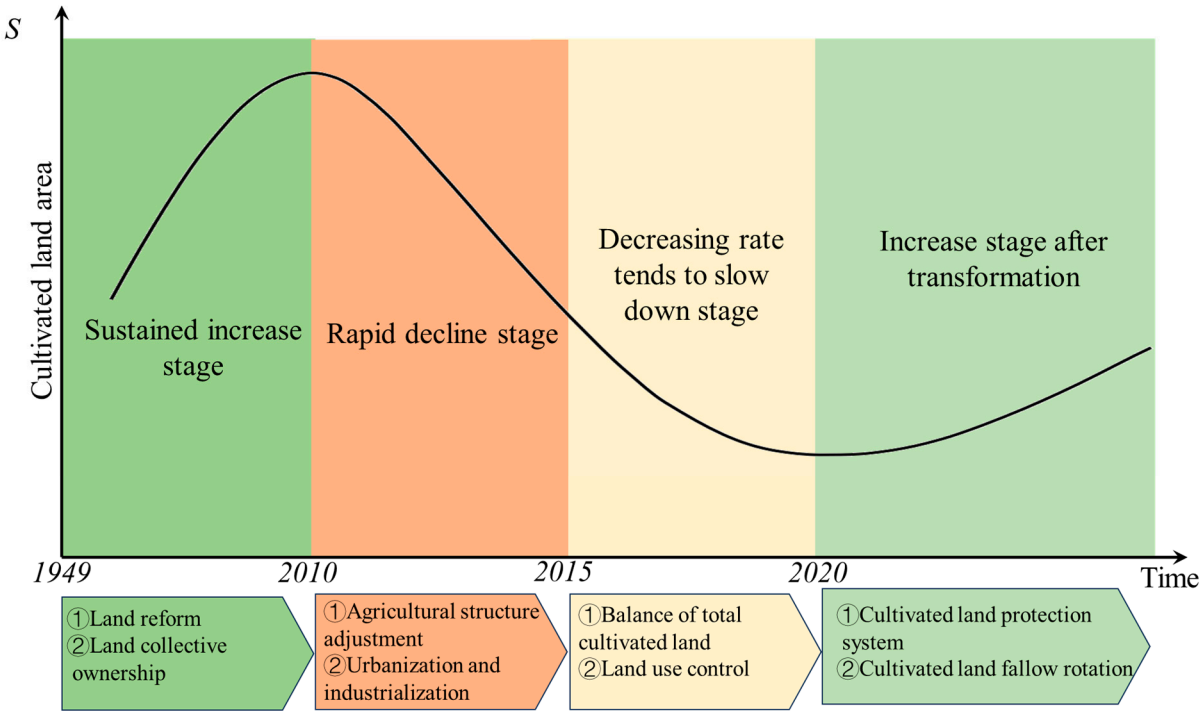


Figure 5. CUL area vs. time. Change in CUL area in the process of urban–rural integration.

3.4. Driving Factor for General Compliance and Regional Differences of T-CUL

In this research, GeoDa spatial econometric regression analysis was used to detect the intrinsic correlation between the types of T-CUL and the driving factors in the two periods of 2000–2010 and 2010–2020 in the Sino–Vietnamese border area. First, the county base map in Shp format for different periods and the attribute table of independent and dependent variables were formed in ArcGIS 10.2, and the weight matrix was constructed in GeoDa based on these data. The regression module was subsequently debugged, selecting the data series of quantitative driving factors such as the dependent variable and independent variable in the Independent Variable, while also selecting the spatial weight file (obtained using Rook adjacency matrix in adjacency space weights) and adopting a suitable regression type based on spatial correlation test to reflect the intensity and direction of the role of each driving factor on the T-CUL. Finally, the spatial regression model fitting effect can be tested using the Schwartz Criterion, the fitting coefficient R2, the Akaike information criterion, and the natural log likelihood (Tables 2 and 3). It is emphasized that following such a gauge in model selection, ① when the Lagrange multiplier (lag) is significant and the Lagrange multiplier (error) is not significant, the SLM is chosen; ② when Lagrange multiplier (lag) is not significant and the Lagrange multiplier (error) is significant, the SEM is chosen; ③ when the Lagrange multiplier (lag) is significant, the Lagrange multiplier (error) is significant, and the robust LM (lag) is also significant, the SLM is selected; ④ the SEM is selected when the Lagrange multiplier (lag) is significant, and the Lagrange multiplier (error) is significant when the robust LM (error) is also significant; ⑤ when the Lagrange multiplier (lag) is not significant and Lagrange multiplier (error) is not significant, the OLS is chosen.

From 2000 to 2010, the response of the T-CUL to various influencing factors exhibited varying degrees of sensitivity. Here are some key findings.

Table 2. Results of spatial regression analysis of T-CUL and driving factors in Sino–Vietnamese border areas.

Driving Factors	2000–2010				2010–2020			
	CUL to WL	CUL to GL	CUL to COL	WA to CUL	CUL to WL	CUL to GL	CUL to COL	WA to CUL
	SLM	SLM	OLS	SLM	SLM	SLM	SEM	SLM
Total population	4.82	−9.28 ***	5.13 ***	−49.40	7.51	2.26 **	3.17 *	−8.82
Urbanization rate	12.38 ***	8.59	4.95	−18.70	−0.74 **	0.06	3.10 ***	9.48
GDP	−6.20	−8.26	−5.95 **	−62.52	−2.79	−2.77	4.30	11.71
Proportion of secondary and tertiary industries	3.67	25.74	4.50 *	76.60	−2.12	1.93	−4.68	−6.64
Agricultural expenditure	3.01	4.66	6.34	110.25	6.27 *	−0.31	−4.38	−8.01
Agricultural machinery total power	8.83	−8.84	6.66	90.70 **	5.807	1.57	−2.69	−9.47
Total value of farm product	−10.49	36.81	−3.90	−27.03	−2.57	−1.74 *	2.76	7.33
Grain sown area	13.65	−16.32 *	−0.15	−69.09	−1.18	0.96	3.086	7.81
Elevation	−13.74 **	15.52	−0.04	−46.58 *	−2.08 **	1.72 *	−2.70 **	−6.66 **
Air temperature	10.39	−9.30	6.93	71.46	−0.33	−1.10	3.36	8.21 *
Precipitation	11.83	−9.98	1.24 *	14.27	−3.30	4.42	0.50 *	5.82
Highway mileage	9.07 ***	3.69	4.71	10.70	13.93	−1.31	3.62 *	4.61
Distance to the port	0.40	−32.16	0.83 ***	−13.91	1.04	−0.13	−3.24	−7.77
Lambda							0.25 **	
W-Y	0.62 ***	0.78 ***		0.89 ***	0.59 ***	0.77 ***		0.64 ***

Note: * is significant at a 10%, ** 5%, and *** 1% confidence level, while others are not significantly correlated.

Table 3. Metrics for spatial regression analysis results.

Metrics	2000–2010				2010–2020			
	CUL to WL	CUL to GL	CUL to COL	WA to CUL	CUL to WL	CUL to GL	CUL to COL	WA to CUL
	SLM	SLM	OLS	SLM	SLM	SLM	SEM	SLM
R^2	0.83	0.88	0.92	0.73	0.84	0.94	0.78	0.91
AIC	82.51	68.87	16.12	−42.8	50.21	84.55	72.63	6.2
SC	93.13	79.49	26.03	−32.18	60.82	95.17	88.25	16.82
Log Likelihood	−26.25	−19.44	5.942	36.1	−10.1	−27.27	−21.31	11.9

The transition from CUL to WL showed significant correlations. It was positively correlated with the urbanization rate and road mileage at the 1% confidence level and negatively correlated with elevation at the 5% confidence level. The issue of hollowing out in the border areas became more prominent during this period. On the one hand, increasing urbanization and rising wages for the young labor force, mainly engaged in non-agricultural work, led to a decline in farmers' willingness to cultivate their fields. On the other hand, farmers sought income opportunities by planting economic forests on their CUL, gradually converting them into WL over time. Road mileage played a role in promoting ecological projects, such as protective forestland and afforestation, contributing to ecological security in border areas. Elevation played a crucial role, especially in areas

like Jingxi City, Napo County, and Funing County, where karst landscapes and poor production conditions resulted in fragmented CUL and high irrigation water costs, driving the transition to WL.

The transition from CUL to GL was negatively correlated with the total population and the area sown for food at the 1% and 10% confidence levels, respectively. Lower population density and reduced food cultivation area led to less interference from human activities, allowing for more robust GL growth and the displacement of some CUL.

The transition from CUL to COL exhibited various correlations. It was positively correlated with the total population and the distance to the port at the 1% confidence level, negatively correlated with GDP at the 5% confidence level, and positively correlated with the proportion of secondary and tertiary industries and the amount of precipitation at the 10% confidence level. Regions near ports with higher GDP, a greater presence of secondary and tertiary industries, and sufficient precipitation, experienced CUL being converted into COL due to the need for port and economic trade zone development. The increased demand for CUL in regions with higher GDP and a greater focus on non-agricultural sectors inevitably led to a decline in agricultural land.

The transformation of WA into CUL was positively correlated with the total power of agricultural machinery at the 5% confidence level and negatively correlated with elevation at the 10% confidence level. Greater agricultural machinery power reflected increased demand for continuous cultivation, while lower elevation facilitated the reclamation of WA into CUL.

In 2010–2020, T-CUL was more active than that in the previous stage; the coordinated effect of various influencing factors on T-CUL intensified, and the transformation of CUL into WL and COL was the main type of transformation. The driving factors for the transformation of CUL into WL were relatively stable and mainly attributed to the urbanization rate, elevation, and net per capita income of farmers. Urbanization enhanced the importance of urban and rural factors, triggered rapid industrial development, and improved farmers' wages, which had dual effects on T-CUL. In 2010, with the establishment of "Exchange and Cooperation Mechanism on Border Forest Protection and Wildlife Conservation" between China and Vietnam, "Ecological Forestry," "Returning CUL to Forests," and the "Tianbao Programme" created a good growing environment for the border forests, and ensured the safety of border forest resources in the two countries.

The transformation of CUL into GL exhibited specific correlations with influencing factors. It was positively correlated with the total population and elevation at the 5% and 10% confidence levels, respectively. Conversely, it was negatively correlated with the total agricultural output value at the 10% confidence level. This indicates that the transformation of CUL to GL predominantly occurred in fringe zones located far from the county center. These areas typically had a lower population concentration, less advanced agricultural production technology, relatively lower per-capita agricultural output values, and higher elevations. Additionally, in some regions, policies encouraging the return of farmland to forests and the establishment of GL on steep slopes contributed to the transformation of CUL into GL.

The transformation of CUL into COL was influenced by multiple factors, making it more complex than other types of transformation. It was affected by the total population, urbanization rate, road mileage, elevation, and precipitation, among other factors. Areas with a higher degree of transformation from CUL to urban and rural COL were typically urban or near county towns with concentrated populations, high levels of urbanization, good transportation infrastructure, and flat terrain. For example, locations like Dongxing City and Ningming County experienced an increased population concentration, leading to a greater demand for COL and the subsequent conversion of CUL. Favorable location conditions continued to drive the transformation of CUL into COL, exemplified by the common construction of rural housing in border areas. To address this, the government should follow the guidance of new land spatial planning, coordinate the integrated development of urban and rural areas, implement a balanced approach to CUL occupation and

replenishment, control the overall development intensity of land space, and strengthen control over the transformation of CUL into COL around the county level.

The transformation of WA into CUL was related to factors such as elevation and temperature. Lower elevations and better temperatures facilitated the conversion of water areas near rivers into CUL. However, the reclamation of rivers and mudflats could induce soil erosion, necessitating optimized control measures in line with government policies.

4. Discussion and Conclusions

4.1. Discussion

Kernel density estimation, geo-information spectra, stage analysis of T-CUL, and spatial measurements were used in the article to discuss the characteristics of spatial and temporal patterns, evolutionary trends, and influencing factors of the T-CUL in the study area.

Compared with other regions, T-CUL in border mountainous areas exhibited both similarities and unique characteristics. Firstly, the behavior of cultivated land use led to different directions of T-CUL. In contrast to developed cities in eastern China where CUL was primarily converted into COL [42], border mountainous areas saw mutual transformations between CUL and WL. During the agricultural society period, there was an expansion of CUL and a reduction in WL. In the urbanization era, there was an abandonment of CUL followed by the restorative growth of WL.

Secondly, while urbanization and industrialization were fundamental driving forces for T-CUL in many regions, including developed countries like Europe and Japan [46], the border mountainous areas presented a different scenario. Economic development in these border regions lagged behind that in inland core areas due to influences from natural and geo-economic environments. The external pull of urbanization and industrialization development led to the migration of a significant number of rural laborers, particularly the younger workforce, to cities [47]. This migration contributed to the transformation of a substantial amount of CUL, aligning with T-CUL resulting from labor force separation [48].

Natural factors, such as altitude and the challenges posed by agricultural mechanization and scale in karst terrain, also played a role in facilitating CUL transformation. The widening gap between labor productivity and agriculture in plain areas increased the likelihood of CUL becoming marginalized, further aligning with T-CUL driven by CUL marginalization [23].

Additionally, the external ecological benefits generated by economic and societal development in a market environment were limited. This led to adjustments in CUL planting structures and changes in utilization patterns, with a noticeable shift toward non-agricultural uses. Particularly, issues related to the imperfections in farmland property rights systems and the shortcomings in interest allocation mechanisms for CUL protection subjects became increasingly evident. These issues were reflected in problems like vacant homesteads and the marginalization of CUL. Looking ahead, future research should consider narrowing the spatial scope and focus on the implementation of differentiated land policies in the near-border area (0–3 km). It should also delve into the potential coupling mechanism between T-CUL and border residents' behavior, farmers' planting preferences, and property rights systems. Additionally, government initiatives related to land space planning and CUL protection policies in border areas should carefully balance economic development with CUL protection, taking into account spatial differences in T-CUL. Innovative models for CUL protection tailored to local conditions should be developed, and a new pattern of multi-scale coordination of CUL protection areas should be established to ensure land security in border regions.

4.2. Conclusions

Based on the land use data of the Sino–Vietnamese border area from 2000, 2010, and 2020, along with social and economic data from each research unit, this study provides a comprehensive analysis of the spatial and temporal transformation patterns of CUL. The

analysis utilizes kernel density analysis, geo-information, and a spatial econometric model to investigate the factors influencing T-CUL. The key findings are as follows:

(1) The density of CUL in the study area exhibited an initial increase followed by a continuous decrease. CUL was concentrated in the eastern plains but fragmented in the western hilly regions. The focus of CUL distribution shifted outward from the center. While density areas at all levels remained relatively stable during the study period, high-density regions were primarily located in Daxin and Longzhou Counties in Guangxi's border area, as well as in Lvchun and Malipo Counties in Yunnan's border area. Notably, from 2010 to 2020, CUL agglomeration became more pronounced, but CUL also experienced varying degrees of contraction, particularly in Funing County, Malipo County, and Jingxi City.

(2) T-CUL in the Sino–Vietnamese border areas displayed substantial regional disparities. Generally, T-CUL was more prevalent in the east compared with that in the west, aligning with regional topographical characteristics. Over the study period, exchanges between WL and CUL were dominant, and the spatial expansion trend of CUL transformation into COL became increasingly evident. Presently, the development trend of CUL shrinking transformation is intricate, with changes in CUL quantity transitioning from a rapid decline to a slower decline.

(3) The T-CUL in the Sino–Vietnamese border area resulted from the interaction of natural factors, human factors, and human–land interaction factors. Different factors played varying roles in driving the four types of T-CUL, each with its own direction and intensity. Notably, the transformation of CUL into WL was strongly influenced by the urbanization rate, highway mileage, and elevation, among other factors. the transformation of CUL into GL was widely affected by population and altitude. CUL to COL transformation was influenced by both natural conditions and economic, technological, and social factors. Finally, the transformation of WA into CUL was related to elevation and the total power of agricultural machinery.

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