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Land Use Changes on the Loess Plateau and Their Driving Factors

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Abstract: Land use change is a key research focus in the comprehensive management of a country's territory, as well as an important aspect of ecological protection. The Loess Plateau, as a priority region for ecological restoration, can benefit from understanding the nature and drivers of its land use changes. This study examines land use classification data from 2005 to 2020 to examine changes in land use types and their underlying causes, simultaneously incorporating population and annual precipitation data to assess correlations. The results indicate that: (1) The size of cultivated land and unused land continuously fell; forest and grassland areas first saw an increase and then witnessed a decrease, resulting in an overall decline; water areas experienced an initial trend of decrease followed by an increase but remained generally diminished; urban, industrial, and residential land continuously expanded. (2) Over the period of 2005 to 2020, the comprehensive land use dynamic index was 1.07%, suggesting relatively stable changes in land use types. (3)Urban, industrial, and residential land decreased initially and then increased; farmland and unused land showed negative dynamics; forest and grassland exhibited positive dynamics followed by negative; water areas showed negative dynamics followed by positive. (4) Population growth and annual precipitation are key factors driving notable changes in land use.

Keywords: Loess Plateau, Land Use Change, Driving Factors, GIS, Remote Sensing

1. Introduction

Recently, as population, resource, and environmental issues have intensified, global change research has become a highly regarded field internationally. Among these, Land Use/Land Cover Change (LUCC), as a critical component of global change research, has drawn significant attention [1]. In 1993, the joint “LUCC Scientific Research Program” developed by the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) identified LUCC as a core research focus in global change studies [2]. In recent years, China has taken a significant step forward with outstanding achievements in LUCC research. Progresses include in-depth investigations of national-level hotspots at the macro scale, as well as examinations of land use status, evolution processes, development trends, and driving mechanisms in various ecological zones and key economic development regions [3].

As one of China’s four major plateaus, the Loess Plateau is home to a population of approximately 120 million. However, due to its unique topography and ecological characteristics, its ecosystem is

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fragile and variable. Research on land use changes and their driving factors in the Loess Plateau can thus provide valuable insights for the region's management and ecological conservation [4].

Previous studies include work by Liu Yu and Fu Bojie, who applied simple linear regression to investigate shifts in vegetation coverage on the Loess Plateau, focusing on the spatiotemporal patterns of vegetation restoration and its relationship to land use change [5]. Wang Fei and colleagues, using GIS methods, calculated land use transition matrices and land use dynamic indices to evaluate changes in the Loess Plateau's land use from 1985 to 2005, thereby revealing the characteristics and driving forces behind different land use categories [6]. In another study, Meng Qingxiang and collaborators incorporated land use change data to compute ecological resilience, examining its effects on ecological benefits and proposing integrated management strategies for ecological restoration and land use [7]. Additionally, Zhao Hongfei and coauthors employed geostatistics and trend analyses to further investigate the environmental impacts of land use change, emphasizing its influence on ecosystem services [8].

The goal of this study is to conduct a systematic investigation of land use changes and their underlying causes in the Loess Plateau, thereby providing a scientific basis and recommendations for ecological management in this region, and laying a foundation for research that is going to be conducted in the near future.

2. Data Sources and Research Methods

2.1. Data Sources

This study utilizes data spanning 16 years (2005-2020), including land use classification data, precipitation, and population data. The land use classification data (1 km resolution) was obtained from the Earth Resource Data Cloud (last accessed on November 28, 2024), and the population data (100 m resolution) was sourced from WorldPop (last accessed on November 28, 2024)[9][10]. All datasets are remote sensing image data products.

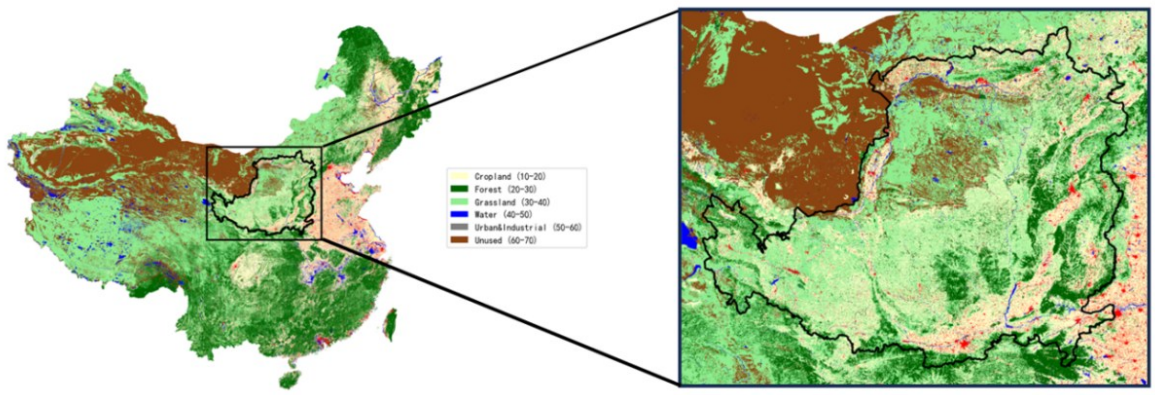


Figure 1: Study Area – Loess Plateau (Northern Latitude 33°43'–41°16' N, Eastern Longitude 100°54'–114°33' E, including parts of Shanxi, Shaanxi, Gansu, Ningxia, Qinghai, and Inner Mongolia)

2.2. Research Methods

2.2.1. Degree of Dynamic Land Use Change on the Loess Plateau

The dynamic degree of land use change indicates the magnitude or overall scale of transformation for a specific land use category over a defined time frame.It demonstrates the extent, rate, scale, and relative shifts in land use over a given period. This measure is divided into the single dynamic degree of land use and the comprehensive dynamic degree of land use.

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Single Land Use Dynamic Degree

The individual dynamic degree of land use refers to the change occurring in a specific land use category within the study region over a designated time period. It indicates both the speed and magnitude of alterations across different land use types during the specified time frame. The formula for its calculation is provided below[6]:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

Where$K$ is the dynamic degree of a particular land use type during the study period; U_a and U_b are the quantities of a particular land use type at the beginning and end of the study period, respectively.

Comprehensive Land Use Dynamic Degree

The comprehensive dynamic degree of land use signifies the overall pace at which all land use types within the study area undergo changes over a specified period. This metric serves as an indicator to distinguish regional variations in the rates of land use transformations and can illustrate the aggregated effects of socio-economic activities on land use alterations within the region. The formula for calculating it is presented below[6]:

$$S = \left(\sum_{n=1}^{m} \left(\frac{\Delta S_{i-j}}{S_i}\right)\right) \times \frac{1}{t} \times 100\% \quad (2)$$

Where S_i is the total area of the i-th land use type at the beginning of monitoring; ΔS_{i-j} is the total area converted from the i-th land use type to other land use types during the monitoring period. t is the time period; The land use dynamic degree S reflects the rate of land use change in the study sample area corresponding to the time period t.

2.2.2. Land Use Transition Matrix

The land use transition matrix depicts the changes among various land use categories. It not only outlines the distribution of land use types at the start and conclusion of the study period but also records the shifts each land use type undergoes during that timeframe. This matrix is utilized to examine the patterns of regional land use changes, as well as the origins and composition of each land use category by the end of the study period. The elements within the matrix represent the areas occupied by different land use types. Moreover, a land use change transition probability matrix can be formulated for the region, facilitating the prediction of land use change trends under specific scenarios. Its mathematical representation is provided below[6]:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \quad (3)$$

2.2.3. Methods for Analyzing the Correlation of Land Use Changes

The Pearson correlation coefficient is a measure used to assess the degree of linear association between two variables, X and Y. The magnitude of this coefficient indicates the strength of the correlation, where a higher absolute value signifies a more robust relationship between the variables. This is demonstrated through the resemblance of waveforms, as a stronger correlation results in more similar waveform patterns. The equation for computing the Pearson correlation coefficient is provided below[8]:

$$p_{X,Y} = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E(XY) - E(X)E(Y)}{\sqrt{E(X^2) - E^2(X)}\sqrt{E(Y^2) - E^2(Y)}} \quad (4)$$

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Where: p is the Pearson correlation coefficient;cov is the covariance between variables X and Y; σ_X and σ_Y are the standard deviations of Xand Y, respectively. E is the mean.

The Spearman correlation coefficient is a correlation measure that is more broadly applicable than the Pearson correlation coefficient. It does not require the variables to follow a normal distribution orprior knowledge of the data distribution. The calculation formula for the Spearman correlation coefficient is:

$$\rho_s = \frac{\sum_{i=1}^{N}(R_i-\bar{R})(S_i-\bar{S})}{[\sum_{i=1}^{N}(R_i-\bar{R})^2 \sum_{i=1}^{N}(S_i-\bar{S})^2]^{\frac{1}{2}}} \quad (5)$$

Where R_i and S_i are the rank values of the i-th observation, respectively; $\bar{R}$ and $\bar{S}$ are the average ranks of x and y, respectively; N is the total number of observations.

3. Characteristics of Land Use Change on the Loess Plateau

3.1. Spatiotemporal Characteristics of Land Use

3.1.1. Temporal Characteristics of Land Use

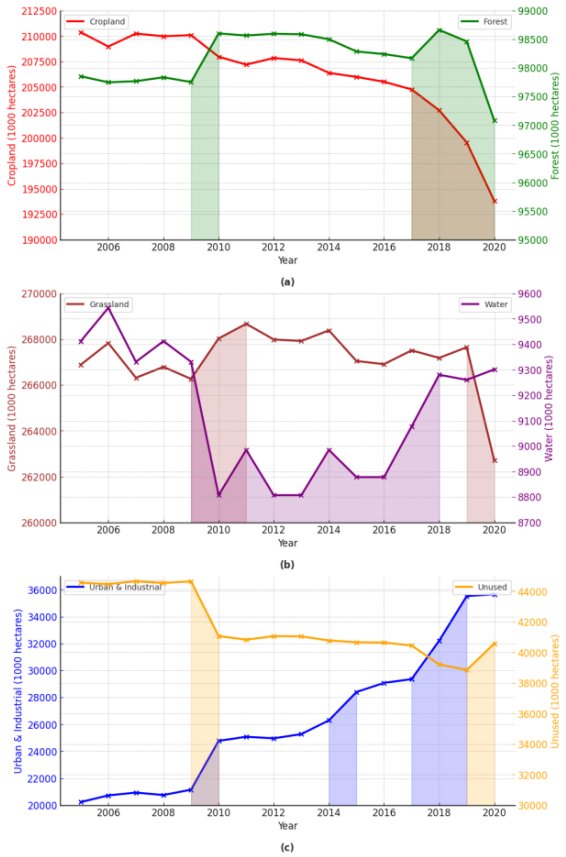


Figure 2: a-c: Annual area of each land use type (2005-2020)

Overall, various land use types exhibited certain fluctuations during most of the study period.

Firstly, it can be seen from the line charts that the area of cropland showed a general declining trend (Figure 2a). From 2005 to 2017, the area of Arable land slightly decreased but exhibited a fluctuating trend overall. However, the area of cultivated land has significantly declined since

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2017,potentially attributed to changes in land use or the degradation of arable land [11]. The overall trend for unused land also declined, albeit at a relatively smaller scale (Figure 2c).

The area of forest land also fluctuated throughout the entire period (Figure 2a). A notable increase occurred between 2009 and 2010, which may be linked to the implementation of the "Returning Farmland to Forest" policy [12]. From 2017 to 2020, the area of forest land first increased and then decreased, with a substantial decline in 2019. Grassland followed a comparable pattern, with a significant expansion from 2009 to 2011 but sharply decreased from 2019 to 2020, while exhibiting fluctuations during the remaining periods (Figure 2b).

The area of water bodies sharply declined between 2009 and 2010, exhibited a fluctuating trend from 2011 to 2016, and then significantly increased from 2016 to 2018 (Figure 2b).

The areas of urban, industrial, and residential land showed an overall significant upward trend, particularly during the periods of 2009–2010, 2014–2015, and 2017–2019. These periods of substantial increase reflect the overall trend of urbanization development (Figure 2c).

3.1.2. Spatial Characteristics of Land Use Change

Analyzing the spatial characteristics of land use change on the Loess Plateau over a 16-year period is relatively complex, as annual data do not reveal obvious changes. Therefore, this study conducts a comparative analysis using land use data from 2005, 2010, 2015, and 2020(as shown in Figure 3). The results reveal that cultivated land is primarily distributed near water bodies, especially concentrated in the boundary areas of the Loess Plateau. Forest Land, Grassland, and Unused Land are interspersedly distributed throughout the region, covering most parts of the Loess Plateau. Urban, Industrial, and Residential Land exhibit a spatial distribution similar to that of cultivated land, spreading along the main river basins of the Loess Plateau and accompanied by surrounding cultivated land. From 2005 to 2020, urban, industrial, and residential land gradually expanded outward from the central areas in 2005. The expansion rate was relatively rapid, and the distribution pattern became increasingly distinct. The overall distribution aligns with the findings presented by Zhou Shugui et al. [4]. However, Zhou et al.'s study lacked a detailed analysis of the spatial distribution.

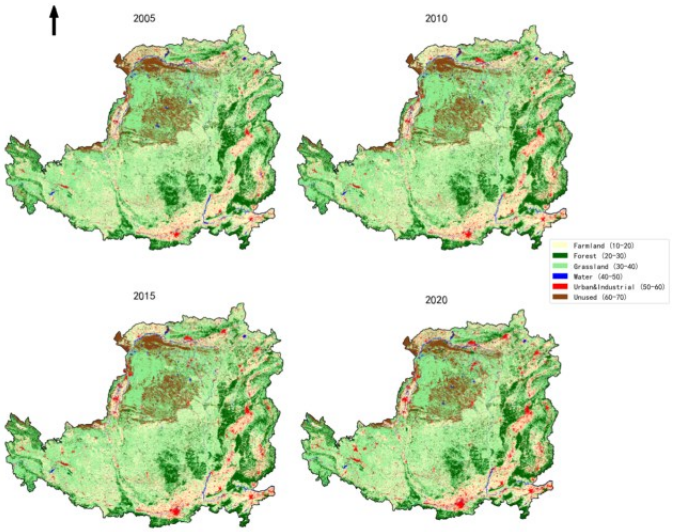


Figure 3: Land Use Classification Maps in 2005, 2010, 2015, and 2020

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3.2. Analysis of Land Use Dynamics

3.2.1. Single Land Use Dynamic Degree

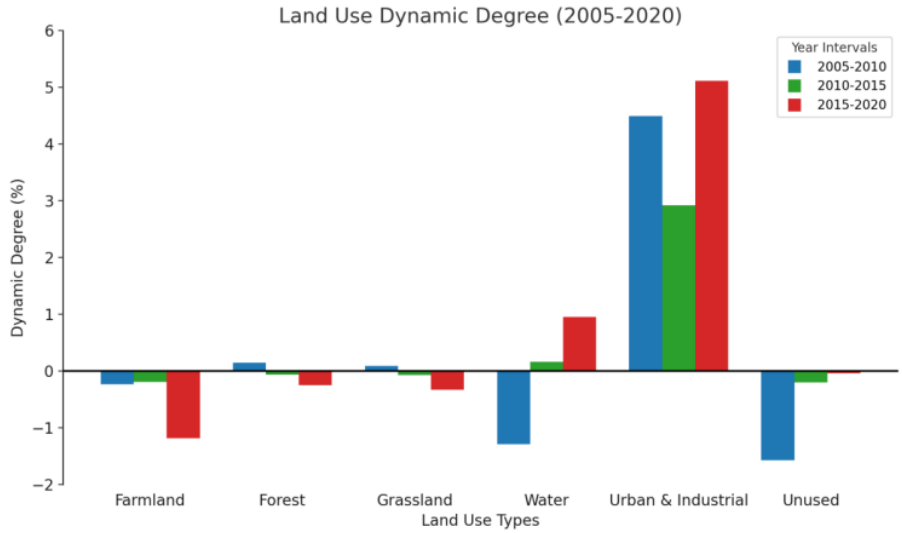


Figure 4: Single Land Use Dynamic Degree

The formulas above calculated the single land use dynamic degree for different land use types during three intervals: 2005–2010, 2010–2015, and 2015–2020, and plotted the results as a histogram(as shown in Figure 4). The findings are as follows:

Urban, industrial, and residential land consistently exhibited positive and relatively high dynamic degrees, indicating a continuous increase in these areas.

Cultivated land showed a continuous decline, with a sharp decrease between 2015 and 2020.

Forest and grassland followed a similar pattern of change: initially positive dynamic degrees followed by negative values, though the magnitudes were not large.

Unused land, like cultivated land, continuously declined, with its largest reduction occurring from 2005 to 2010.

3.2.2. Comprehensive Land Use Dynamic Degree

The comprehensive land use dynamic degree for the Loess Plateau from 2005 to 2020 was calculated to be 1.07%, indicating moderate overall land use changes over this period.Specifically, the comprehensive land use dynamic degrees for 2005–2010, 2010–2015, and 2015–2020 were 1.3%, 0.6%, and 1.31%, respectively. The results show that the overall rate and intensity of land use change during 2005–2010 and 2015–2020 were essentially the same. In contrast, the period 2010–2015 had only about half the dynamic degree of the other two periods, suggesting a more moderate level of change during that time frame.

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3.3. Analysis of the Land Use Transition Matrix

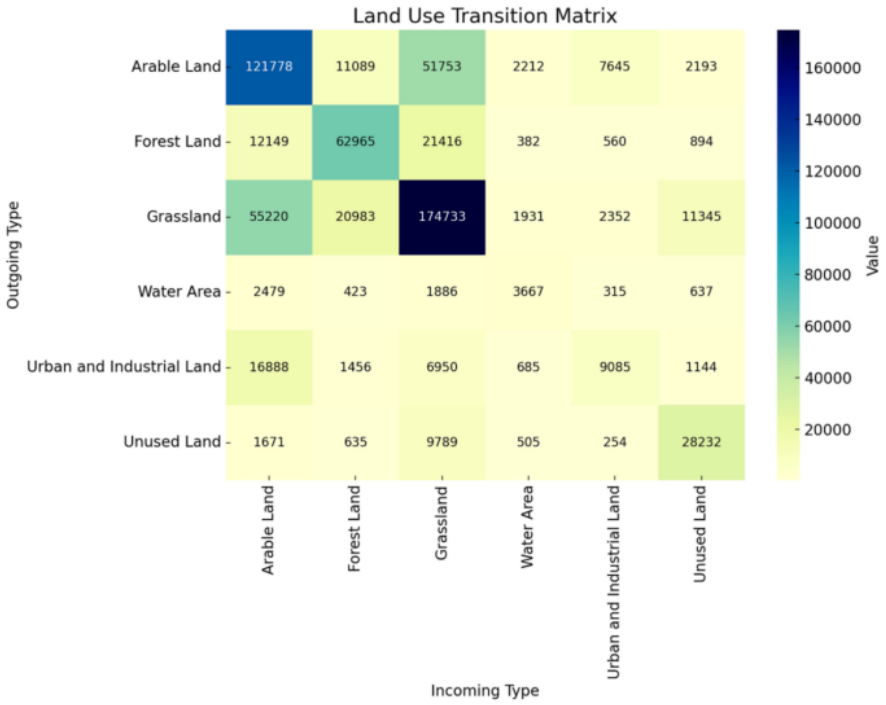


Figure 5: Land Use Transition Matrix

By calculating the land use transition matrix for 2005–2020(as shown in Figure 5), it can be observed that the largest transitions occurred among cultivated land, forest land, and grassland, followed by urban/industrial/residential land, with the smallest transitions involving unused land.

From 2005 to 2020, totally, 88,407 km^2 of cultivated land were converted into other land use types. Of the converted cultivated land, 62.46% became grassland, 13.74% became forest land, and 19.10% became urban, industrial, and residential land. Only 2.80% of Arable land turned into water bodies, and 1.89% became unused land. Meanwhile, 66,204 km^2 from other land use types were converted back into cropland, sparking off a net decrease in the total cultivated land area.

Forest land experienced a moderate level of conversion at 34,586 km^2. Grassland showed a relatively large amount of conversion at 91,794 km^2, which was 1.04 times that of cultivated land.

Urban&industrial land, along with unused land, underwent relatively small conversion outflows—11,123 and 16,213 km^2, respectively. However, 27,123 km^2 from other land use types were transformed into urban&industrial land, leading to an overall increase in these areas. This reflects the acceleration of urbanization and the effectiveness of land management in the Loess Plateau.

4. Analysis of the Causes of Land Use Change on the Loess Plateau

Land use changes in any region result from the joint effects of various elements, including natural conditions, human activities, economic influences, and policy-related drivers. In order to know the driving forces behind land use change, the researchers can examine the correlation between these changes and the aforementioned factors. Traditional research methods include calculating correlation coefficients and conducting multiple linear regression. This study utilizes annual data from 2005 to 2020 to calculate the Pearson and Spearman correlation coefficients between normalized population data and the normalized area data of various land use types, thereby investigating the reasons for the observed changes(as shown in Figure 6).

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Since urban and industrial land use exhibited a large dynamic degree, and land use transitions during 2005–2020 primarily involved cultivated land, these two land use types were the focus of the analysis to attribute the observed changes.

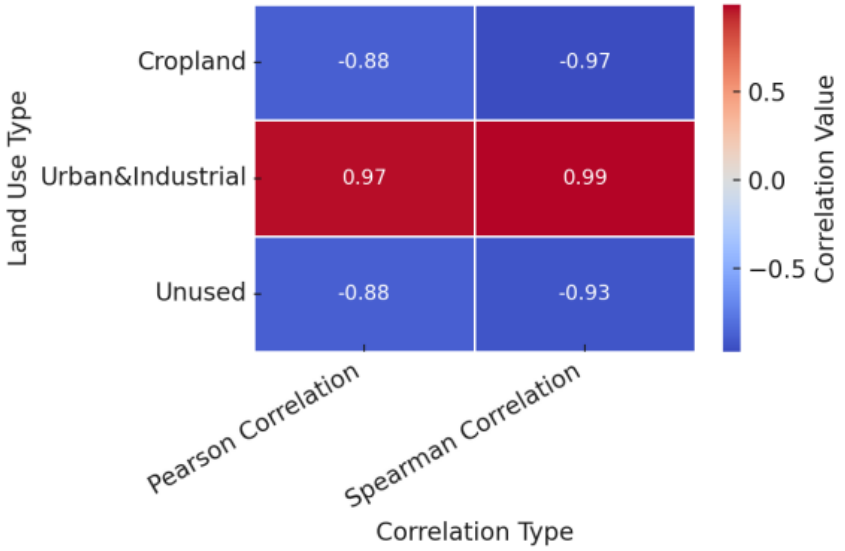


Figure 6: Correlation Coefficients

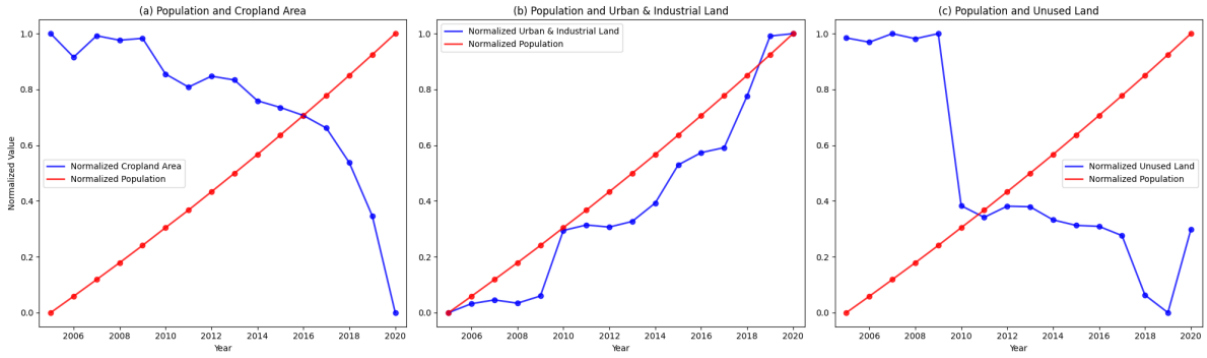


Figure 7: Combined Line Chart of Normalized Population Data and Normalized Land Use Areas

From a purely trend-based perspective, as the normalized population data increased, the proportion of cultivated land generally decreased. Urban land use increased continuously, showing a significant and positively monotonic upward trend. In contrast, unused land started from a high value, experienced a substantial decline midway, and then slightly recovered, though it did not return to its initial level(as shown in Figure 7).

From the correlation perspective, population and urban land use exhibited a strong coupled with positive correlation, which can be reflected by the correlation coefficients of 0.97 (Pearson) and 0.99 (Spearman). As population grows, the proportion of urban land use also rises. Simultaneously, population and cultivated/unused land both exhibited a strong negative correlation with population growth. The correlation coefficients were -0.88/-0.97 for cultivated land and -0.88/-0.93 for unused land (Pearson/Spearman), indicating that as the population increases, the proportions of cultivated land and unused land consistently decrease.

(1) Urban&Industrial Land vs. Population Changes: A strong positive correlation was observed. An increase in population density significantly expands the area of urban&industrial land. Zhou et al. investigated the driving factors of land use change on the Loess Plateau from the late 1980s to 2008,

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obtaining similar results. However, Zhou et al. did not directly examine the correlation between construction land and population density, but rather inferred it indirectly through forest, grassland studies, and transition matrices [4].

(2) Cultivated Land Area vs. Population: A strong negative correlation exists between population and cultivated land area. As population increases, cultivated land area significantly decreases. In recent years, the Loess Plateau's rapid economic development and population growth have driven a substantial increase in land of construction and, to some extent, vegetation degradation, thereby reducing cultivated land area [8].

(3) Unused Land Area vs. Population: Population growth inevitably leads to a substantial increase in construction land and a drastic reduction in unused land.

5. Conclusion

The main findings are as follows:.

- Trends in Land Use Changes: Using 16 periods of land use data from 2005 to 2020, the areas of cultivated land, grassland, and unused land generally showed a decline. Water bodies initially decreased but later increased, remaining stable overall. Forest land increased before decreasing, displaying fluctuating trends. The areas of urban, industrial, and residential land saw significant growth, indicating a steady rise in urbanization.
- Dynamic Degrees of Land Use: The land use dynamic degree changed to some extent. Comprehensive land use dynamic degree data showed that the comprehensive land use dynamic degree of the region was 1.07% between 2005 and 2020, indicating relatively moderate land use changes. From the perspective of single land use dynamic degrees, the dynamic degrees of urban, industrial, and residential land initially decreased and then increased, remaining positive throughout; the dynamic degrees of cultivated land and unused land were both negative; the dynamic degrees of forest land and grassland were initially positive and then negative; the dynamic degree of water bodies showed a trend of first being negative and then positive.
- Correlations with Population: By calculating the Pearson and Spearman correlation coefficients, the correlations between population and various land use types were analyzed. The results showed that cultivated land, urban/industrial/residential land, and unused land had strong correlations with population size.

This study acknowledges limitations in its analysis, as it primarily relied on population and precipitation data. Changes in land use types are influenced by multiple factors, including natural factors, human activities, economic factors, and policy factors.

- Natural Factors: Future studies could incorporate additional data such as ground temperature to provide a more comprehensive analysis.
- Human Activities: Further exploration of the impacts of afforestation and the "Returning Farmland to Forest" policy would enhance understanding.
- Economic Factors: Integrating regional GDP data could offer insights into the economic drivers of land use changes.
- Policy Factors: Analyzing national governance policies and investment levels specific to the Loess Plateau would provide a clearer picture of policy influences.

However, due to significant limitations in obtaining relevant data for the Loess Plateau region, especially detailed annual data in recent years, this research has certain constraints. Future researchers should attempt to collect and integrate the aforementioned data to produce data products that meet accuracy requirements, facilitating more in-depth studies.

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