Evolution Characteristics and Simulation Prediction of Forest and Grass Landscape Fragmentation Based on the "Grain for Green" Projects on the Loess Plateau, P.R. China

Li Gu
Northwest Agriculture and Forestry University
Zhiwen Gong (gongzhiwen@nwafu.edu.cn)
Northwest A&F University
Yuankun Bu
Northwest A&F University

Research

Keywords: Land use change, Landscape fragmentation, FLUS model, "Grain for Green" Project

Posted Date: January 6th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-138854/v1

Evolution Characteristics and Simulation Prediction of Forest and Grass Landscape Fragmentation Based on the "Grain for Green" Projects on the Loess Plateau, P.R. China

Li Gu[a], Zhiwen Gong[b*] , Yuankun Bu[a]

a College of Forestry, Northwest A&F University, No.3 Taicheng Road, Yangling 712100, China

b College of Economics and Management, Research Center of Resource Economics and Environment Management, Northwest A&F University, No.3 Taicheng Road, Yangling 712100, China

*Correspondence: e-mail: gongzhiwen@nwafu.edu.cn; Tel.: +86-18710920696

Abstract: Forest fragmentation is one of the major environmental issues that the international community is generally concerned about under the background of global climate change. Studying the impact and the interaction mechanism of land use change processes on landscape fragmentation is important to gaining a comprehensive understanding of the ecosystem response to human activities and global climate change. Based on the implementation background for the "Grain for Green" Project, we selected the Loess Plateau as the research area and used the coupled future land use simulation (FLUS) model and landscape fragmentation model to explore the temporal and spatial changes in forest and grass landscape fragmentation. The results showed that (1) Woodland, grassland, and cropland are the main landscape types, accounting for about 90% of the total area. In addition, the area of cropland initially increased and then decreased, while the area of woodland and grassland exhibited the opposite trend Oover the last 35 years. In particular, the period from 2000 to 2015 was a forest and grass restoration stage, and the average annual rate of forest and grass restoration reached 0.56%. (2) The FLUS model was used to predict the land use on the Loess Plateau in 2030. The kappa coefficient was 0.85, and the figure of merit coefficient (FOM) was 0.11 for a 1% random sampling, which are within a reasonable range, and the simulation results are also consistent with the objective change in the current social and economic development. (3) The fragmentation of woodland and grassland were dominated by edge type and core type. The core type had a concentrated distribution and an absolute advantage, accounting for more than 75% of the total area. It is predicted that the landscape fragmentation will gradually slowdown in 2030 under different intensities of the "Grain for Green" project. The dynamics of landscape fragmentation based on land use changes are conducive to the reasonable

planning and objective evaluation of woodland and grassland spatial allocation and quality improvement, and provide an important basis for the formulation of ecological protection and land management policies.

Key Words: Land use change, Landscape fragmentation, FLUS model, “Grain for Green” Project.

1. Introduction

Forests play a vital role in the service functions of global ecosystems by providing a series of service functions such as maintaining the biodiversity, soil and water conservation, global carbon and water cycles, and climate regulation (Pan et al., 2011; Fang et al., 2014). According to the estimates of the Food and Agriculture Organization of the United Nations (FAO), the forest area in the word is about 4.0×107 km2; and as the main body of the terrestrial ecosystem, it accounts for 31% of the total land area (Bonan, 2008; Keenan et al., 2015). However, with the rapid development of agriculture and cities, about 40% of the woodland has been converted to land cover types such as cropland, pastures, and other artificial building lands around the world (Achard and Hansen, 2012), and the problem of forest loss and fragmentation is increasing (Riitters et al., 2000). Forest fragmentation refers to the process in which a large continuous forest is divided into smaller, independent patches of forest (Riitters et al., 2002). At present, 70% of the forests on the five continents with forests are mainly distributed within 1 km of the edges of the woodland (Nick et al., 2015). At present, an increasing number of studies have focused on the issue of forest fragmentation. Numerous studies have shown that forest fragmentation will lead to various negative effects, such as a decrease in the regional biodiversity, increased soil erosion, increased risk of invasion by invasive species, decreased material flow in the forest ecosystem, and energy flow reduction (Cushman et al., 2012; Long et al., 2010; Riitters et al., 2000). Especially in developing countries, forest fragmentation has led to huge losses in economic, environmental, and cultural benefits (Zuidema et al., 1996). In particular, in China, the growth of forest area has attracted worldwide attention, but the problem of forest fragmentation has become increasingly prominent, which has led to low forest quality and weakened ecological service capabilities (Wu et al., 2018). These factors have made it difficult to adapt to the growing demand for ecological products in society, which is becoming one of the bottlenecks in the construction of an ecologically friendly civilization.

Studying the characteristics of forest fragmentation would help us understand the relationship between the landscape pattern and ecological processes and thus to determine the driving force of internal landscape fragmentation (Reddy et al., 2018; Wang et al., 2014). With the development of remote sensing (RS) technology, large-scale data acquisition and dynamic monitoring capabilities can provide reliable, high-precision data (Zhao et al., 2020). The powerful spatial information processing and analysis capabilities of the geographic information system (GIS) can be used to accurately evaluate and analyze forest resources (Franklin, 2001), and the combination of GIS and RS can be used to analyze forest fragmentation and to reveal the dynamic spatial evolution (Carranza et al., 2015). Currently, traditional forest fragmentation studies have mostly used landscape pattern indexes to describe the composition and structural characteristics of landscape types. For example, using the patch size, the total patch area, the patch size variation coefficient, the shape index, the fractal dimension, and other indicators to dynamically analyze the forest landscape pattern and to reveal the important impact of human activities (D'eon and Glenn, 2015; Abdullah and Nakagoshi, 2007; Uuemaa et al., 2009). However, its main disadvantage is that the results lack a clear spatial location meaning, and therefore, they are not sufficiently practical. Clarifying the spatial process of forest fragmentation and quantitatively describing the method of forest fragmentation will help to reveal the evolution mechanism of the different forest types in the different ecological environments (Sharma et al., 2017). Based on this, a new method of landscape fragmentation process modeling based on the Forman theory was applied to the research of forest fragmentation at the national, regional, provincial, and county levels (Carranza et al., 2015). Compared with the traditional landscape index method, the landscape fragmentation model can produce a fragmentation map with a clear spatial significance, and it can reveal the type, area, and spatial distribution characteristics of the forest fragmentation in more detail (Sharma et al., 2017).

The Loess Plateau is one of the areas in the world with serious soil erosion and forest fragmentation (Feng et al., 2016). The coexistence of drought, water shortages, and soil erosion is a bottleneck restricting agricultural production and ecological construction (Gong et al., 2019), and extensive deforestation to expand grain planting has caused an increase in the area experiencing soil erosion to about 45.5 million ha (Zheng et al., 2005). Owing to the influence of temperature, precipitation, and altitude, the vegetation shows obvious horizontal and vertical zonal distribution differences (Gu et al., 2019). Grassland is the largest landscape type, which is widely distributed throughout the Loess Plateau and plays a vital role in the ecosystem service functions (Zhang et al., 2016). To reduce the deterioration of the ecological environment, a series of ecological protection projects have been implemented in China since 1999 (Zhang et al., 2016; Wu et al., 2014), such as The “Grain for Green” Project. The Loess Plateau took the lead as a pilot area for this project, and measures such as afforestation and the conversion of sloping cropland to forest and grassland have effectively increased the vegetation coverage (Chang et al., 2011). The total afforestation area on the Loess

Plateau has reached 18.906 million ha (Jiang et al., 2018), and a large amount of sloping farmland has been converted into grassland and woodland (Deng et al., 2014). Returning cropland or barren slope cropland to woodland (grassland) has been discontinued for more than 20 years (Wang et al., 2020). Land type has undergone unprecedented large scale, transformative changes, and the ecological restoration effect has been significant (Niu et al., 2019). In particular, the grassland accounts for about 40% of the total land area on the Loess Plateau (Gang et al., 2018).Grassland and woodland have contributed the most to ecosystem services on the Loess Plateau (Xu and Ding, 2018). At present, the dynamic changes in the vegetation and the ecological effects brought about by these ecological restoration projects on the Loess Plateau have attracted a great deal of attention (Kang et al., 2019; Yuan et al., 2014; Guo and Gong, 2016). However, studies have found that many ecological restoration projects simply pursue forest area growth through tree planting, or they restore the forest ecosystem to its natural state before it is disturbed (Wang et al., 2007; Chen et al., 2008), but they have not addressed the relationship between the ecosystem and the surrounding environment to achieve true rehabilitation and reconstruction (Hobbs et al., 2014). F0r wxample, the “Grain for Green” Project on the Loess Plateau has achieved initial results, but understanding the spatial distribution and landscape fragmentation is very urgent, and it needs to be improved as the ecosystem is facing huge changes (Yu et al., 2018). In particular, several studies have shown that the land use change caused by the implementation of this project has made the ecosystem more fragmented (Zhang and Yin, 2019), but there is no precedent for the combined study of the landscape fragmentation of forest and grassland ecosystems. In particular, regarding the evolution parameters of forest fragmentation, there is still a lack of clear spatial significance and a quantitative description at the regional scale. This is important for establishing regional ecological corridors, improving biodiversity, controlling soil erosion, and enhancing the continuity of the landscape.

In this study, we selected the Loess Plateau as the research area, and comprehensively analyzed the land use changes from 1980 to 2015. The future land use simulation (FLUS) model was used to simulate and predict the future spatial layout of the land use based on the land change influence of factors such as economics to reveal the evolution of the spatial and temporal pattern of land use on the Loess Plateau over the next 15 years. We also established a forest fragmentation model with a clear spatial meaning and quantified and analyzed the spatial distribution characteristics and the temporal evolution of the forest and grass landscape fragmentation on the Loess Plateau. The results of this study provide a reference for the spatial layout of the “Grain for Green” Project in the future and for the development of more targeted strategies for forestry production and forest spatial allocation, thereby improving the implementation efficiency of the “Grain for Green” Project.

2. Materials and Methods

2.1 Study Area

The Loess Plateau is located in the middle and upper reaches of the Yellow River in China (33°43'-41°16'N, 100°54'-114°33'E), including the western part of the Taihang Mountains, the eastern part of Wushaoling, the northern part of Qinling, and the southern part of the Great Wall, covering 7 provinces and autonomous regions, namely, Qinghai Province, Gansu Province, the Ningxia Hui Autonomous Region, the Inner Mongolia Autonomous Region, Shaanxi Province, Shanxi Province, and Henan Province (Gang et al., 2018). The total area is about 64 × 104 km2, accounting for 6.7% of China's land area (Figure 1). The average altitude is 1,000 to 1,500 m, and the annual precipitation is 150 to 750 mm (NDRC et al., 2010). The rainfall is generally low and unevenly distributed, and the annual average temperature is 3.6–14.3°C (Wang et al., 2020). The topography is complex, the soil nutrient content is low, and the terrain is high in the northwest and low in the southeast. Owing to long-term erosion by running water, thousands of gullies have been formed. Owing to over-exploitation of fragile ecosystems for thousands of years, the serious soil erosion, and the fragile ecological environment, the Loess Plateau has become one of the most severely eroded areas in the world.

The Loess Plateau is located in a transition zone between a semi-humid climate and a semi-arid and arid climate. Most of the areas are semi-arid, and the bioclimatic environment changes significantly from southeast to northwest. Except for the desert grasslands north of the Great Wall, most of the Loess Plateau is forest, forest grassland, and grassland (Chang et al., 2011). The vegetation on the Loess Plateau is dominated by forests, forest grasslands, and grasslands. Among them, the forests are mainly distributed to the south of the Pianguan-Lishi-Yan'an-Ningxian-Heshui-Gangu-Tianshui line, where the forest growth conditions are better, and to north of this line (i.e., the northwestern part of the plateau) are a variety of grassland areas, and the natural vegetation is mostly warm-temperature mesophytic shrubs and mesophytic meadows with grass and shrubs, except for the existence of forests in places with good local moisture conditions.

2.2 Data Source and Processing

The land use data for the Loess Plateau used in this study were obtained from the Geospatial Data Cloud of the Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn), including the three periods of 1980, 2000, and 2015, and the spatial resolution of the data is 30 m × 30 m. The land use classification was conducted using the classification system of the Chinese Academy of Sciences, and the land use types were divided into six categories: cropland, woodland, grassland, water bodies, built-up land, and unused land (Figure 1). After preprocessing the data using the ENVI 5.1 platform, including atmospheric corrections, geometric corrections, stitching, and cropping, the method of supervised classification combined with human-computer interaction visual interpretation was adopted, and Google Earth historical images were combined to perform error correction of the manually selected region of interest (ROI) after field verification. The total land use classification accuracies for 1980, 2000, and 2015 are 88.75%, 89.27%, and 89.01%, respectively, and the kappa indexes are 0.85, 0.87, and 0.86, respectively, after error correction, which meets the application accuracy requirements.

The basic geographic information data for the Loess Plateau, including administrative boundaries, roads, railways, rivers, and rural residential areas, were obtained from the 1:1 million national basic geographic database published by the National Basic Geographic Information Center (http://www.webmap.cn). The data for the digital elevation model (DEM) were downloaded from the ASTER-GDEM 30 m resolution digital elevation data provided by the geospatial data cloud. The slope and aspect data were calculated based on the DEM data using the ArcGIS software. The spatial resolution of all of the data used in this study is 30 m, and the spatial coordinate system used was Krasovsky_1940_Albers. The meteorological data were obtained from the China Meteorological Data Network (http://data.cma.cn/).

2.3 Analytical Methods

2.3.1 LULC change matrix

The land use transfer matrix reflects the conversion directions and the conversion areas of the various land use types within the research period (Hua, 2017). Its mathematical form is

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix},$$

where S_{ij} is the area; n is the number of land use types; and i and j are the land use types at the beginning and end of the study period, respectively.

The annual rate of forest cover change was calculated by comparing the area under forest cover in the same region at two different times. The annual rate of change was determined using the compound interest formula (Puyravaud et al., 2003).

$$r = \frac{1}{t_2 - t_1} \times ln\frac{a_2}{a_1} ,$$

where r is the annual rate of change (percentage per year); and a_1 and a_2 are the forest cover estimates at times t_1 and t_2, respectively.

2.3.2 FLUS Models

The FLUS model was established based on the system dynamics model (SDM) and the cellular automata model (CAM) by integrating the artificial neural networks (ANNs) algorithm and the roulette wheel selection (RWS) mechanism (Chen et al., 2014), which were used to deal with the uncertainty and the relative complexity of the changes in multiple types of land use under the synergy of nature, society, and economy, to create a high-precision land-use change simulation (Yang et al., 2020). Based on the analysis of the existing research on the driving factors of land use change (Gong et al., 2018; Lambin et al., 2003; Xie et al., 2017; Verburg and Overmars, 2007), we finally selected the 12 driving factors related to the natural, social, and economic aspects (Figure 1).

Moreover, simulation scenarios have largely been applied in the formulation and assessment of land use planning and land use policy (Cairns et al., 2016; Jenerette and Wu, 2001). In this study, based on the comprehensive consideration of the regional resource endowments and the effect and intensity of the project implementation, five simulation scenarios of returning cropland to forest and grassland were set up by adjusting the probability of the transition from cropland to woodland or grassland. These scenarios are Scenario A: keep the probability of the transition from cropland to woodland or grassland in the land use transfer matrix. Scenario B: increase the probability of the transition from cropland to woodland or grassland by 10% and 10%, respectively. Scenario C: increase the probability of the transition from cropland to woodland or grassland by 20% and 20%, respectively. scenario D: increase the probability of the transition from cropland to woodland or grassland by 30% and 30%, respectively. Scenario E: increase the probability of the transition from cropland to woodland or grassland by 40% and 40%, respectively.

The ANNs was based on the cellular automata model, which is composed of an input layer, a hidden layer, and an output layer, and each neuron corresponds to a variable in the CA (Openshaw, 1998). The essence of the simulation process is to establish the spatial relationships between the driving factors and the initial land types (Liu et al., 2008). The specific process is described by follows:

$$sp(p,k,t) = \sum_j w_{j,k} \times sigmoid\{net_j(p,t)\} = \frac{\sum_j w_{j,k}}{1 + \ e^{-net_j}(p,t)}$$

where $sp(p,k,t)$ is the suitability probability of the land type k at pixel p and time t; $w_{j,k}$ is the weight between the hidden layer and the output layer, which is adjusted during the training; $net_j(p,t)$ is the signal received by the jth hidden layer at pixel p and training time t; and the $sigmoid$ activation function is from the hidden layer to the output layer. For the suitability probability $sigmoid()$ output by the ANNs, the sum is always 1 at iteration time t and pixel p, that is,

$$\sum_k sp(p,k,t) = 1$$

The adaptive inertial competitive cellular automata based on the roulette selection is the key module of the FLUS model, which combines the neighborhood weights, conversion rules, and suitability probability distribution of each land type to achieve the rationalized configuration of the spatial distribution of the total number of pixels of each land type in the future, and finally, it simulates the land use change (Li et al., 2017). This process is essentially a loop iteration process, and it makes the output result continuously approach the target value (Liu et al., 2017). In this study, we chose to run the iterative loop in a 9×9 Moore neighborhood,

$$TP_{p,k}^t = P_{p,k} \times \Omega_{p,k}^t \times Inertia_k^t \times (1 - sc_{c\to k})$$

$$\Omega_{p,k}^t = \frac{\sum_{N\times N} con(c_p^{t-1} = k)}{N \times N - 1} \times w_k$$

$$Inertia_k^t = \begin{cases} Inertia_k^{t-1} & if \ \left|D_k^{t-1}\right| \le \left|D_k^{t-2}\right| \\ Inertia_k^{t-1} \times \dfrac{\left|D_k^{t-2}\right|}{\left|D_k^{t-1}\right|} & if \ \left|D_k^{t-1}\right| < \left|D_k^{t-2}\right| < 0 \\ Inertia_k^{t-1} \times \dfrac{\left|D_k^{t-2}\right|}{\left|D_k^{t-1}\right|} & if \ 0 < \left|D_k^{t-2}\right| < \left|D_k^{t-1}\right| \end{cases}$$

Where $TP_{p,k}^t$ is the comprehensive probability that the grid p changes from the initial land use type to the land use type k at time t; $\Omega_{p,k}^t$ is the probability of land use type k appearing in grid p; $Inertia_k^t$ is the inertia coefficient of ground type k at time t; $sc_{c\to k}$ is the conversion cost from land use type c to land use type k; $\sum_{N\times N} con(c_p^{t-1}=k)$ is the total number of grids occupied by land type k under the N×N Moore window at time t-1; w_k is the variable weight between the different land use types; N is the molar neighborhood value in the CA; and D_k^{t-1} is the difference between the macroscopic demand and the allocated amount of land use type k at time t-1.

The FLUS model simulation accuracy uses the kappa coefficient and the figure of merit coefficient (FOM). The kappa coefficient is between 0 and 1. Generally, when kappa>0.5, the model's simulation accuracy is poor; when 0.5<kappa≤0.75, the model's simulation accuracy is general; and when 0.75<kappa≤1, the model's simulation accuracy is high (Liu et al., 2017). Theoretically, for the FOM coefficient, the larger the parameter value, the better the simulation effect and the higher the accuracy. However, practical verification shows that the results are mostly within 0.3, and are most commonly 0.1 to 0.2 (Pontius and Millones, 2011).

2.3.3 Forest Fragmentation Analysis

Forest fragmentation model can detect landscape changes and can clarify the corresponding spatial process. It is constructed using the quantitative characteristics of the boundaries between adjacent forest pixels and a moving window algorithm (odd numbers, such as 3×3 and 9×9) (Parent, 2009). In this study, a forest fragmentation model was established to evaluate the forest and grass fragmentation on the Loess Plateau using the ArcGIS Landscape Fragmentation tool (LFT v2.0) (Vogt et al., 2007), and the land use types were reclassified as forest and non-forest using the ArcGIS spatial analysis tool (Parent, 2009). In this study, the forest class contained woodland and grassland, and non-forest class contained cropland, built-up land, water, and unused land. The forest fragmentation was divided into six categories: patch, edge, perforated, and core (small, medium, and large) using a specified edge width of 100 m (Lang and Tiede, 2003), which was identified by referencing observations made during field visits.

3. Results

3.1 Temporal and Spatial Changes in the Landscape Pattern

Woodland, grassland, and cropland are the three main landscape types on the Loess Plateau, and their areas account for about 90% of the total area (Tables 2_3). Among them, the area of grassland is the largest, accounting for more than 40%. Cropland and woodland are next, and the other types account for only about

10% of the total area, which is a small proportion and is scattered. The grassland and cropland are widely distributed throughout the Loess Plateau, while the woodland is mostly distributed in the southeast, and the unused land is concentrated in the northwest (Figure 1).

Land use type conversions have resulted in major changes. The changes in cropland and woodland are the most obvious. From 1980 to 2000, the area of cropland increased, and the new cropland was mainly converted from grasslands. From 2000 to 2015, the area of cropland decreased (-0.31%), and a large amount of sloping cropland was converted into grassland and woodland. Specifically, the conversion of cropland into woodland was mainly concentrated in Shaanxi Province, followed by northern Shanxi Province. The conversion of cropland to grassland was mainly concentrated at the junction of Shanxi, Shaanxi, and Inner Mongolia, and in the northeastern part of Gansu Province.

In contrast, the woodland and grassland area initially decreased and then increased. The woodland and grassland area decreased during 1980-2000, and the average annual rate of change of the woodland and grassland was -0.03%. From 2000 to 2015, the woodland and grassland area decreased, and the main source of increase was due to conversion from cropland, which was mainly due to increased forest protection and the vigorous implementation of policies, such as returning cropland to woodland and grassland. However, due to less conversion of woodland and more conversion of grassland, the total woodland area increased and the grassland area decreased. The conversion rate of the woodland area was 0.33%, and that of grassland was -0.06%.

Moreover, the expansion of built-up land was the most obvious, which was another notable feature of landscape changes on the Loess Plateau. The increase in built-up land was mainly due to the conversion of cropland. The average annual rate of change of built-up land reached 0.49% from 1980 to 2000, and then, it decreased to 3.15% after 2000. With the expansion of built-up land, the reduction in unused land area was relatively large. The average annual rate of change was up to -0.56% from 2000 to 2015.

3.2 Restoration and Loss of Woodland and Grassland

The area of woodland and grassland decreased from 365,486.72 km^2 to 363,448.47 km^2 from 1980 to 2000, and the loss of woodland and grassland was relatively serious with an annual rate of change reaching -0.10% (Table 4). The implementation of the “Grain for Green” Project greatly affected the land use structure. In contrast, the land use change was dominated by the conversion of cropland into woodland and grassland from 2000 to 2015, which was a stage of forest and grass restoration. The area of woodland and grassland increased by 3,543.60 km^2, with an average annual rate of forest and grass restoration reaching 0.56%. The cropland used for the ecological conversion was mainly cultivated slope land and dry land in hilly areas with slopes of greater than 25°, and it was mainly distributed in semi-arid areas, followed by semi-humid areas, with a small amount distributed in arid areas.

3.3 Accuracy Test and Prediction Simulation for the FLUS Model

The total numbers of pixels of each land use type in 2015 and 2030 were predicted using the Markov matrix based on the data for 2000 and 2015 (Table 5). The simulated values for 2015 were used to test the prediction accuracy of the Markov chain, and the simulated values for 2030 were used as the total pixel numbers in the future for the FLUS model. By comparing the simulation results with the actual land use status in 2015, it was found that the kappa coefficient was 0.85 for a 1% random sampling, and the FOM coefficient was 0.12, so each test was within a reasonable range and the simulation results are in line with the objective changes in the current social and economic development.

Under the five different implementation scenarios for the "Grain for Green" projects, the land use structure predicted by the FLUS model continued to change in 2030, but it would still be focused on cropland, woodland, and grassland. Around residential areas, built-up land will continue to consume the cropland, grassland, and other land, but the trend will slow down. The woodland area will increase, mainly through the conversion of the surrounding cropland; and the water area will remain stable over the next ten years (Figure 3, Table 5).

The area of cropland is the largest under scenario A by 2030, i.e., 19,927.39 km^2. Owing to the impact of the different intensities of returning cropland to woodland and grassland, the area of cropland is the smallest under scenario E by 2030, i.e., 195502.73 km^2. Both woodland and grassland will continue to grow over the next 15 years. Among them, the woodland and grassland have the least areas under Scenario A,, and they have the highest areas under Scenario E respectively. The built-up land will continue to grow continuously. However, overall, the amount of built-up land in 2030 does not vary significantly under the five different land use scenarios.

3.4 Change in Forest Fragmentation

The forest and grass fragmentation on the Loess Plateau is dominated by edge and core type. The core type fragmentation has a concentrated distribution and is the largest, accounting for more than 75% of the entire area of woodland and grassland. The percentage of perforated and patch type is very small, less than

5%. In different years, the areas of the various spatial process types transformed into each other. From a spatial perspective, except for in Inner Mongolia, the patch type fragmentation was widely distributed in the other provinces, and the forest and grass landscapes in the northwest and central areas of the Loess Plateau were most severely fragmented, and it was mostly concentrated in cities and forests, cropland, and in the transition zone between the city and the grassland. Moreover, the gravity center of the fragmentation has basically not changed, but there has been an overall westward shift. The core type fragmentation was mainly distributed in Shaanxi Province and in the Luliang Mountains and Taihang Mountains in Shanxi Province. The perforated and edge type fragmentation were relatively scattered.

The fragmentation degree generally initially increased in intensity and then slowed down (Figure 4), that is, the core area continued to increase, and the proportion of patch and edge areas continued to decrease. The most severe fragmentation occurred around 2000, with the patch and edge areas accounting for the highest proportions (1.30% and 23.38%, respectively) (Table 6) and the core area accounting for a relatively low proportion (67.21%). After 2000, the edge and patch areas exhibited an overall decrease. The patch area decreased from 1.28% to 1.14%, and the edge area decreased from 22.89% to 20.32%. The core area gradually increased, with a particularly large core area increase of 3.7% from 1980 to 2015, which dominated the absolute advantage. The results obtained by coupling the FLUS model and the landscape fragmentation model to predict the fragmentation of the forest and grass landscapes under different intensities of returning cropland to woodland and grassland indicate that the degree of landscape fragmentation gradually decreased. Among them, the percentage of the large core area of the returning cropland to woodland and grassland (intensity of 30%) was the highest, reaching 70.72%, and the proportion of patch area was the lowest (1.11%).

4. Discussion and Conclusions

4.1 Factors Affecting Land Use Change

The land use has changed dramatically in the last 35 years. The area of cropland initially increased and then decreased, and the area of woodland and grassland initially decreased and then increased, but the overall pattern of land use and land cover did not change significantly. The pattern was grassland > cropland> woodland > unused land > built-up land > water bodies. Human activities are one of the leading factors in the dynamic changes in land use patterns (Wang et al., 2010; Verburg and Chen, 2010). The Loess Plateau has also begun rapid, large-scale urbanization due to the rapid social and economic development, population growth, and the implementation of the Northwest Development Strategy (Jiang et al., 2016). This has directly affected the expansion of built-up land, resulting in the encroachment of other land use types, such as cropland, woodland, grassland, and unused land, and affecting the structure, process, and functions of the forest ecosystem. At present, the built-up land on the Loess Plateau is still expanding at a relatively high speed (Wang et al., 2007). However, the “Grain for Green” Project has resulted in a typical land use change process. Since the project was implemented, a large amount of arable slope land has been converted into grassland and woodland. Before the implementation of this project, the woodland area decreased by 544.06 km2, with an average annual decrease of -0.03%; and the grassland area decreased by 1494.19 km2, with an average annual decrease of -0.03% (Table 2). After the implementation of this project, the woodland area increased by 6461.12 km2, with an average annual increase of 0.33%; and the average annual decrease in the grassland area increased by -0.06% (Table 3). The effect of the vegetation restoration was significant, and soil erosion has been effectively controlled. Moreover, it had obvious effects on the social development and ecological environment. However, the area returned to grassland accounted for about 10% in the process of returning cropland to woodland (grassland), but only 1% actually stabilized (Jiang et al., 2016). In addition, it should be noted that the conversion of cropland to other land types is not entirely due to the ecological conversion of cropland (Wang et al., 2010). Cropland abandonment and the conversion of cropland into woodland and grassland also occurred, but the vegetation was degraded due to improper management (McVicar et al., 2007). Accurately identifying the spatial scope of the “grain for Green” Project and determining a way of promoting grassland construction and improving the effectiveness of grassland construction is an important issue that deserves more attention.

Climate is another factor affecting land use change (Zhang et al., 2009). Affected by global climate change, the temperature on the Loess Plateau has increased to a certain extent, with an average temperature increase rate of 0.033°C/a, which means that the temperature has risen by approximately 1.32°C over the last 40 years. This is much higher than the average growth rate of the global temperature (0.013°C/a) and that in China (0.022°C/a), so the climate warming trend is extremely significant (Wang et al., 2013). Sun et al. (2016) found that in the central and southeastern parts, the temperature increase promotes vegetation growth, while in the northwest, it inhibits vegetation growth. In particular, after the implementation of the project, the precipitation on the Loess Plateau significantly increased at a rate of 5.16 mm·a-1 (Deng et al., 2014), which was vital to the ecological restoration of the Loess Plateau since it provided water for large-scale vegetation restoration, increased the soil reservoir capacity, simultaneously relieved the drought and water shortages, and decreased soil erosion.

4.2 Prediction of Land Use Changes

An objective and reasonable simulation of future land use can not only grasp the change law and development, but it could also be used to test the rationality of the current social and economic policies concerning land use change orientation (Seto et al., 2002). Land use change is a nonlinear compound fluctuating process (Zhang et al., 2016), and the driving factors are the basis for affecting the intensity of land expansion and causing land use changes, which are becoming more and more complex with the continuous development of social and economic factors (Verburg et al., 2002). Its rationality and representativeness are important to the accuracy of the mode. The FLUS model has been used in land use simulations on the national scale. The Kappa coefficient is 0.67, the overall simulation accuracy is 0.75, and the model confidence is within a reasonable interval of l (Liu et al., 2017). Our results show that the Kappa coefficient reached 0.9181 at 1% random sampling. Moreover, we also used the FoM coefficient, which can describe the simulation accuracy better than the Kappa coefficient. In theory, the larger the parameter value, the better the simulation effect and the higher the accuracy. However, practical verification revealed that the results are mostly within 0.3 (Pontius et al., 2008), and the results from 0.1 to 0.2 are the most common (Chen et al., 2014). Comparing the land use simulation of the Loess Plateau in 2015 with the actual situation, the FoM coefficient is 0.12, which is within a reasonable range. Generally speaking, all of the tests are within a reasonable range, which is in line with the land use changes, and the driving factors selected in this study have a good ability to explain the spatial layout of the land use. In this study, the results have practical value and are beneficial to optimizing the spatial pattern of land use on the Loess Plateau, especially the spatial patterns of the woodland and grasslands. However, we can only verify that the method has good suitability for this research, whether it is universal or not requires additional practical demonstrations. Because this method solidifies the change direction and intensity of the various land use types to a certain extent (Meyfroidt et al., 2013), it ignores the uncertainty in and dynamic influences of the driving factors on the land expansion capacity under the temporal and spatial differences (Wang et al., 2019). In the future, the determination of the driving factors should comprehensively consider the diversity, heterogeneity, temporal and spatial differences, and dynamics.

4.3 Fragmentation of forest and grass land

The dynamic process of forest and grass fragmentation before and after the project implementation was analyzed using the landscape fragmentation model, which could make up for the shortcomings of the existing forest fragmentation studies, which have mostly focused on the static spatial pattern at a certain point in time and have ignored the spatial process (Ochoa-Gaona, 2001). Fragmentation was common and severe in some areas over the last 35 years. The transformation of woodland and grassland into cropland plays a leading role in landscape fragmentation, and the rapid expansion of built-up land has also increased the extent of landscape fragmentation. However, since the implementation of the project, the proportion of the area of woodland and grassland has increased significantly, the degree of landscape fragmentation has decreased. The main feature of this change is that the core area has increased, which shows that the impact of human disturbance is very significant. In particular, the patches and edges are concentrated in the transition zones between the city and the woodland, the cropland and the woodland, and the shrub land and the woodland (Figure 4). Compared with previous research results, the degree of landscape fragmentation determined in this study is relatively low (Yang et al., 2018). The main reason for this is that the woodland and grassland were analyzed together in order to investigate the landscape fragmentation, so the core area was larger. The woodland and grassland on the Loess Plateau have unique distribution characteristics, and the grassland occupies an important position in the ecosystem service functions (Zhang et al., 2020). If the degree of forest fragmentation is analyzed separately, the fragmentation will be more severe.

Decreasing forest fragmentation is a long-term and complex process (Riitters et al., 2020). The relationship between social and economic development and forest fragmentation is complex and diverse rather than linear (Estoque and Murayama, 2016). The development of eco-tourism, infrastructure construction, and cropland expansion aggravate forest fragmentation; while socioeconomic development has a positive impact on alleviating forest fragmentation through forest restoration and growth (Su et al., 2012). Because of this, measures need to be taken to avoid the negative impacts of social and economic development on forest fragmentation. By coupling the FLUS model and the landscape fragmentation model, we set different intensities for the conversion of cropland, which enabled the more detailed identification and prediction of the landscape fragmentation types, areas, and spatial distributions. As time progressed, the degree of landscape fragmentation generally initially intensified and then slowed down, which indicates that project implementation could decrease forest fragmentation, especially under the 30% ratio of returning cropland to woodland and grassland. This also indicates that the process of forest fragmentation cannot be ignored and corresponding intervention measures should be taken.

Objectively speaking, determining a way to promote forest growth has always been the primary direction of forestry policy and research in China. However, determining a way to decrease forest fragmentation has not yet attracted the full attention of scholars, and the existing studies are not sufficient to support systematic policy management of forests practices. It is expected that improving the integrity and methods of forest ecosystem management will be an important task for a long period of time in the future, which should follow internal laws and should overcome forest fragmentation in forestry policy practices and academic research.

5. Acknowledgements

This project was supported by the China Postdoctoral Fund (Grant No.2019M663843), and the Shaanxi Province Natural Science Foundation (Grant No.2013JQ5013). The authors thank all of the individuals who provided helpful suggestions and critical comments on this manuscript.

6. Conflict of Interest

The authors have no conflicts of interest to declare.

7. Additional Information

Li Gu prepared the figures and tables and wrote the main manuscript text. Zhiwen Gong was mainly responsible for the content of the thesis, revision, and language adaptation; and she is the corresponding author. All of the authors reviewed the manuscript, and Yuankun Bu prepared the figures and tables. All of the authors have reviewed the manuscript.

References

[1] Pan, Y.D., Birdsey, R.A., Fang, J.Y., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S.L., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science, 333, 988-993. http://dx.doi.org/10.1126/science.1201609.

[2] Fang, J.Y., Guo, Z.D., Hu H.F., Kato, T., Muraoka, H., Son, Y., 2014. Forest biomass carbon sinks in East Asia, with special reference to the relative contributions of forest expansion and forest growth. Global Change Biology, 20(6), 2019-2030. http://dx.doi.org/10.1111/gcb.12512.

[3] Keenan, R.J., Reams, G.A., Achard, F., Freitas, J.V., Grainger, A., Lindquistf, E., 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. Forest Ecology and Management, 352(7): 9-20. http://dx.doi.org/10.1016/j.foreco.2015.06.014.

[4] Achard, F., Hansen, M.C., 2012. Global Forest Monitoring from Earth Observation. CRC Press, Boca Raton.

[5] Bonan, G.B., 2008. Forests and climate change: forcing, feedbacks, and the climate benefits of forests. Science, 320, 1444-1449. http://dx.doi.org/10.1126/science.1155121.

[6] Riitters, K.H., Wickham, J.D., O'Neill, R.V., Jones, K.B., Smith, E.R., 2000. Global-scale patterns of forest fragmentation. Conservation Ecology, 4, 1924-1925. http://dx.doi.org/10.5751/ES-00209-040203.

[7] Riitters, K.H., Wickham, J.D., O'Neill, R.V., Jones, K.B., Smith, E.R., Coulston, J.W., Wade, T.G., Smith, J.H., 2002. Fragmentation of Continental United States Forests. Ecosystems, 5, 815-822. http://dx.doi.org/10.1007/s10021-002-0209-2.

[8] Cushman, A.S., Shirk, A., Landguth, E.L., 2012. Separating the effects of habitat area, fragmentation and matrix resistance on genetic differentiation in complex landscapes. Landscape Ecology, 27, 369-380. http://dx.doi.org/10.1007/s10980-011-9693-0.

[9] Long, J.A., Nelson, T.A., Wulder, M.A., 2010. Characterizing forest fragmentation: Distinguishing change in composition from configuration. Applied Geography, 30, 426–435. http://dx.doi.org/10.1016/j.apgeog.2009.12.002.

[10] Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., Lovejoy, T. E., Sexton, J. O., Austin, M. P., Collins, C. D., 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Science Advance, 1(2), e1500052. http://dx.doi.org/10.1126/sciadv.1500052.

[11] Zuidema, P.A., Sayer, J.A., Dijkman, W., 1996. Forest fragmentation and biodiversity: The case for intermediate-sized conservation areas. Environmental Conservation, 23, 290-297. http://dx.doi.org/10.1017/s037689290003914x.

[12] Wang, X., Blanchet, F.G., Koper, N., 2014. Measuring habitat fragmentation: An evaluation of landscape pattern metrics. Methods in Ecology and Evolution, 5, 634-646. http://dx.doi.org/10.1111/2041-210X.12198.

[13] Zhao, Q.J., Wen, Z.M., Chen, S.L., Ding, S., Zhang, M.X., 2020. Quantifying Land Use/Land Cover and Landscape Pattern Changes and Impacts on Ecosystem Services. International Journal of Environmental Research and Public Health, 17, 126. http://dx.doi.org/10.3390/ijerph17010126.

[14] Franklin, S.E., 2001. Remote Sensing for sustainable forest management. Lewis Publishers, USA.

[15] Carranza, M.L., Hoyosc, L., Frate, L., Acosta, A.T.R., Cabido, M., 2015. Measuring forest fragmentation using multitemporal forest cover maps: Forest loss and spatial pattern analysis in the Gran Chaco, central Argentina. Landscape and Urban Planning, 143, 238-247. http://dx.doi.org/10.1016/j.landurbplan.2015.08.006.

[16] D'eon, R.G., Glenn, S.M., 2015. The influence of forest harvesting on landscape spatial patterns and old-growth-forest fragmentation in southeast British Columbia. Landscape ecology, 20(1), 19-33. http://dx.doi.org/10.1007/s10980-004-0286-z.

[17] Abdullah, S.A., Nakagoshi, N., 2007. Forest fragmentation and its correlation to human land use change in the state of Selangor, peninsular Malaysia. Forest Ecology and Management, 241(1-3), 39-48. http://dx.doi.org/10.1016/j.foreco.2006.12.016.

[18] Uuemaa, E., Antrop, M., Roosaare, J., Marja, R., Mander, Ü., 2009. Landscape metrics and indices: An overview of their use in landscape research. Living Reviews in Landscape Research, 3, 1. http://dx.doi.org/10.12942/lrlr-2009-1Villard.

[19] Sharma, M., Chakraborty, A., Garg, J.K., Josh,. PK., 2017. Assessing forest fragmentation in north-western Himalaya: a case study from Ranikhet forest range, Uttarakhand, India. Journal of Forest Research, 28(2):319-327. http://dx.doi.org/10.1007/s11676-016-0311-5.

[20] Gong, Z.W., Yao, S.B., Gu, L., 2019. Effects of Bio-physical, Economic and Ecological policy on forest transition: A Spatial Econometric Analysis for Loess Plateau, P.R. China. Journal of Cleaner Production, 1-16. http://dx.doi.org/10.1016/j.jclepro.2019.118571.

[21] Gu, L., O'Hara, K.L., Li, W.Z., Gong, Z.W., 2019. Spatial Patterns and Interspecific Associations among Trees at Different Stand Development Stages in the Natural Secondary Forests on the Loess Plateau, China. Ecology and Evolution, 1-12. http://dx.doi.org/10.1002/ece3.5216.

[22] Zhang, X., Zhao, W.W., Liu, Y.X., Fang, X.N., Feng, Q., 2016. The relationships between grasslands and soil moisture on the Loess Plateau of China: A review. Catena, 145: 56-67. http://dx.doi.org/10.1016/j.catena.2016.05.022.

[23] Wu, Z., Wu, J., He, B., Liu, J., Wang, Q., Zhang, H., Liu, Y., 2014. Drought offset ecological restoration program- induced increase in vegetation activity in the Beijing- Tianjin Sand Source Region, China. Environmental Science & Technology, 48, 12108-12117. https://doi.org/10.1021/ es502408n.

[24] Chang, R..Y, Fu, B.J., Liu, G.H., Liu, S.G., 2011. Soil Carbon Sequestration Potential for "Grain for Green" Project in Loess Plateau, China. Environment management, 48(6): 1158-1172. https://doi.org/10.1007/s00267-011-9682-8.

[25] Wang, Y.H, Brandt, M., Zhao, M.F., Xing, K.X., Fensholt, R., 2020. Do afforestation projects increase core forests? Evidence from the Chinese Loess Plateau. Ecological Indicators, 117:1-11. https://doi.org/10.1016/j.ecolind.2020.106558.

[26] Deng, L., Shangguan, Z.P., Sweeney, S., 2014. "Grain for Green" driven land use change and carbon sequestration on the Loess Plateau, China. Scientific Reports, 4, 7039. https://doi.org/10.1038/srep07039.

[27] Niu, Q.F, Xiao, X.M., Zhang, Y., Qin, Y.W., Zhou, X.M., 2019. Ecological engineering projects increased vegetation cover, production, and biomass in semiarid and subhumid Northern China. Land Degradation & Development, 30(13): 1620-1630. https://doi.org/10.1002/ldr.3351.

[28] Gang, C.C., Zhao, W., Zhao, T., Zhang, Y., Gao, X., Wen, Z., 2018. The impacts of land conversion and management measures on the grassland net primary productivity over the Loess Plateau, Northern China. Science of the Total Environment, 645: 827-836. https://doi.org/10.1016/j.scitotenv.2018.07.161.

[29] Kang, H., Li, H.H., Zhao, S.J., 2019. Land use pattern change and forecast analysis of energy and chemical industry base in the Loss Plateau. Fresenius Environmental Bulletin, 28(4): 2835-2841.

[30] Hobbs, R.J., Higgs. E., Hall, C.M., Bridgewater, P., Chapin, F.S., Ellis, E.C., Ewel, J.J., Hallett, L.M., Harris, J., Hulvey, K.B., 2016. Managing the whole landscape: historical, hybrid, and novel ecosystems. Frontiers in Ecology and the Environment, 12(10): 557-564. https://doi.org/10.1890/130300.

[31] Zhang, D.J., Yin, R.S., 2019. Spatial characteristics of degraded land and their implications to the design and implementation of landscape restoration programs: West China as an example. Forest Policy and Economics. 107. https://doi.org/10.1016/j.forpol.2019.05.011.

[32] Hua, A.K., 2017. Application of CA-Markov model and land use/land cover changes in Malacca River watershed, Malaysia. Applied Ecology and Environmental Research, 15(4), 605-622. https://doi.org/10.15666/aeer/1504_605622.

[33] Puyravaud, J.P., Dufour, C., Aravajy, S., 2003. Rain forest expansion mediated by successional processes in vegetation thickets in the Western Ghats of India. Journal of Biogeography, 30(7): 1067-1080. https://doi.org/10.1046/j.1365-2699.2003.00882.x.

[34] Chen, Y.M., Li, X., Liu, X.P., Ai, B., 2014. Modeling urban land-use dynamics in a fast developing city using the modified logistic cellular automaton with a patch-based simulation strategy. International Journal of Geographical Information Science, 28(2), 234-255. https://doi.org/10.1080/13658816.2013.831868.

[35] Yang, Y.Y., Bao, W.K., Liu, Y.S., 2020. Scenario simulation of land system change in the Beijing-Tianjin-Hebei region. Land Use Policy, 96, 104677. https://doi.org/10.1016/j.landusepol.2020.104677.

[36] Gong, J., Hu, Z., Chen, W., Liu, Y., Wang, J., 2018. Urban expansion dynamics and modes in metropolitan Guangzhou, China. Land Use Policy, 72, 100-109. http://dx.doi.org/10.1016/j.landusepol.2017.12.025.

[37] Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. annual review of environment and resources, 28 (1), 205-241. http://dx.doi.org/10.1146/annurev.energy.28.050302.105459.

[38] Xie, H., He, Y., Xie, X., 2017. Exploring the factors influencing ecological land change for China's Beijing–Tianjin–Hebei region using big data. Journal of Cleaner Production. 142, 677-687. http://dx.doi.org/10.1016/j.jclepro.2016.03.064.

[39] Verburg, P.H., Overmars, K.P., 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned croplands in Europe with the Dyna-CLUE model. Landscape Ecology, 24 (9), 1167. http://dx.doi.org/10.1007/s10980-009-9355-7.

[40] Liu, X., Li, X., Shi, X., Wu, S., Liu, T., 2008. Simulating complex urban development using kernel-based non-linear cellular automata. Ecological Modelling, 211, 169-181. http://dx.doi.org/10.1016/j.ecolmodel.2007.08.024.

[41] Openshaw, S., 1998. Neural network, genetic, and fuzzy logic models of spatial interaction. Environment and Planning A, 30, 1857-1872. http://dx.doi.org/10.1068/a301857.

[42] Li, X, Chen, G., Liu, X., 2017. A new global land-use and land-cover change product at a 1-km resolution for 2010 to 2100 based on human- environment interactions. Annals of the American Association of Geographers, 2017, 107(5): 1040-1059.

[43] Liu, X., Liang, X., Li, X., Xu, X.C., Wang, S.J., 2017. A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. Landscape and Urban Planning, 2017, 168: 94-116. http://dx.doi.org/10.1016/j.landurbplan.2017.09.019.

[44] Pontius, O.G, Millones, M., 2011. Death to Kappa: birth of quantity disagreement and allocation disagreement for accuracy assessment. International Journal of Remote Sensing, 32(15), 4407-4429. http://dx.doi.org/10.1080/01431161.2011.552923.

[45] Parent, J., 2009. Landscape fragmentation analysis (version 2).University of Connecticut Press, USA.

[46] Vogt. P., Riitters, K., Estreguil, C, Kozak, J., Wade, T.G., Wickham, J.D., 2007. Mapping spatial patterns with morphological image processing. Landscape Ecology, 22, 171-177. http://dx.doi.org/10.1007/s10980-006-9013-2.

[47] Lang, S., Tiede, D., 2003. vLATE extension fur ArcGIS – vektorbasiertes tool zur quantitativen landschaftsstrukturanalyse, ESRI Anwenderkonferenz 2003. Innsbruck, Austria.

[48] Wang, D., Fu, B.J., Lu, K.S., Zhang, Y.X., Feng, X.M., 2010. Multifractal analysis of land use pattern in space and time: A case study in the Loess Plateau of China. Ecological Complexity, 7, 487-493. https://doi.org/10.1016/j.ecocom.2009.12.004.

[49] Verburg, P.H., Chen, Y.Q., 2000. Multiscale characterization of land-use patterns in China. Ecosystems 3, 369-385. https://doi.org/10.1007/s100210000033

[50] Jiang, W.Y., Yang, S.L., Yang, X.X., Gu, N., 2016. Negative impacts of afforestation and economic forestry on the Chinese Loess Plateau and proposed solutions. Quaternary International , 399(18), 165-173. http://dx.doi.org/10.1016/j.quaint.2015.04.011.

[51] National Development and Reform Commission (NDRC), Ministry of Water Resources (MWR), Ministry of Agriculture (MA), State Forestry Administration (SFA), 2010. People's Republic of China. In: Programming for Comprehensive Management of the Loess Plateau (2010-2030), pp. pp4-14.

[52] Wang, G., Innes, J.L., Lei, J., Dai, S., Wu, S.W., 2007. China's forestry reforms. Science, 318, 1556-1557. http://dx.doi.org/10.1126/science.1147247.

[53] Chen, H., Shao, M., Li, Y., 2008. The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China. Journal of Hydrology 360, 242-251. http://dx.doi.org/10.1016/j.jhydrol.2008.07.037.

[54] McVicar, T.R., Li, L., Niel, T.G.V., Zhang, L., Li, R., Yang, Q., Zhang, X., Mu, X., Wen, Z., Liu, W., Zhao, Y., Liu, Z., Gao, P., 2007. Developing a decision support tool for China's re-vegetation program: simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. Forest Ecology and Management, 251, 65-81. http://dx.doi.org/10.1016/j.foreco.2007.06.025.

[55] Wang, X.M., Zhang, C.X., Hasi, E., Dong, Z.B., 2010. Has the Three Norths Forest Shelterbelt Program solved the desertification and dust storm problems in arid and semiarid China? Journal of Arid Environment 74, 13-22. http://dx.doi.org/10.1016/j.jaridenv.2009.08.001.

[56] Zhang, H., Gao, X., Li, Y., 2009. Climate impacts of land-use change in China and its uncertainty in a global model simulation. Climate Dynamics, 32, 473-494. https://doi.org/10.1007/s00382-008-0388-4.

[57] Wang, H.J., Chen, Y.N., Chen, Z.S., 2013. Spatial distribution and temporal trends of mean precipitation and extremes in the arid region, northwest of China, during 1960-2010. Hydrological Process, 27, 1807-1818. http://dx.doi.org/10.1016/j.quaint.2015.04.011.

[58] Sun, W,Y., Mu, X,M., Song, X.Y., Wu, D., Cheng, A.F., Qiu, B., 2016. Changes in extreme temperature and precipitation events in the Loess Plateau (China) during 1960-2013 under global warming. Atmospheric Research, 168, 33-48. http://dx.doi.org/10.1016/j.atmosres.2015.09.001.

[59] Zhang, Y., Peng, C., Li, W., Tian, L., Zhu, Q, Chen, H., Fang, X., Zhang, G., Xiao, X., 2016. Multiple afforestation programs accelerate the greenness in the 'Three North' region of China from 1982 to 2013. Ecological Indicators, 61, 404-412. https://doi.org/10.1016/j.ecolind.2015.09.041.

[60] Verburg, P.H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., Mastura, S.S., 2002. Modeling the spatial dynamics of regional land use: The CLUE-S model. Environmental Management, 30, 391-405. https://doi.org/10.1007/s00267-002-2630-x.

[61] Yang, Z.Q., Dong, J.W., Xu, X.L., Zhao, G.S., Chen, W., Zhou, Y., 2018. Spatiotemporal pattern of forest fragmentation in the Loess Plateau. Resources Science, 40(6): 1246-1255.

[62] Zhang, J., Qu, M., Wang, C., Zhao, J., Cao, Y., 2020. Quantifying landscape pattern and ecosystem service value changes: A case study at the county level in the Chinese Loess Plateau. Global Ecology and Conservation, 23, e01110. http://dx.doi.org/10.1016/j.gecco.2020.e01110.

[63] Riitters, K., Wickham, J.D., O'Neill, R., Jones, B., Smith, E., 2020. Global-Scale Patterns of Forest Fragmentation. Ecology and Society, 4(2), 1924-1925. http://dx.doi.org/10.5751/ES-00209-040203.

[64] Estoque, R.C., Murayama, Y., 2016. Quantifying landscape pattern and ecosystem service value changes in four rapidly urbanizing hill stations of Southeast Asia. Landscape Ecology, 31(7), 1-27. http://dx.doi.org/10.1007/s10980-016-0341-6.

[65] Su, S., Xiao, R., Jiang, Z., Zhang, Y., 2012. Characterizing landscape pattern and ecosystem service value changes for urbanization impacts at an eco-regional scale. Applied Geography, 34, 295-305. http://dx.doi.org/10.1016/j.apgeog.2011.12.001.

[66] Wu, W., Li, Y.H., Hu, Y.N., Viu, C.L., Yan, X.L., 2018. Impacts of Changing Forest Management Areas on Woodlandscapes and Habitat Patterns in Northeastern China. Sustainability, 10(4), 1211. http://dx.doi.org/10.3390/su10041211.

[67] Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lu, Y., Zeng, Y., Li, Y., Jiang, X., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nature Climate Change, 6, 1019-1022. http://dx.doi.org/10.1038/nclimate3092.

[68] Zheng, F., He, X., Gao, X., Zhang, C., Tang, K., Zheng, F., He, X., Gao, X., Zhang, C., Tang, K., 2005. Effects of erosion patterns on nutrient loss following deforestation on the Loess Plateau of China. Agriculture Ecosystems Environment, 108, 85-97. http://dx.doi.org/10.1016/j.agee.2004.12.009.

[69] Jiang, C., Zhang, H., Zhang, Z., 2018. Spatially explicit assessment of ecosystem services in China's Loess Plateau: patterns, interactions, drivers, and implications. Global and Planetary Change, 161, 41-52. http://dx.doi.org/10.1016/j.gloplacha.2017.11.014.

[70] Xu, D., Ding, X., 2018. Assessing the impact of desertification dynamics on regional ecosystem service value in North China from 1981 to 2010. Ecosystem Services, 30, 172-180. http://dx.doi.org/10.1016/j.ecoser.2018.03.002.

[71] Yu, Z., Liu, X., Zhang, J., Xu, D., Cao, S., 2018. Evaluating the net value of ecosystem services to support ecological engineering: framework and a case study of the Beijing Plains afforestation project. Ecological Engineering, 112, 148-152. http://dx.doi.org/10.1016/j.ecoleng.2017.12.017.

[72] Yuan, W.P., Li, X.L., Liang, S.L., Cui, X.F., Dong, W.J., 2014. Characterization of locations and extents of afforestation from the Grain for Green Project in China. Remote Sensing Letters, 5(3), 221-229. https://doi.org/10.1080/2150704X.2014.894655.

[73] Guo, J., Gong, P., 2016. Forest cover dynamics from Landsat time-series data over Yan'an city on the Loess Plateau during the Grain for Green Project. International Journal of Remote Sensing, 37, 4101-4118. https://doi.org/10.1080/01431161.2016.1207264.

[74] Seto, K.C., Woodcock, C.E., Song, C., Huang, X., Lu, J., Kaufmann, R.K., 2002. Monitoring land use change in the pearl river delta using landsat tm. International Journal of Remote Sensing, 23(10), 1985-2004. https://doi.org/10.1080/01431160110075532.

[75] Meyfroidt, P., Lambin, E.F., Erb, K.H., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. Current Opinion in Environmental Sustainability, 5(5), 438-444. https://doi.org/10.1016/j.cosust.2013.04.003.

[76] Wang, B.S., Liao, J.F., Zhu, W., Qiu, Q.Y., Wang, L., Tang, L.N., 2019. The weight of neighborhood setting of the FLUS model based on a historical scenario: A case study of land use simulation of uran agglomeration of the Golden Triangle of Southern Fujian in 2030. Acta Ecologica Sinica, 39, 4284-4298.

[77] Ochoa-Gaona, S., 2001. Traditional land-use systems and patterns of forest fragmentation in the highlands of Chiapas, Mexico. Environmental Management, 27(4), 571-586. https://doi.org/10.1007/s002670010171.

[78] Reddy, C., Pasha, S., Vazeed, K., Saranya, V., 2018. Quantifying nationwide land cover and historical changes in forests of Nepal (1930-2014): implications on forest fragmentation. Biodiversity & Conservation, 1-32. https://doi.org/10.1007/s10531-017-1423-8

Figures

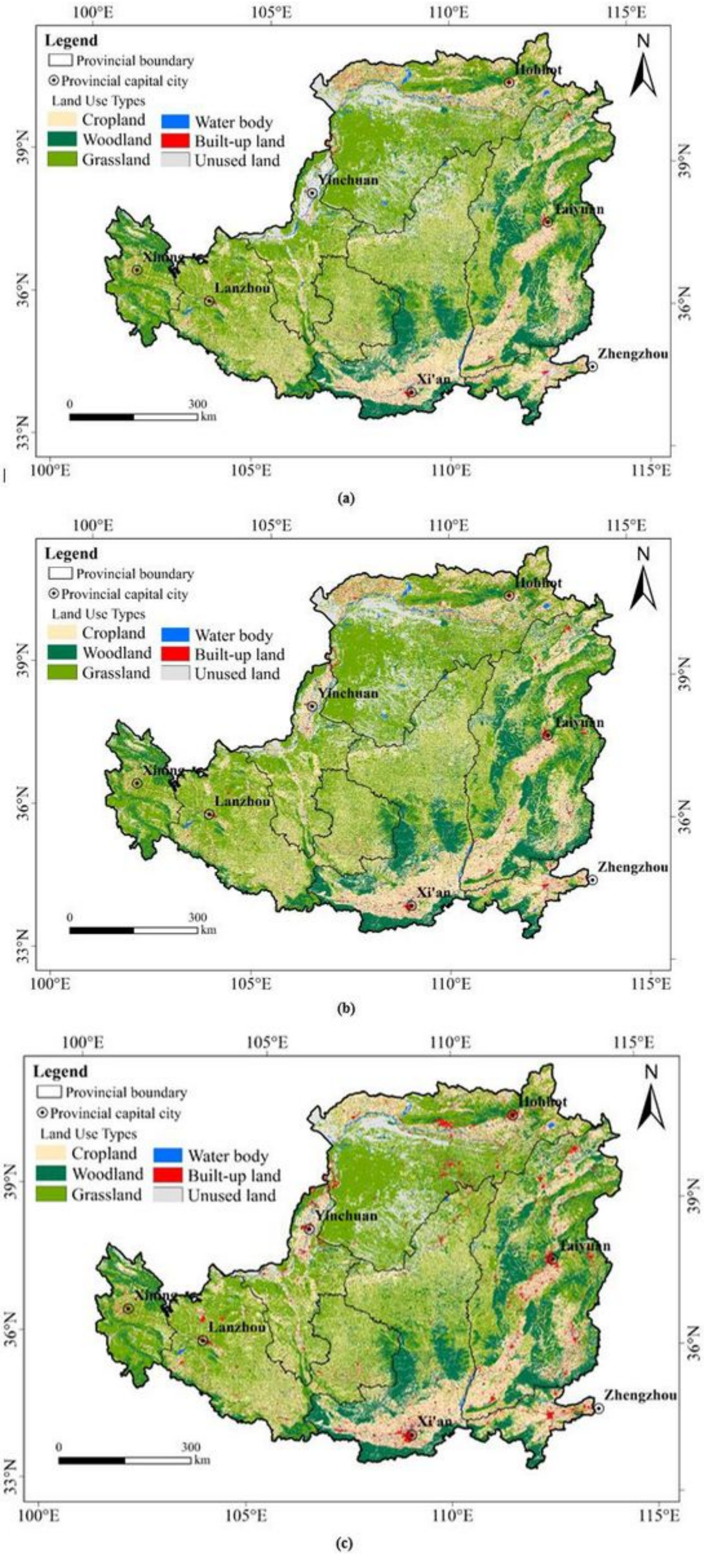

Figure 1

Spatio-temporal characteristics and variation patterns of the LUCC on the Loess Plateau in 1980(a), in 2000(b) and in 2015(c). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

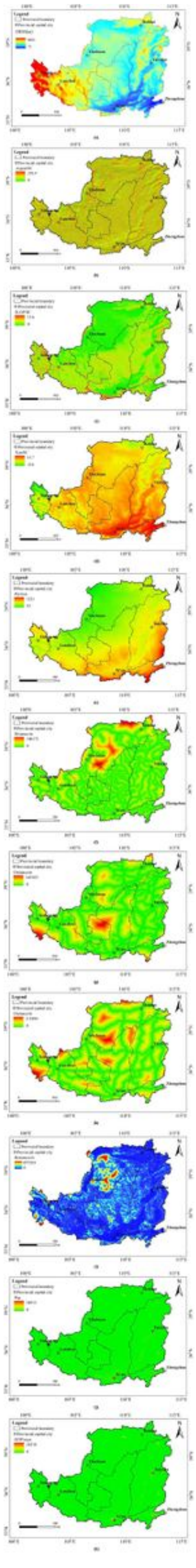

Figure 2

Driving trends of land use change on the Loess Plateau Note: a is DEM, b is aspect, c is slop, d is average annual temperature, e is average annual precipitation, f is the distance to river, g is distance to railway, h is distance to road, i is distance to residential area, j is population density, k is GDP. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

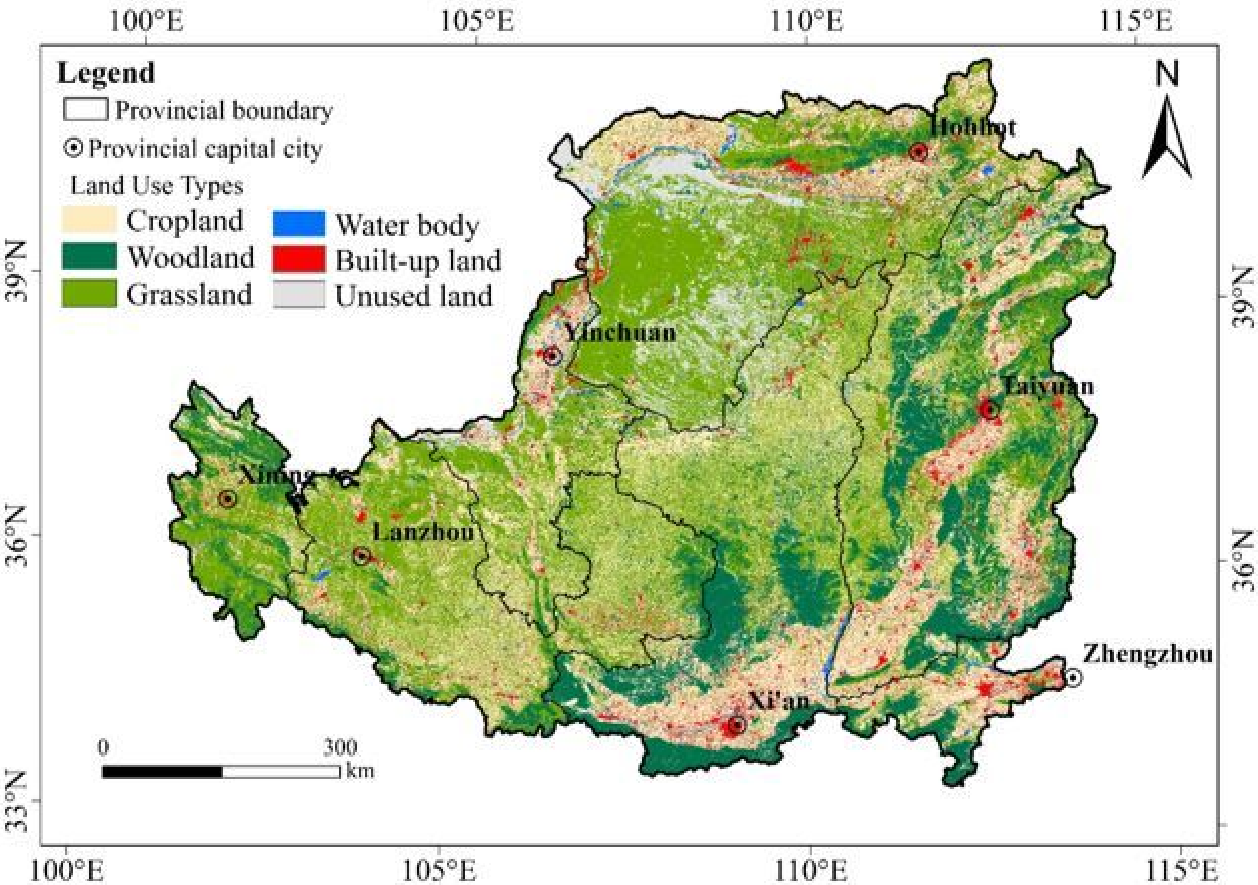

Figure 3

Land distribution map of the Loess Plateau in 2030 based on same transfer matrix. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

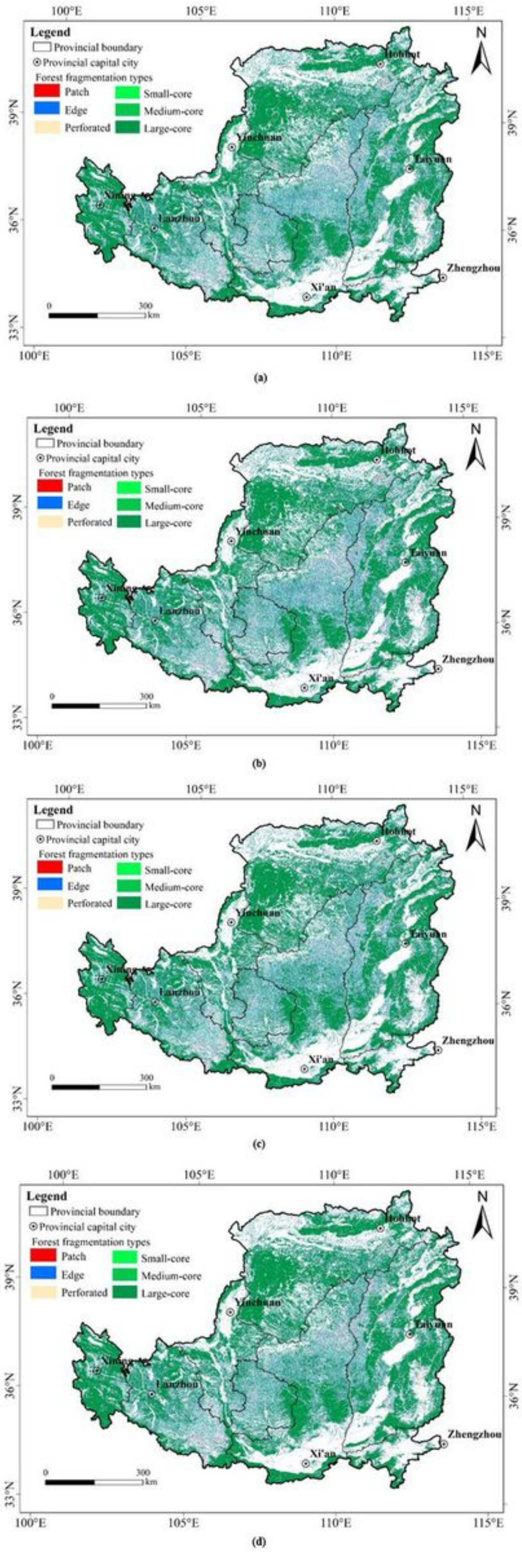

Figure 4

Spatio-temporal pattern of forest and grass fragmentation on the Loess Plateau Note: a is for 1980, b is for 2000, c is for 2015, and d is for 2030 based on same transfer matrix. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.