

Article

Driving Factors of Rural Land-Use Change from a Multi-Scale Perspective: A Case Study of the Loess Plateau in China

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Abstract: The issue of multi-scale driving forces within land systems has emerged as one of the pivotal research directions for innovative exploration in the field of land science. However, the understanding of the differences in driving factors across different scales remains relatively inadequate. Based on multi-source data spanning from 2000 to 2020, this study applied GeoDetector models to reveal the evolution of the spatiotemporal pattern of land-use change and the scale differences in driving factors in rural areas of the Loess Plateau region from both prefecture-level scale and township scale. The results indicated that the land-use changes in rural areas of the Loess Plateau had exhibited distinct spatial differentiation characteristics over the past 20 years. Specifically, the land-use change dynamic degree on the Loess Plateau exhibits an upward trend from west to east (slope = 0.031) and a downward trend from north to south (slope = −0.039). Secondly, the spatial scale differences in driving forces of rural land-use change in the Loess Plateau were manifested through variations in dominant factors and differences in the sensitivity of land-use change to various factors. The reasons for these differences lay in scale effects and cumulative effects. These findings would provide decision-making support for policy-makers in formulating future sustainable land-use policies for rural areas. Additionally, it would contribute to further advancing the exploration of multi-scale driving forces within rural land systems.



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Keywords: rural land-use/cover change; spatiotemporal pattern; influencing factors; multi-scale; Loess plateau

1. Introduction

Land, serving as the material foundation for human production activities and the direct object of labor, provides the necessary spatial carrier for various purposeful land resource development and utilization activities [1]. Land-use/cover change (LUCC), functioning as a central link connecting human activities and the natural environment, has become a highly noteworthy focus within the field of global environmental science research [2]. Essentially, LUCC embodies the process of mutual transformation among land elements within a complex giant system involving multidimensional interactions and influences across natural, economic, and social dimensions. To deeply clarify the spatial scale effects of the driving mechanisms behind LUCC, it is imperative to systematically analyze the driving factors and the intrinsic mechanisms of their interactions at different spatial

scales (such as local, regional, national, and even global scales) from a multidimensional perspective. Using interdisciplinary research methods and comparing typical LUCC cases across different geographical regions and historical periods, the driving mechanisms rules and spatial scale effect models can be extracted, providing practical guidance for formulating specific land-use policies and ultimately fostering sustainable development in human society and efficient utilization of natural resources.

With the growth of the global population and increasing pressure on land resources, scholars have conducted continuous and in-depth explorations into the evolutionary characteristics of LUCC across different temporal and spatial scales. The research scope not only limits to analyzing the driving factors [3,4] but also broadly covers the response mechanisms of climate and ecological issues such as climate change [5], ecological environment quality [6] and carbon sequestration [7] to LUCC. Moreover, scholars utilized diverse indicators, including comprehensive land-use dynamic degree [8], single land-use dynamic degree [9], land-use change rate [10], and land-use change matrix [11], to assess the trends, rates, and intensity of land-use change. Furthermore, several land-use simulation models, such as the FLUS model [12,13], the CLUE model [14], and the GeoSOS model [15], were commonly applied to predict future land-use change under different development scenarios. In addition, spatial econometric models, geographically weighted regression models [16], and the GeoDetector [17,18] were employed to analyze the driving factors and evolution mechanism. However, the spatial econometric models and geographically weighted regression models could not effectively capture the similarity of factors within the same region and the differences between different regions. The GeoDetector model was a statistical method used to detect the spatial variability of geographical factors or phenomena and reveal the driving forces behind them [19].

Currently, numerous scholars have investigated LUCC, but they have primarily focused on single-scale studies [16–18,20,21], neglecting the analysis of differences in driving factors across different scales. Furthermore, existing multi-scale research on land-use change primarily focused on larger scales, such as the county level and above, with insufficient research on the driving forces of land-use change at the township level and below [18]. In terms of study areas, the focus had mainly been on the eastern regions with faster economic development, while research in the central and western regions was relatively weaker, especially in ecologically fragile areas [8,13]. Moreover, current studies on the driving forces of land-use change across different scales were conducted separately for different study areas, making it impossible to conduct spatial longitudinal [2]. Therefore, within the same geographical area, the differences in driving factors for rural land-use change across different spatial scales and their transmission mechanisms were scientific questions that urgently need to be addressed, especially in the ecologically fragile regions of central and western China.

As the largest developing country in the world, China faces increasingly prominent issues related to the relationship between people and land amid its rapid urbanization process [22]. In particular, the Loess Plateau region, with a fragile ecological environment, is one of the most severely affected by soil and water loss in China and even globally [23]. Intensified climate change in recent decades has continuously exacerbated the fragility and instability of the ecological environment in this area, further intensifying tensions in the relationship between people and land [24]. To address this ecological challenge, the Chinese government has strengthened governance in this region since 1999, implementing a series of ecological conservation projects such as the Grain for Green Program. However, these measures have also led to significant changes in regional land-use patterns, exhibiting strong spatial heterogeneity. Furthermore, China's unique historical background and national conditions have resulted in the separation of urban and rural development, which

has caused a severe imbalance in resource allocation between urban and rural areas. The issue of rural decline is particularly prominent in the Loess Plateau. Against this backdrop, township-level and smaller administrative units, as the grassroots units in China's administrative system, play a pivotal role in connecting the upper and lower levels. They not only reflect the detailed situation of land-use change at a small scale but also provide more precise basic data support for exploring large-scale economic and geographical laws. Therefore, conducting in-depth research on the mechanism of LUCC differentiation at the multi-scale level is of great significance and urgent need for local governments to adopt targeted development strategies [25]. This paper takes the Loess Plateau as the study area and utilizes land-use, socio-economic, transportation, topographic, and climatic data. From multiple dimensions, including change intensity, spatial pattern, and driving factors, it comprehensively analyzes the spatiotemporal evolution and driving mechanisms of rural land-use change on the Loess Plateau over the past 20 years at different scales, including prefecture and township levels using methods such as the land-use dynamic degree and GeoDetector. Additionally, it proposes policy recommendations for sustainable rural land-use management in the Loess Plateau region in the future.

Based on this, this study makes marginal contributions to exploring LUCC and its multi-scale driving mechanisms in the Loess Plateau in the following aspects: (1) It focuses on land-use change in rural areas, enriching the empirical basis for deeply understanding the mechanisms of rural land-use change in China against the backdrop of urbanization; (2) It analyzes the spatiotemporal evolution patterns of rural land-use change at multiple scales and explores the scale differences in driving factors of land-use change at both prefecture level and township level, enriching the multi-scale theoretical research on land-use change mechanisms; (3) It takes the Loess Plateau in China as the research object, with special attention to the changes in rural land use in ecologically fragile areas during China's rapid urbanization process.

2. Theoretical Framework

Human activities and natural environments were the fundamental factors driving land-use change [26,27]. Human activities, as the dominant factor driving land-use change, primarily influence land-use change through factors such as population change, economic development, transportation conditions, and land-use/management policies [2,28]. Firstly, rapid population growth leads to an increased demand for land resources, which may prompt the expansion of land-use types such as cropland and built-up land and potentially result in the reclamation of ecological land [29]. Especially in densely populated areas, the fragile relationship between humans and land further drove rapid changes in land use. Conversely, population decline may lead to cropland being abandoned and subsequently converted into ecological land. Secondly, economic factors were a significant driving force behind changes in rural land use. With the development of the market economy, the relatively low profitability of agricultural production has led farmers to prefer using their cropland for purposes with higher economic returns, such as industrial, commercial, or residential development. Meanwhile, an increase in residents' income levels would prompt people to improve their living conditions, thereby increasing the demand for built-up land, including homesteads [30,31]. Additionally, transportation conditions were also considered one of the main driving forces influencing land-use change [32]. The development of transportation roads reduced transportation costs, enhanced the accessibility and utilization value of land, and played a significant role in driving the development and utilization of land along the routes. For example, in areas strongly influenced by roads, built-up land, and cropland dominated. In contrast, areas with weaker road influence were mainly composed of ecological land, such as woodland and grassland. More importantly, land-use policies

also exerted a decisive influence on land-use change through regulatory measures [33]. For example, to protect the ecosystem of the Loess Plateau, China implemented the “Grain for Green” program, which promoted the conversion of cropland to woodland and grassland.

Natural environments primarily influence land-use change through differences in factors such as terrain, slope, temperature, and precipitation [34]. The conditions of terrain and slope determined the choice of land use [35]. For example, in areas with large topographic relief or steep slopes, due to unfavorable conditions for crop growth and inconvenience in agricultural production, farmland tends to be converted into woodland and grassland. Additionally, climate change was also considered one of the main driving forces influencing land-use change. For instance, climate warming has led to the continuous northward expansion of the planting boundaries of some crops, altering the local agricultural planting pattern [36] (Figure 1).

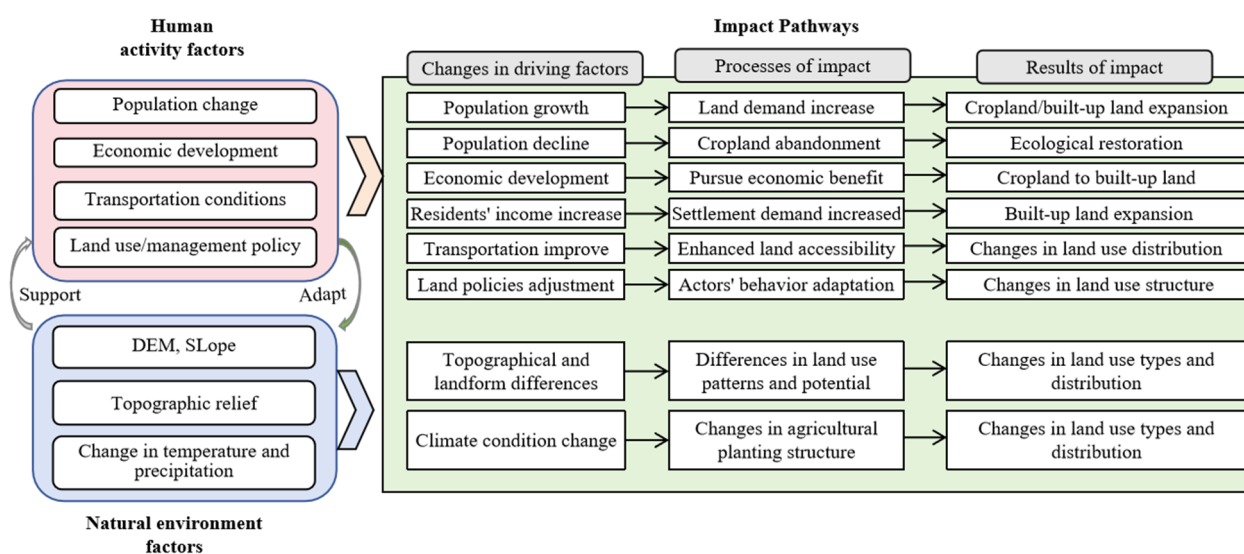


Figure 1. Analysis framework of Land-use change.

3. Materials and Methods

3.1. Study Area

The Loess Plateau (33°41' N–41°16' N, 100°52' E–114°33' E) is located in the northern part of central China, covering an area of about 640,000 km², including five provinces (Shaanxi, Gansu, Qinghai, Shanxi, and Henan) and two autonomous regions (Ningxia and Inner Mongolia), with a total of 45 prefecture-level cities and 4305 townships (towns) (Figure 2). From the perspective of territory types, the Loess Plateau is divided into six geographical divisions according to the “Comprehensive Management Planning Outline for the Loess Plateau Region (2010–2030)” (<https://zfxgk.ndrc.gov.cn>, accessed on 1 December 2024): valley plain region, Loess Plateau–gully region, Loess hilly–gully region, agricultural irrigation region, rocky mountainous region, sandy and desert region. With the acceleration of the urbanization process and the promotion of ecological environment management, the rural population and land-use pattern of the Loess Plateau have undergone profound changes. In terms of the rural population, a large number of the rural labor force choose to go out for work, resulting in a serious outflow of the rural population and widespread hollowing because of poor natural conditions and relatively backward economic development. In terms of land use, with the acceleration of urbanization, the scale of rural construction land is increasing, which makes the protection of cultivated land face great pressure. The problem of decreasing rural population and increasing construction land in the Loess Plateau is a common feature of many areas with rapid urbanization development.

Therefore, it is representative to choose the Loess Plateau as the case area to study rural land-use change.

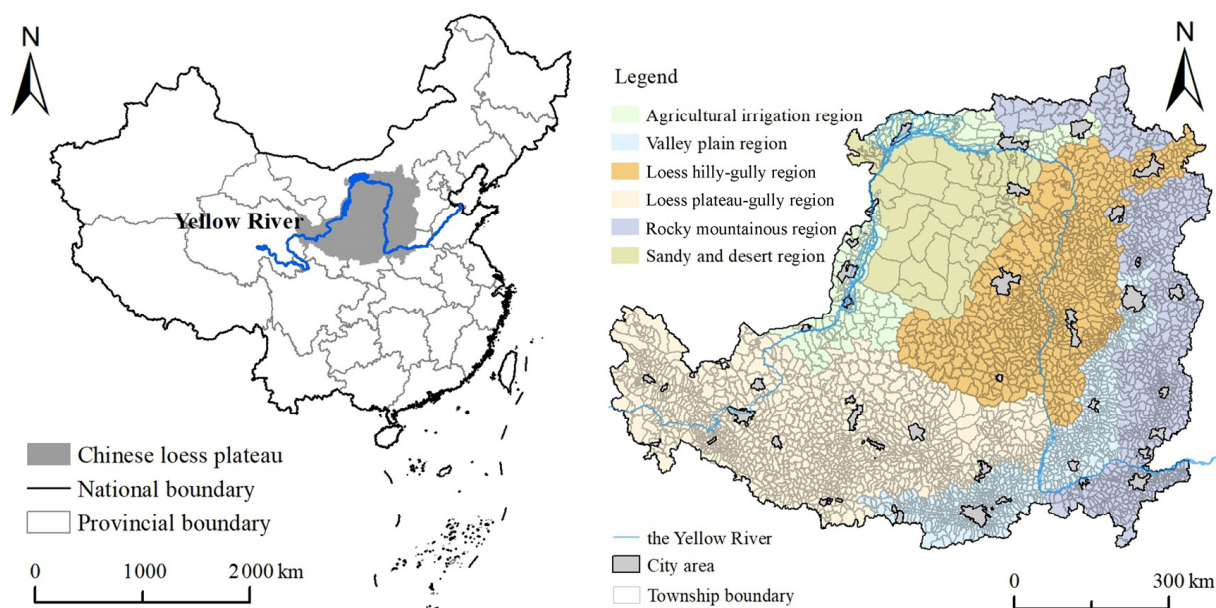


Figure 2. The location of the study area.

3.2. Data Sources and Processing

The data used in this study included land-use data, socio-economic data, topographic data, and climate data. The land-use data were obtained from the Resources and Environmental Sciences Data Platform (RESDP) of the Chinese Academy of Sciences (<https://www.resdc.cn/>, accessed on 1 December 2024). The spatial resolution of land-use data was 30 m, which was mainly obtained through manual visual interpretation using Landsat remote sensing image data of the United States as the main information source. The land-use type was divided into six first-level land types, which are cropland, woodland, grassland, water body, built-up land (industrial and mining, urban and rural residential areas), and unused land. Socio-economic data mainly included population, economy, and transportation. Among them, the population and GDP data were sourced with one-kilometer raster data provided by RESDP. Traffic network data were derived from OpenStreet Map, OSM (<http://m.osmttools.de/>, accessed on 1 December 2024). The climate data mainly consisted of the temperature and precipitation raster data provided by RESDP, with a spatial resolution of one kilometer. The temperature and precipitation data were produced using the thin plate spline function of Anusplin version 3.2 software based on the annual values of meteorological elements from more than 2400 stations in China (Table 1).

This study focused on rural land-use change at prefecture-level scale and township scale. In China, rural areas were typically defined as the vast regions outside urban built-up areas. Generally, streets (where urban communities were established) and central towns (seats of county governments) in China belong to urban areas and are located within the urban built-up areas. Therefore, in this study, 815 streets and central towns in the Loess Plateau were excluded to identify the rural areas. Additionally, due to the insufficient distinction in spatial scale between county-level administrative units and township-level administrative units, we had chosen to research rural land-use changes and their influencing factors at both the prefecture-level scale and the township scale. To mitigate the impact of administrative boundary adjustments on research findings, we conducted statistical analyses on land-use change and driving factors separately, using the administrative boundaries of 2020 as the basis (from the National Earth System Science Data Center,

NESSDC). Based on the reference of the theoretical framework, we selected 12 indicators (DEM, slope, topographic relief, precipitation, temperature, population, population density, GDP, per capita GDP, road density, Grain for Green, per rural settlement area) as impact factors (Table 1). Utilizing the administrative boundaries of 2020 and with the assistance of ArcGIS version 10.6.1 software, we conducted statistical analysis to determine the average value of each impact factor across 3490 townships and 45 prefecture-level cities, respectively.

Table 1. Spatial resolution and source of the data used in this study.

Datasets		Spatial Resolution	Year	Source
Land use		30 m	2000, 2020	RESDP
Administrative boundary		-	2020	NESSDC
Driving factors	DEM	90 m	-	RESDP
	Slope	90 m	-	RESDP
	Topographic relief	90 m	-	RESDP
	Precipitation	1 km	2000, 2020	RESDP
	Temperature	1 km	2000, 2020	RESDP
	Population	1 km	2000, 2020	RESDP
	Population Density	1 km	2000, 2020	RESDP
	GDP	1 km	2000, 2020	RESDP
	Per capita GDP	1 km	2000, 2020	RESDP
	Road density	1 km	-	OSM
	Grain for Green	1 km	2000, 2020	RESDP
	Per rural settlement area	1 km	2000, 2020	RESDP

3.3. Methods

3.3.1. Land-Use Change Dynamic Degree (LUDD)

Land-use change analysis usually adopts a transfer matrix for quantitative measurement. Based on land-use data, we calculated the land-use change in rural areas of the Loess Plateau from 2000 to 2020. In order to better analyze the characteristics of land-use change and reveal land-use change intensity, we adopted the LUDD model for quantitative expression, and the calculation formula was as follows [37]:

$$D_i = \frac{\sum_j^n |\Delta S_{i,j}|}{S_a} \times \frac{1}{t} \times 100\%$$

$$D_a = \frac{\sum_i^n \sum_j^n |\Delta S_{i,j}|}{S_a} \times \frac{1}{t} \times 100\%$$

where D_i represents the dynamic degree of land-use type i ; D_a represents the dynamic degree of spatial unit a ; $|\Delta S_{i,j}|$ represents the absolute value of the area converted between land-use type i and other land-use type j during the period from the start to the end of the study period; S_a is the area of spatial unit a ; t is the length of the study period. n represents the number of land-use types. For example, $\sum_j^n |\Delta S_{cropland,j}|$ is equal to the sum of the areas of mutual conversion between cropland and other land-use types, such as built-up land, woodland, and grassland in spatial unit a during the study period. $\sum_i^n \sum_j^n |\Delta S_{i,j}|$ is equal to the sum of the areas of mutual conversion between each land-use type in a spatial unit during the study period.

3.3.2. GeoDetector Model

The GeoDetector model consists of four sub-detectors: factor detector, risk detector, interaction detector, and ecological detector. In our work, the factor detector was utilized

to identify the main influencing factors and the scale differences in rural land-use change across various scales in the Loess Plateau. The core assumption of this model was that if a particular independent variable had a significant impact on the dependent variable, then there would be a similarity in their spatial distribution. The GeoDetector model was immune to multicollinearity among multiple independent variables, and the magnitude of factor driving force was measured by the q statistic. The physical meaning of the q -value was that the independent variable explains $(100 \times q)\%$ of the dependent variable. The formula was as follows [18]:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{h=1}^L N_h \sigma_h^2$$

where L represents the stratification of the dependent variable Y or the independent variable X , which refers to classification or zoning. N_h and σ_h represents the number of units and the variance within layer h , respectively. N and σ represent the total number of units and the variance of the entire study area, respectively. The range of the q -value is $[0, 1]$, and a higher value indicates a stronger explanatory power of the independent variable for the dependent variable.

4. Results

4.1. Land-Use/Cover Change in the Loess Plateau

From 2000 to 2020, the major types of land-use transfer in the Loess Plateau were cropland to grassland, cropland to built-up land, and grassland to cropland. Specifically, 11,410 km² of cropland were converted to grassland. The transfer area of cropland to built-up land was 8097 km², and the area of grassland converted to cropland was 7448 km². In addition, the conversion of grassland to woodland, cropland to woodland, and grassland to built-up land also had a large scale, respectively, 4063 km², 3608 km², and 3389 km². The above six types of land-use conversion accounted for 69.12% of the total land-use conversion area in the Loess Plateau during the study period (Table 2).

Table 2. Land-use change in the Loess Plateau during 2000–2020 (10³ km²).

Land-Use Types		2020					
		Cropland	Woodland	Grassland	Waterbody	Built-Up Land	Unused Land
2000	Cropland	0.000	3.608	11.410	0.930	8.097	0.533
	Woodland	1.234	0.000	2.273	0.134	0.663	0.128
	Grassland	7.448	4.063	0.000	0.532	3.389	2.395
	Waterbody	0.592	0.083	0.381	0.000	0.246	0.331
	Built-up land	1.169	0.076	0.176	0.042	0.000	0.015
	Unused land	0.714	0.383	2.943	0.312	0.700	0.000

The spatial distribution of land-use transition in the Loess Plateau was significantly different (Figure 3). The scale of land-use transfer increased from west to east and from north to south. The CL→WL transfer patches are mainly distributed in the areas between 109° E–113° E and 36° N–38° N, including Yan'an and Yulin Cities in Shaanxi Province, Shuozhou and Changzhi Cities in Shanxi Province. The CL→GL transfer patches are mainly distributed in the areas between 106° E–111° E and 34° N–38° N, including Yan'an and Yulin Cities in Shaanxi Province, Qingyang and Pingliang Cities in Gansu Province. The CL→BL transfer patches are mainly distributed in the areas between 111° E–114° E and 34° N–38° N, including Changzhi and Luliang Cities in Shanxi Province, Xi'an City in Shaanxi Province. The GL→CL transfer patches are mainly distributed in the areas

between 110° E– 113° E and 36° N– 38° N, including Yulin City in Shaanxi Province, Ordos and Hohhot Cities in Inner Mongolia. The GL→WL transfer patches are mainly distributed in the areas between 112° E– 114° E and 35° N– 38° N, including Erdos City in Inner Mongolia, Qingyang City in Gansu Province, and Yan'an City in Shaanxi Province. The GL→BL transfer patches are mainly distributed in the areas between 109° E– 112° E and 37° N– 40° N, including Ordos City in Inner Mongolia and Yulin City in Shaanxi Province.

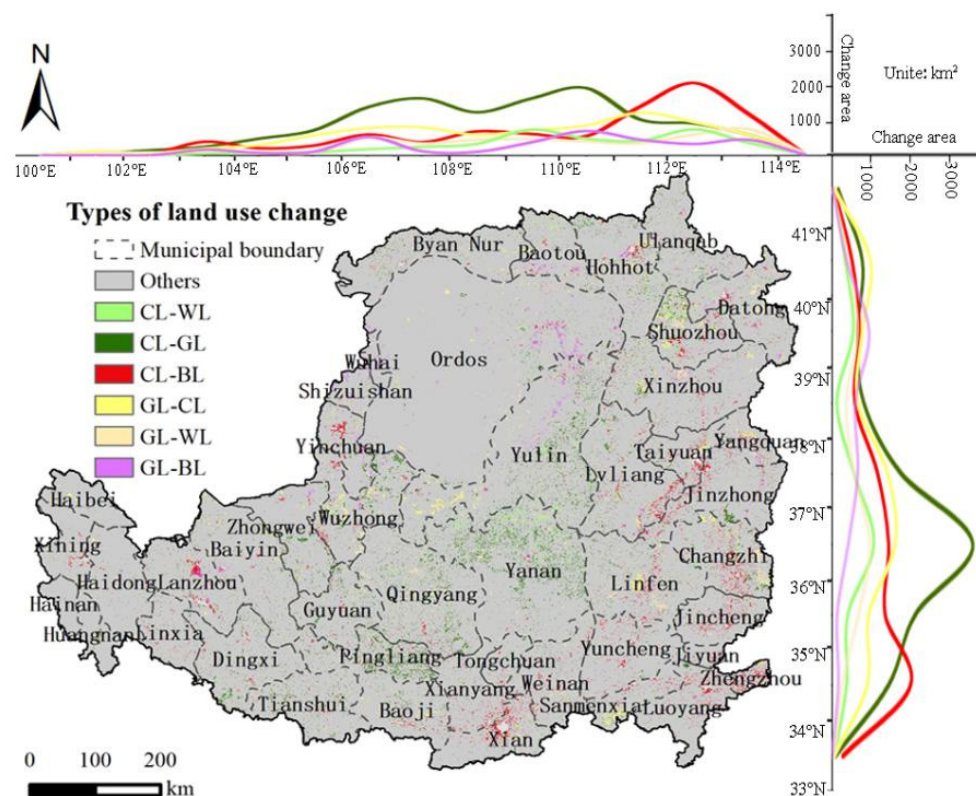


Figure 3. The spatial distribution of land-use change in the Loess Plateau during 2000–2020. CL: cropland, WL: woodland, GL: grassland, BL: built-up land, UL: unused land.

The characteristics of land-use change among different territory types were also significant differences (Figure 4). Specifically, the dominant land-use change mode was cropland to built-up land in the valley plain region. From 2000 to 2020, 1390 km^2 of cropland had been transformed into built-up land because the valley plain region was the main concentration area of high-quality cultivated land in the Loess Plateau. Besides, the Loess Plateau–gully region and the Loess hilly–gully region were the main concentration areas of the project “Grain for Green” in the Loess Plateau. Thus, the dominant land-use change mode of the Loess Plateau–gully region and Loess hilly–gully region was cropland to grassland. For example, 4065 km^2 and 4362 km^2 of cropland were converted to grassland in the Loess Plateau region and Loess hilly–gully region during the study period, respectively. In addition, the agricultural irrigation region was the main grain-producing area in the Loess Plateau, and the dominant land-use change mode in this area was the transfer from grassland to cropland during the study period (the area was 1106 km^2). In contrast, in the rocky mountainous region where land resources were scarce, a large amount of cropland had been converted into built-up land due to urbanization. In the past 20 years, 2100 km^2 of cropland has been converted into built-up land. Especially in sandy and desert regions, the land-use change mode was mainly the mutual transformation between grassland and unused land. Among them, the conversion area of grassland to unused land

due to desertification was 1502 km², and the conversion area of unused land to grassland due to sand control projects was 1469 km².

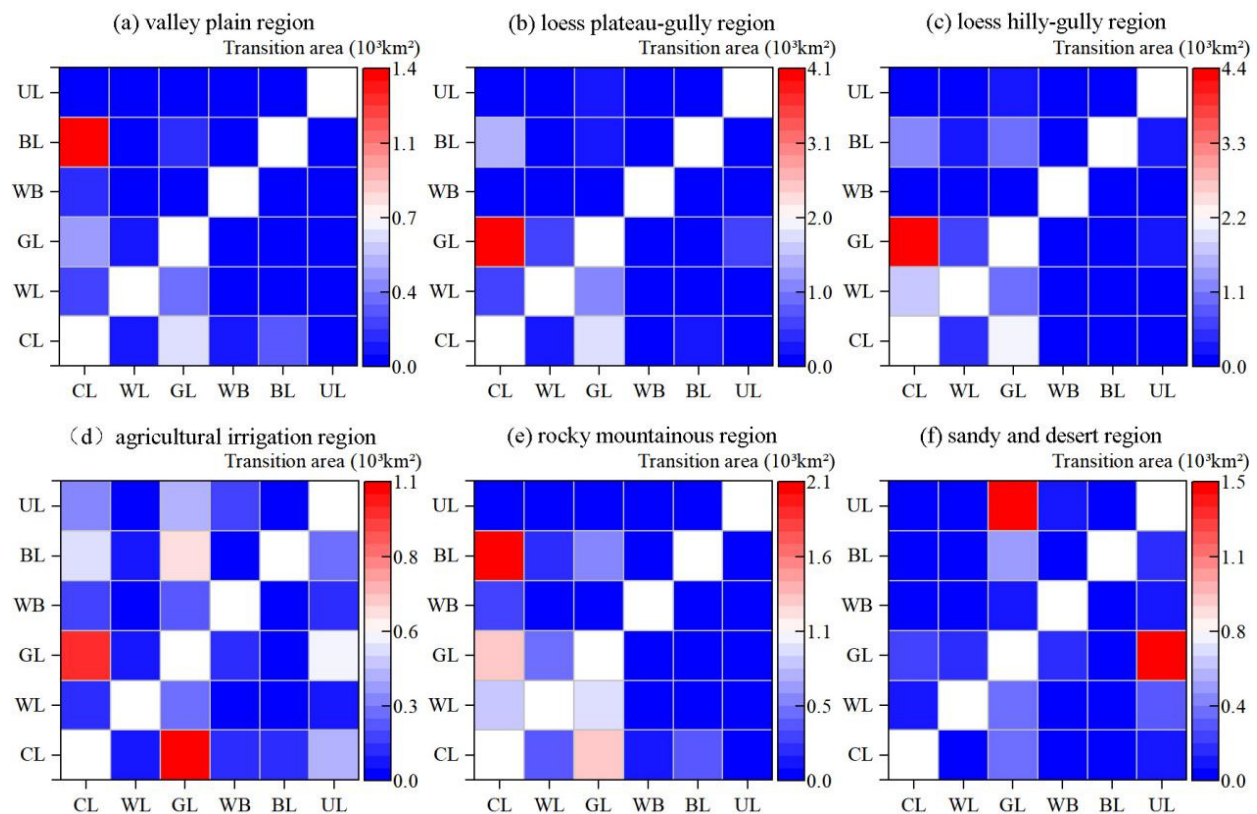


Figure 4. Characteristics of rural land-use change in different territory types from 2000 to 2020. The X-axis was the type of land use in 2000, and the Y-axis was the type of land use in 2020. CL: cropland, WL: woodland, GL: grassland, WB: water body, BL: built-up land, UL: unused land.

4.2. Land-Use Change Dynamic Degree in the Loess Plateau

The dynamic analysis showed that land-use change in the Loess Plateau had been stable on the whole since the 21st century, but the spatial differentiation was obvious. From 2000 to 2020, the dynamic degree of land-use change in the Loess Plateau was 0.43, which belongs to the medium change intensity in China [1]. Spatially, the dynamic degree of land-use change in the Loess Plateau showed increased fluctuation from west to east (slope = 0.031). From north to south, the land-use change dynamic degree was characterized by a decline in volatility (slope = −0.039). Shuozhou City in Shanxi Province and Zhengzhou City in Henan Province were the drastic-change areas of land-use change dynamic degree in the Loess Plateau. In Shuozhou City, the main types of land-use change were CL→BL, CL→WL, CL→GL, and GL→CL. The main types of land-use change in Zhengzhou City were CL→BL, GL→CL, and CL→WB. In addition, the considerable change areas are mainly distributed in Ningxia Province, concluding Yinchuan City, Shizuishan City, and Wuzhong City. At the township scale, there were 176 townships ($LUDD \geq Act + 2Sdct$) with drastic land-use changes, which were mainly distributed around municipal built-up areas in the east of the Loess Plateau. In the south of the Loess Plateau, the land-use cover drastic-change townships were mainly distributed in Xian, the capital city of Shannxi Province. In the west of the Loess Plateau, the land-use cover drastic-change townships were mainly distributed in Lanzhou, the capital city of Gansu Province, and Xining, the capital city of Qinghai Province (Figure 5, Table 3).

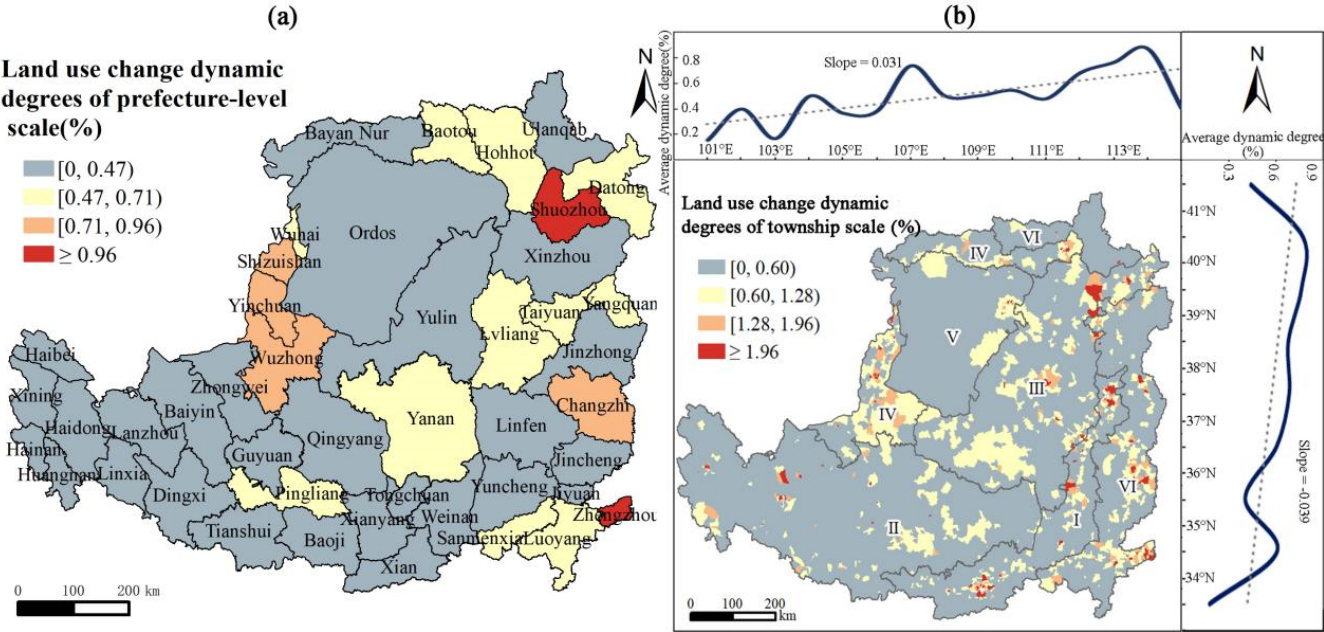


Figure 5. Land-use change dynamic degrees of prefecture-level scale (a) and township scale (b) in the Loess Plateau during 2000–2020. I: valley plain region, II: Loess Plateau–gully region, III: Loess hilly–gully region, IV: agricultural irrigation region, V: sandy and desert region, VI: rocky mountainous region. The solid line refers to the trend of LUDD with longitude or latitude. The dashed line refers to the slope of LUDD with longitude or latitude.

Table 3. Classification statistics of land-use change degree at township scale and prefecture-level scale in the Loess Plateau.

Administrative Scales	Classification Standard	Rane	Numbers
Township scale	[0, Act)	<0.60	2361
	[Act, Act + Sdct)	[0.60, 1.28)	740
	[Act + Sdct, Act + 2Sdct)	[1.28, 1.96)	211
	≥Act + 2Sdct	≥1.96	178
Prefecture-level scale	[0, Acp)	<0.47	28
	[Acp, Acp + Sdcp)	[0.47, 0.71)	11
	[Acp + Sdcp, Acp + 2Sdcp)	[0.71, 0.96)	4
	≥Acp + 2Sdcp	≥0.96	2

Note: “Act” and “Acp” represent the average value of land-use change degree at the township scale and the prefecture-level scale, respectively. “Sdct” and “Sdcp” are the standard deviations of land-use change degree at the township scale and the prefecture-level scale, respectively.

4.3. Impact Factors Detection of Land-Use Change in Different Spatial Scale

At the prefecture-level scale, socio-economic development, climatic conditions and topographic conditions were the main factors affecting the spatial difference of land-use change. Economic development has significantly enhanced residents’ living and production standards, such as increased income levels and improved road infrastructure. This led to the expansion of rural settlements. Therefore, economic development factors were the main factor affecting the spatial difference of land-use change. The results of factor detection showed that factors such as per capita GDP, road density, and GDP had strong explanatory power, and the q values were 0.658, 0.476, and 0.447, respectively, and all passed the significance test. Secondly, climate factor was also an important factor for the spatial difference of land-use change at the prefecture-level scale. The Loess Plateau was the core area of the “Grain for Green” project in China. The conversion of cropland to woodland and grassland was the main type of land-use change in this area. The impact of precipitation on

the implementation of the “Grain for Green” project was particularly significant. Therefore, the precipitation factor had good explanatory power for the spatial differences in land-use change, with a q-value of 0.599, passing the significance test. Additionally, topographic factors also had a certain explanatory power for the spatial differences in land-use change at the prefecture-level scale, but their explanatory power was weaker than that of economic development and climatic factors (Table 4).

Table 4. The factor detector results of rural land-use change in different scales.

Variables	Units	Township Scale q-Value	Prefecture-Level Scale q-Value
DEM	meter	0.101 **	-
Slope	degree	0.144 **	-
Topographic relief	meter	0.128 **	0.262 *
Precipitation	mm	0.035 **	0.599 **
Temperature	°C	0.07 **	-
Population	person	0.054 **	-
Population Density	person/km ²	0.197 **	-
GDP	RMB	0.102 **	0.447 **
Per capita GDP	RMB/person	0.117 **	0.658 **
Road density	km/km ²	0.271 **	0.476 **
Grain for Green	km ²	0.215 **	-

Note: One-way ANOVA (** = $p < 0.01$; * = $p < 0.05$); “-” indicates that the significance test has not been passed.

At the township scale, transportation conditions, land-use/management policies, population changes, and topographical conditions were the primary factors influencing the spatial differences in land-use change. Since the distribution of rural settlements was road-oriented, the enhancement of rural transportation conditions facilitated the spatial aggregation and expansion of rural settlements. The factor detection results at the township scale also indicated that road network density had the highest explanatory power with a q-value of 0.271, passing the significance test. Secondly, the impact of population factors on land-use change became prominent at the township scale, with population density having an explanatory power of 0.197, which also passed the significance test. Especially in townships with high population density, the pursuit of better living conditions stimulated the expansion of construction land. Conversely, townships with low population density often faced population loss or were characterized by vast territories with a sparse population, leading to a relatively stable pattern of construction land use. Additionally, topographical factors also significantly influenced land-use change at the township scale, particularly slope and topographic relief, with explanatory powers of 0.144 and 0.128, respectively, both passing the significance test. Areas with flat terrain were conducive to the expansion of construction land, while areas with steep and fragmented terrain were key targets for the “Grain for Green” project (converting cropland to woodland or grassland). Lastly, the implementation of the “Grain for Green” project played a particularly important role in land-use change at the township scale, with the explanatory power of the factor related to converting cropland to woodland/grassland being 0.215, passing the significance test. Especially under the constraints of the Land Administration Law and the Regulations on the Protection of Basic Farmland, the land-use pattern in rural areas tended to be more stable, and the implementation of the “Grain for Green” project had become a significant policy driver of large-scale land-use change in rural areas.

4.4. Multi-Scale Differences in Driving Factors of Major Land-Use Types Change

We further analyzed the multi-scale driving factors of major land-use type change to fully understand the differentiation characteristics of multi-scale effects in the Loess Plateau. Cropland, woodland/grassland, and built-up land were the major land-use types with the highest change dynamic degree in the Loess Plateau.

The main types of cropland change on the Loess Plateau were CL→BL, CL→WL/GL, and GL→CL. At the prefecture-level scale, economic development and transportation conditions had the most significant impact on cultivated land change (Figure 6). However, population changes, the implementation of the “Grain for Green” project, and topographical conditions had strong explanatory power for cropland change at the township scale. Over the past two decades, population migration on the Loess Plateau has primarily been from rural to urban areas, particularly in townships surrounding urban built-up areas, leading to the expansion of these areas and the occupation of a large amount of cropland. From the perspective of topographical conditions, townships with significant cropland changes on the Loess Plateau were mainly distributed in the valley plain region, agricultural irrigation region, and Loess hilly–gully region. The cropland changes in the valley plain region and agricultural irrigation region were mainly due to the reduction in cropland scale caused by urbanization and population migration. In contrast, changes in cropland in the Loess hilly–gully region were primarily influenced by the “Grain for Green” project.

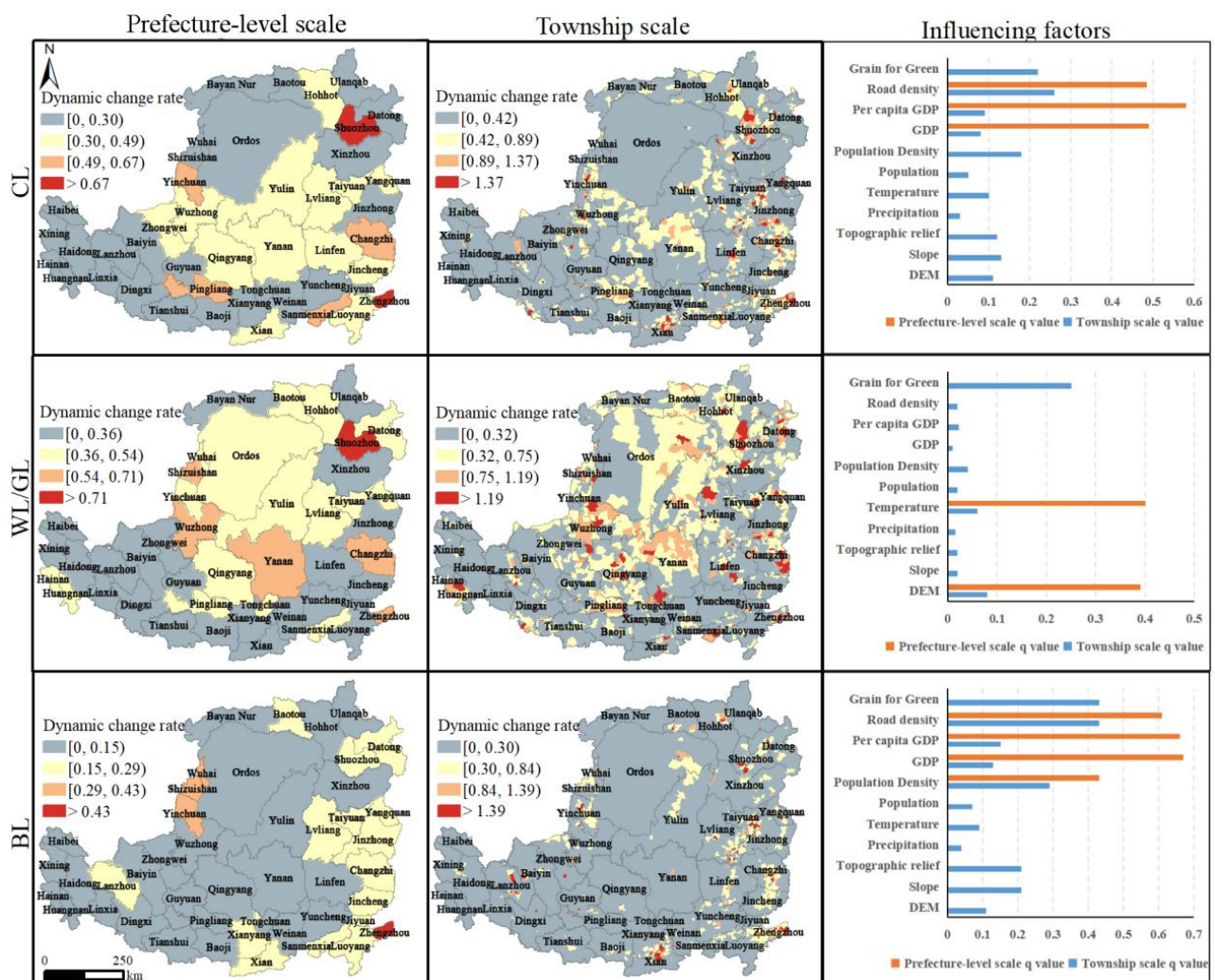


Figure 6. The driving factors of major land-use types in prefecture-level scale and townships scale.

The main types of woodland and grassland changes on the Loess Plateau included CL→WL/GL and GL→CL. Spatially, areas with significant woodland and grassland changes were primarily distributed in the severely eroded Loess hilly–gully region. Unlike cropland changes, the core driving factors of woodland and grassland changes were more inclined towards natural environmental conditions. Factor detection analysis indicated that topographical conditions, climatic conditions, and the “Grain for Green” project were the primary factors influencing woodland and grassland changes. At the prefecture-level scale, topographical and climatic factors had a significant impact on woodland and grassland changes. Due to the relatively small differences in topography and climate conditions at the township scale, the implementation of the “Grain for Green” project became the primary driving factor affecting woodland and grassland changes at this scale.

The main types of built-up land change on the Loess Plateau included CL→BL and GL→BL. At the prefecture-level scale, socio-economic development and transportation conditions were the primary factors driving changes in construction land use. At the township level, besides socio-economic development factors, land-use policies and topographical conditions also played significant roles in influencing changes in built-up land change. It could be observed that economic development and population growth were the fundamental driving forces behind the expansion of built-up land. From the perspective of the dynamic degree of change in built-up land, areas with intense changes in built-up land were mainly distributed in agricultural irrigation region, valley plain region, and certain parts of a rocky mountainous region on the Loess Plateau.

Overall, there was a certain spatial similarity in the dynamic degree of rural land-use change on the Loess Plateau at both the township and prefecture-level scales, primarily occurring in the northeastern and southeastern parts of the plateau. From the analysis of influencing factors, at the township scale, land-use change was significantly influenced by driving factors. However, at the prefecture-level scale, the significance of driving factors on land-use change varied considerably depending on the different types of land use.

5. Discussion

5.1. Main Characterization of Multi-Scale Differences in Driving Forces of Land-Use Change

Under the background of rapid urbanization, rural land-use change in the Loess Plateau was jointly influenced by various factors, including population, economy, transportation, urbanization, land-use/management policies, terrain, slope, climate, and more. The impact degrees of these factors on land-use changes varied significantly across different spatial scales. In this study, we considered socio-economic development, climate change, and topographical conditions as the primary driving forces of rural land-use change at larger spatial scales (such as the prefecture-level scale or larger), whereas transportation conditions, land-use policies, and population changes were the main driving forces at smaller spatial scales (township scale or smaller). These findings were similar to previous research results [38,39]. Our research further revealed that the multi-scale differences in driving forces of rural land-use change on the Loess Plateau were manifested not only in the difference of dominant factors but also in the sensitivity of land-use changes to various factors. According to the significance test results between dependent and independent variables at different scales, five indicators passed the significance test at the prefecture-level scale, while 11 indicators passed at the township scale. Through comparison, it was found that spatial differences in driving factors were more easily reflected in the spatial differentiation of rural land-use changes at smaller spatial units.

5.2. Mechanism Analysis of Multi-Scale Differences in Driving Forces of Land-Use Change

By comparing and analyzing the differences in the core driving factors of rural land-use change across different scales on the Loess Plateau, we thought that these differences were attributed to scale effect and cumulative effect [40,41]. The scale effect refers to the phenomenon that certain driving factors could only demonstrate their impact on land-use change at specific spatial scales, such as climate change. Factor detection analysis revealed that the scale difference of the climate change driving factor was more prominent in the process of woodland/grassland change. As mentioned in Section 4.4, the differences in climatic conditions at the township scale were relatively small, resulting in a much weaker explanatory power of climate change for woodland/grassland changes at this scale. Notably, we found that temperature differences have a stronger explanatory power for woodland/grassland changes than precipitation factors. This was particularly true in the Loess hilly–gully region, where the dynamics of woodland/grassland changes were significant, and the terrain was highly undulating. This may be due to the large vertical temperature differences caused by elevation changes, which had a certain impact on the transitions between woodland/grassland and cropland [42]. In contrast, the cumulative effect implied that at smaller spatial scales, the influence of some driving factors on land-use change was limited in scope. However, when these changes accumulate over time and space, they may produce significant impacts at higher spatial scales [43]. For instance, the scale difference of the economic development driving factor was most evident in the process of cropland change. At the township scale, despite the significant rural economic development in the context of rapid urbanization, the primary change was in farmers' livelihoods, with less impact on the utilization attributes of cropland, especially in the traditional agriculture-dominated Loess Plateau region. However, at the prefecture-level scale, it was necessary to consider the cropland changes across different types of townships within the same spatial area, particularly those surrounding urban built-up areas, where the expansion of construction land usually leads to the occupation of large amounts of cropland.

Moreover, the universality and suitability of policies were also significant reasons influencing the scale differences in driving factors of land-use change. Specifically, the Grain for Green Program was a universal policy in the Loess Plateau region, with each prefecture-level city having its targets for converting cropland back to woodland/grassland. Therefore, at the prefecture-level scale, every region diligently implemented the policy and tasks of transforming cropland into woodland and grassland, which diminished the significance of the policy's impact on land-use change. Additionally, the Grain for Green Program also had suitability characteristics. During the implementation of the policy, full consideration was given to the topographic features (such as slopes greater than 15°) [25,35]. Townships with complex terrain were the key areas for policy implementation, while those with flat terrain were rarely involved. Consequently, at the township scale, the impact of the Grain for Green Program on land-use change was more pronounced.

5.3. Implications for Rural Land Management in the Loess Plateau

As globalization and urbanization accelerate, rural land use faces unprecedented challenges and opportunities. Considering the spatial scale differences in the driving factors of land-use change, future rural land use in the Loess Plateau should adhere to multi-scale planning and management, implement differentiated land-use strategies, and strengthen ecological environment protection. Firstly, it is necessary to strengthen multi-scale planning and management. For instance, a national spatial planning system that links multiple levels, including the national, provincial, municipal, county, and township levels, should be established to ensure the coordination and consistency of planning at all

levels [44]. Especially at the township scale, land-use planning should be refined, with clear boundaries for various types of land use, strict protection of permanent basic farmland, and reasonable delineation of ecological protection red lines and urban development boundaries. Secondly, differentiated land-use strategies should be implemented. Based on factors such as topography, climate conditions, and economic development levels in different regions, differentiated land-use policies should be formulated. For example, in the Loess hilly–gully region and sandy-desert region on the Loess Plateau, priority should be given to protecting cropland, woodland, and grassland, with restrictions on large-scale development and construction, whereas in resource-rich and relatively economically developed villages in valley plain region and agricultural irrigation region, construction land quotas could be appropriately relaxed to support rural industrial upgrading and urbanization development. Furthermore, ecological environment protection should be strengthened to achieve green development. Given the fragile ecological environment of the Loess Plateau, strict ecological protection systems and regulatory frameworks for ecological protection red lines should be implemented to enhance the protection of ecosystems such as woodland and grassland. Strict control should be exercised over construction projects occupying ecologically sensitive and key functional areas to ensure ecological security [45]. At the same time, adaptive management for climate change should be strengthened. In response to the impact of climate change on rural land use, a climate change monitoring and warning system should be established, and adaptive management measures should be formulated [46]. The implementation of these policies would vigorously promote sustainable rural development and lay a solid foundation for achieving the strategic goals of rural revitalization.

6. Conclusions

Based on a multi-scale research perspective, this paper applied the land-use change dynamic-degree model and the GeoDetector model to reveal the evolution of the spatiotemporal pattern of land-use change and the scale differences in driving factors in rural areas of the Loess Plateau. The results indicated that significant changes had occurred in the land-use pattern of rural areas on the Loess Plateau over the past 20 years. The dynamic degree of land-use change in the Loess Plateau from 2000 to 2020 was 0.43, indicating that the land-use type in the Loess Plateau remained relatively stable during the study period. However, spatially, the changes in rural land use on the Loess Plateau exhibited a regular trend of variation. In particular, in different territory zones, the dominant patterns of land-use change showed significant differences. At different spatial scales, the primary influencing factors of rural land-use changes on the Loess Plateau exhibit variations. Specifically, socio-economic development, climate change, and topographical condition had a more prominent driving effect on rural land-use change at the prefecture-level scale. In contrast, transportation conditions, land-use/management policies, and population change were more prominent drivers of rural land-use change at the township scale. In particular, land-use management policies exerted a significant influence on rural land-use changes. For example, more than 59% of the increase in woodland and grassland originated from the conversion of cropland, influenced by the implementation of the “Grain for Green” policy. The main characterization of multi-scale differences in driving forces of rural land-use change on the Loess Plateau was manifested not only in the difference of dominant factors but also in the sensitivity of land-use changes to various factors. The reason for multi-scale differences in driving forces of rural land-use change on the Loess Plateau mainly lay in scale effect, cumulative effect, and the universality and suitability of policies. Finally, we proposed policy recommendations for land-use management in ecologically fragile

areas from the perspectives of multi-scale planning, location-specific strategies, ecological security, and risk prevention.

The findings of this study not only provide constructive references for sustainable development in the Loess Plateau but also offer theoretical support for establishing scientific connections and assistance mechanisms between China's urban and rural areas. Meanwhile, the research results have important implications and inspirations for other regions globally facing similar rural development and administrative situations. Additionally, this study had certain limitations: due to the constraints of data collection at the township scale, we only analyzed a limited number of driving factors. In future research, we plan to consider incorporating factors at the farmer-household level to improve our understanding of land-use change at different scales in rural areas.

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