Identification of Priority Areas for Forest Land Expansion in Shanxi Province (Postprint)

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Abstract

Over the past 70 years, China has launched large-scale afforestation activities in arid and semi-arid regions and achieved remarkable results. However, due to the influence of human activities and climate, afforestation has failed in some local areas. Although the potential for afforestation in arid regions has been recognized, it remains unclear which specific micro-regions afforestation should focus on. This study takes Shanxi Province, a typical region of the Loess Plateau, as an example, constructs a suitable land identification framework, uses the PLUS model and Markov chain to simulate land use changes under different scenarios in 2030, and analyzes forest land expansion, internal stand change trends, and spatial distribution. The results show that: the current forest land growth potential in Shanxi Province is 5.38%, and the southeastern region is the main potential growth area; forest degradation may occur at the edges of forest land in the central and western regions, while the degree of forest fragmentation is relatively high in the northern region; the frequency of internal stand conversion is relatively high; according to expansion potential, the order is: closed forest land > shrubland > sparse forest land > other forest land. This study can provide a reference for effective management of afforestation in Shanxi Province and improvement of forest carbon sequestration levels.

Full Text

Identification of Priority Areas for Forest Land Expansion in Shanxi Province

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Abstract

Over the past 70 years, large-scale afforestation activities have been conducted in China' s arid and semi-arid regions with remarkable success, yet localized afforestation failures have occurred due to human activities and climatic influences. Although the potential for afforestation in arid areas is recognized, the specific micro-regions where afforestation should be concentrated remain unknown. This study takes Shanxi Province, a typical region of the Loess Plateau, as an example, constructs a framework for identifying suitable forest land, and uses the PLUS model and Markov chain to simulate land use changes under 2030 scenarios, analyzing forest land expansion, trends in internal forest stand changes, and spatial distribution. The results show that the current growth space for forest land in Shanxi Province is 5.38%, with the southeast being the main potential growth area. There is a possibility of forest degradation at the edges of woodlands in the central and western parts of the province, while the degree of forest fragmentation is higher in the north. The frequency of internal forest type conversions is high, and in order of expansion potential: woodland > shrubland > open woodland > other woodland. This study can provide a reference for effective afforestation management and enhanced forest carbon sequestration levels in Shanxi Province.

Keywords: PLUS model; Markov model; afforestation; scenario simulation; priority zone identification; arid and semi-arid areas

1 Introduction

Global land degradation in arid and semi-arid regions continues to expand, with an average annual degradation area of approximately 1000 hm^2. Human activities and natural factors have caused severe land degradation in these regions, making the restoration of degraded land one of the major challenges facing arid and semi-arid areas today. In this context, many countries have launched forest restoration projects, including afforestation, aimed at alleviating local economic losses caused by drought. Forest restoration is one of the effective strategies for maintaining carbon balance and mitigating global warming. Forest ecosystems play important roles in enhancing carbon storage, improving ecosystem carrying capacity, and maintaining ecosystem balance. Due to land overuse, disorderly forestry development, and natural disasters, the world has experienced a net loss of forest area. Studies have shown that under current climate conditions, there is approximately 1000 million hm^2 of potential forest growth space globally, with arid and semi-arid regions accounting for about 36%~42% of potential forest restoration. However, this may be a relatively optimistic estimate. In reality, afforestation in arid and semi-arid regions faces numerous difficulties. Although many countries and organizations actively advocate the importance of forest restoration, there are still no definitive answers regarding where and how to restore forests suitable for these regions, given the urgent trend of global warming.

In summary, research on the important topic of afforestation in arid and semi-arid regions has mainly addressed the following aspects: The first core issue concerns the suitability of afforestation. Regarding suitability during the afforestation process, academia holds two main viewpoints. One is the suitability of vegetation selection [1-3]; in arid and semi-arid regions, planting exotic monocultures often leads to high costs for maintaining biodiversity in later stages, creating unnecessary government burdens [4]. The second is the suitability of afforestation scale; large-scale, blind forest expansion may be more susceptible to local aridification, including afforestation at unsuitable sites [5-7]. These two viewpoints indicate that unsuitable artificial restoration will increase forest management costs in later stages. Although academia increasingly recognizes the severity of this problem, current domestic spatial data and information on afforestation in micro-regions remain incomplete, preventing accurate assessment of spatial suitability for afforestation in arid and semi-arid regions.

The second core issue concerns the contribution of afforestation in arid and semi-arid regions. In many academic studies, research on dryland forests is often less than that on other biomes. Although dryland forests have extremely low vegetation coverage compared to other biomes, they play important roles in the global carbon cycle, and the carbon density of some dryland forests may be higher than or close to that of adjacent forest biomes [8]. The Loess Plateau is a typical representative region where forest vegetation restoration has significantly enhanced regional total carbon storage [9-11]. Therefore, according to China' s Forest Management Plan (2016-2050) (http://www.forestry.gov.cn/), China needs to establish large areas of artificial forests in arid and semi-arid regions to achieve carbon neutrality targets. Implementing afforestation projects in arid regions requires consideration of trade-offs in ecological, economic, and social composite ecosystems. Therefore, surveys of potential afforestation areas and identification of afforestation regions are of great significance for afforestation in arid and semi-arid regions.

The third aspect that requires attention is China' s policy control over afforestation. Forest restoration is regarded as a major component of national independent contributions. From China' s Third National Land Survey, the Chinese government appears to be increasingly cautious about current ecological restoration, strictly controlling the conversion of farmland to forest, grassland, and garden land has become the main trend, and the expression of "returning farmland to forest" is being further weakened, with greater emphasis on the importance of protecting farmland red lines. Therefore, the realization of afforestation in arid and semi-arid regions requires greater attention to regional selection importance and improved afforestation efficiency.

In summary, reviewing the above three aspects of research is important for afforestation in China' s arid and semi-arid regions. The Loess Plateau, as a typical afforestation region in China' s arid and semi-arid areas, has attracted attention from all sectors of society for its forest ecological restoration. Current research on afforestation in the Loess Plateau region mainly focuses on changes during the afforestation process [12-14], evaluation of relevant influencing factors [15-17], and afforestation effectiveness [18-20]. A small number of studies focus on afforestation potential assessment against the background of climate conditions and policies [21-23]. However, methodological challenges remain: First, few studies on forest ecological restoration reflect internal changes within forest stands during the restoration process. For example, in some areas affected by climate and human activities, there is a trend of degradation from shrubland to open woodland within forests, which is not reflected in total forest area but clearly represents forest quality degradation. Second, relevant studies rarely reflect forest dynamics regarding land use change caused by human activity interference. Therefore, combining the above arguments about afforestation in arid and semi-arid regions, this paper argues that the specific afforestation potential areas for forest ecological restoration under land use change caused by human factors need further exploration, and internal changes within forest stands during forest restoration also require further analysis.

Shanxi Province is a typical region of artificial afforestation on the Loess Plateau with vast areas of suitable forest land. In recent years, under farmland protection policies, the reduction in conversion area from farmland to forest and grassland has limited the development space for returning farmland to forest (grass). Additionally, natural factors and poor human management have led to declining forest stand quality. Therefore, this study takes Shanxi Province as the main research area, uses the PLUS model and Markov chain to simulate land use structure changes under different scenarios, particularly subdividing internal conversions between forest stands. The purposes of this study are: (1) to assess the regional suitability of forest growth; (2) to evaluate the growth space and distribution of forest land in Shanxi Province; (3) to identify priority development areas for forest land.

1.1 Study Area Overview

Shanxi Province is located in central China (34°34 ~40°44 N, 110°14 ~114°33 E) on the second topographic step. It extends from the Taihang Mountains in the east to the Lüliang Mountains in the west, with the Fen River valley in the middle, forming a "two mountains with one river" terrain characteristic. The geographic unit is relatively closed, with terrain gradually descending from northeast to southwest. The main landscape units are mountainous plateau, mountains, and hills. The climate is temperate continental monsoon, with uneven seasonal distribution of annual precipitation, ranging from 358~621 mm, and relatively scarce water resources. The main ecosystems within the province are forest ecosystems, wetland ecosystems, and grassland ecosystems, but the ecosystems are generally fragile [24].

1.2 Data Sources

The data used in this study mainly include land use data and driving factors of land use change. Land use type data were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (resolution 30 m$\times$30 m). To intuitively analyze internal conversion within forest land in Shanxi Province, land use types include woodland, shrubland, open woodland, other woodland, farmland, grassland, water area, construction land, and unused land. Driving factors for suitable forest land identification are mainly divided into three categories: soil driving factors (7 items), socioeconomic driving factors (9 items), and climate and environmental driving factors (3 items). Among them, slope and aspect data were calculated based on DEM data, while temperature and precipitation data mainly used the 2010-2020 average values.

2 Models and Methods

This study constructs a comprehensive identification framework based on the Markov chain and PLUS model (Figure 1). First, the Markov chain is used to predict land demand values under different scenarios in Shanxi Province. Second, the PLUS model allocates these predicted values and various land use driving factors to different land use types to obtain spatial distribution of land use under multiple scenarios for comparative analysis.

2.1 Multi-scenario Simulation Based on Land Use Demand Quantity and Spatial Constraints

This study uses the Markov chain to set different scenarios based on sustainable development goals [25-26] and predict future land use demand areas under different scenarios. Changes in land use demand values under different scenarios are mainly achieved by altering the conversion probability matrix between land use types in the Markov chain. The conversion constraint matrix indicates the permission for one land use type to convert to another, where "1" indicates conversion allowed and "0" indicates conversion prohibited. Three development scenarios are established to estimate land use changes under different development scenarios in Shanxi Province.

Baseline Scenario: Under this scenario, no constraints are set on land use, assuming that land transfer probabilities from 2020 to 2030 are the same as those from 2010-2020, with population and economic development patterns continuing the current state. This scenario simulates land use development without external constraints. The land conversion matrix is consistent with the 2010-2020 land conversion matrix (Table 2).

Ecological Conservation Scenario: According to the requirements of the National Forest Economic Plan (2018-2025) and the Shanxi Provincial Territorial Space Plan (2021-2035), the ecological conservation scenario is established. Forest land in Shanxi Province will be further protected, with restrictions on conversion from forest land to other land types (excluding farmland) (Table 3). In this scenario, the probability of various forest types, farmland, grassland, and unused land converting to construction land is reduced by 50%, while the probability of construction land converting to other land types is reduced by

30% (Table 4).

Urbanization Development Scenario: Under the urbanization scenario, construction land will inevitably over-occupy farmland, grassland, etc. Based on this reality, compared with 2010-2020 land transfer probabilities, this study increases the probability of various forest types, farmland, grassland, and unused land converting to construction land by 50%, while the probability of construction land converting to other land types decreases (Table 5). The land conversion matrix is shown in Table 6.

2.2 PLUS Model

The PLUS model consists of two basic modules: the Land Expansion Analysis Strategy (LEAS) and the Cellular Automata model based on Multiple Random Seeds (CARS). The LEAS module extracts the expansion portion of land use types between two periods, uses the random forest method to sample and analyze the driving forces of the expansion portion, and obtains the development probability of various land use types. The CARS module generates patches based on a random seed generation and threshold decreasing mechanism, simulating future land use based on adaptive coefficients, neighborhood effects, and development probability. It should be noted that in the PLUS model, the patch generation threshold is set to 0.5, the random seed probability is 0.01, the random seed ratio is 0.02, the neighborhood range is 8, and the sampling rate is 0.01.

Before simulation, the PLUS model must be used to verify the accuracy of land use simulation in Shanxi Province. First, 15 factors affecting land use/cover change are selected as input to the model, and suitability probabilities for 9 land use types are generated (Figure 2). By comparing with actual land use types in 2020, the Kappa coefficient is calculated to determine the reliability of the PLUS model. If Kappa is between 0.8-1.0, it indicates high simulation results; if between 0.6-0.8, it indicates moderate simulation. The results show a Kappa coefficient of 0.73, indicating high simulation accuracy and that the PLUS model is effective for simulating land cover change in Shanxi Province and can be used to simulate future land use change conditions.

2.3 Model Accuracy Verification

To ensure simulation accuracy, the Kappa coefficient is used to determine the reliability of the PLUS model. By comparing simulation results with actual land use data (Figure 3), the Kappa coefficient is found to be 0.73, indicating high simulation accuracy and that the PLUS model is effective for simulating land cover change in Shanxi Province and can be used to simulate future land use change conditions.

3 Results and Analysis

3.1 Land Use Demand Prediction Under Multiple Scenarios

Under the baseline scenario, urbanization scenario, and ecological conservation scenario, the simulated land use area values for Shanxi Province in 2030 are input into the PLUS model. Forest land growth areas are 23.94 km^2, -4.67 km^2, and 468.59 km^2 respectively, accounting for approximately 5.38% of current total forest land area. Among them, the proportions of forest land and grassland area generally remain around 30%, while farmland area accounts for a relatively large proportion, basically maintained at around 23%. Additionally, internal conversion frequency within forest land is high. Compared with shrubland and open woodland, woodland is the only expanding type, indicating that woodland expansion possibility is higher. Grassland is the main object of conversion to woodland. Farmland loss area mainly converts to urban construction land, indicating that the contradiction between urbanization and farmland protection has become a potential hidden danger for Shanxi Province' s development.

Under the ecological conservation scenario, forest land is well protected. The total area of various forest types increases by approximately 468.59 km^2, accounting for 5.38% of current total forest land area. Woodland is the only expanding forest type, while the other three forest types have slight reductions. The main reason is enhanced conversion rates within forest land, with areas of shrubland, open woodland, and other woodland converting to woodland being 23.94 km^2, 1.74 km^2, and 0.37 km^2 respectively. The urbanization development scenario is an intensification of the baseline scenario, with construction land increasing significantly compared with the 2020 actual situation, increasing by 10.79 km^2. Except for shrubland, forest land generally shows varying degrees of degradation (Table 7).

3.2 Spatial Distribution Simulation of Land Use Under Multiple Scenarios

Forest land expansion areas under the three scenarios are mainly concentrated near the Changzhi Basin in the southeast of the study area, the Taiyuan Basin in the central-west, and the Datong Basin in the north. Woodland has a relatively larger expansion range, shrubland area generally remains unchanged, while open woodland expansion changes are more significant near the Heicha Mountain National Nature Reserve in the northwest and the Yuncheng Basin in the east. Other woodland area decreases slightly. Overall, woodland in the southeast shows large-scale contiguous expansion, followed by the central-west, while forest land distribution in the north shows fragmented characteristics. Affected by climate and terrain, the closer to the southern region, the greater the possibility of forest restoration and expansion (Figure 4).

Under ideal conditions (ecological conservation scenario), after multiple adjustments to relevant parameters, forest land area fluctuates around 468.59 km^2. We speculate this may be related to ecological environment and human activity factors in Shanxi Province, which constrain the potential for further forest development. We estimate that Shanxi Province' s total forest growth space is approximately 468.59 km^2, accounting for 5.38% of current total forest land area.

3.3 Analysis of Typical Areas for Forest Expansion

The ecological conservation scenario is the main reference for future forest restoration projects in Shanxi Province. By extracting more obvious forest expansion areas (Figure 5) and comparing them with forest changes under other scenarios, possible priority development areas for future forest expansion in Shanxi Province are defined (Figure 6), thereby improving the efficiency of afforestation activities and carbon sequestration levels in Shanxi Province. Additionally, due to the use of high-resolution remote sensing land use maps, identification of priority forest development areas can be precise to the county level, which is a main feature of this study.

Zone A is mainly located in the northern part of the study area, including Datong City and Shuozhou City. Forest land in this region shows fragmented distribution. From the perspective of forest stand changes, the area generally shows conversion from farmland to woodland, with relatively stable conversion of other woodlands. The expansion trend of woodland in this region is more obvious, and large areas of woodland growth appear in Shanyin County. Other counties also show varying degrees of forest growth, but relatively dispersed. Therefore, this region should improve the intensification and efficiency of afforestation.

Zone B is mainly distributed in the central-western part of the study area, involving Xinzhou City, Taiyuan City, and Lüliang area, where shrubland is dominant. Compared with other scenarios, woodland in Lan County shows a trend of contiguous growth, while Jiaocheng County, Wenshui County, and other areas are more suitable for shrubland growth. Under the ecological conservation scenario, small areas of woodland appear on the edges of Jiaocheng County, while some woodland degrades to open woodland. We speculate this may be because in this scenario, woodland neighborhood weights reach their peak, making forest conversion more likely. This also requires our attention, as there may be a possibility of forest degradation in this area in the future.

Zone C covers most of the southern part of Jincheng City, with a small portion in the southeast of Yuncheng City. This region is also a key area for the Yangcheng Manghe Rhesus Monkey National Nature Reserve and the Taikuanhe National Nature Reserve, so the overall ecological environment foundation is good. Woodland is mainly distributed in Lingchuan County, and internal conversion between different forest types is relatively stable. We speculate this may be related to the existing ecological environment foundation. Pingxiang County is more suitable for grassland growth, with stable grassland area across different scenarios, while forest expansion is slower. Large areas of woodland growth appear in Changzhi County and Huguan County. In other development scenarios, these two counties are mainly dominated by open woodland, but under the ecological conservation scenario, after adjusting forest parameters, large areas of woodland growth appear, indicating that conversion from open woodland to woodland is more obvious. The potential for woodland expansion in these areas is relatively large.

4 Discussion

4.1 On Afforestation and Forest Restoration

Forest restoration remains one of the most effective strategies for mitigating climate change. Different from traditional "ecological restoration," afforestation activities based on ecological security patterns emphasize "active adaptation" in governance and restoration [27]. The effectiveness of afforestation activities in arid regions, constrained by natural conditions, remains questionable [28-29]. Therefore, how to enhance the scientific nature and "active adaptation" of afforestation has become an important issue for ecological protection in Shanxi Province. The results show that Shanxi Province' s forest ecosystem does not appear to be very stable. Under ideal conditions (ecological conservation scenario), forest degradation has begun to appear at the edges of forests in some areas. If woodland neighborhood weight values are not adjusted, this situation may become more severe. Farmland remains the main land type in Shanxi Province, which poses a threat to constructing a stable forest ecosystem. The basic bottom line of farmland red lines must be considered. Under ideal conditions, Shanxi Province' s future afforestation development space is only 5.38%, but reality is often worse than ideal conditions. Under current climate and policy backgrounds, the potential for afforestation in Shanxi Province is questionable, and large-scale planting is not suitable at present. What can be solved currently is to further optimize forests within limited afforestation space.

Based on the results analysis, Zone A should be designated as a general area for forest expansion. The forest land boundary shape is relatively complex, fragmentation is severe, and frequent human activity interference may pose a threat of construction land expansion. In the new round of afforestation activities, it is necessary to comprehensively consider population, economy, and other social factors in these two areas to determine the elastic boundary of forest expansion in each region, and strengthen the planting of shrubland and grassland. Zone B currently has a large area of shrubland. Although there is potential for conversion from open woodland to woodland, from the perspective of adapting to local conditions, shrubland may be more suitable for the climate conditions of this region. Zone C should be designated as an extremely important area for forest expansion. It has good forest resource endowment and large development space for carbon storage. In temperate and subtropical forests, tree species diversity has a positive impact on carbon storage increase [30]. Therefore, forest expansion in Zone C should focus on enhancing tree species diversity.

4.2 Research Limitations

Finally, it should be noted that this study needs to be advanced in at least two aspects in the future: (1) Model aspect: Although the PLUS model can simulate land use changes under multiple scenarios, the Markov chain-based simulation of multiple development scenarios is somewhat subjective and does not adequately consider the actual economic development of the study area. Although land use change characteristics also have obvious Markov features, the PLUS model does not actually consider land demands from socio-economic development and different production sectors. Moreover, if land change speeds vary significantly in different periods, the prediction results will also have large differences. In many studies, scholars have used system dynamics models to infer land use scenarios under different development scenarios [31-32], which is more rigorous and provides a reference for further extension of this study. (2) Data aspect: Regarding indicator selection for the identification framework, many factors affect forest expansion, such as climate conditions and soil fertility [33-34], but currently there is no available high-precision spatial data for analysis.

5 Conclusion

This study discusses two key issues encountered in all afforestation planning stages: "Where are the suitable afforestation areas?" and "How to concentrate?" This study constructs an identification framework for priority forest development areas in Shanxi Province to analyze these issues, uses the PLUS model and Markov chain to systematically simulate land use changes under different scenarios in Shanxi Province in 2030, and defines potential priority areas for future forest expansion. The study draws the following conclusions: (1) Under current climate and policy conditions, Shanxi Province' s forest growth space in 2030 is very limited, only 5.38%. The main suitable forest areas are concentrated in the southeast, dominated by woodland expansion; followed by the central region, dominated by shrubland expansion, with forest edges facing the risk of woodland degradation; and finally the north, where based on the current severe forest fragmentation, future restoration should focus more on grassland expansion. (2) Internal forest conversion frequency is high. According to expansion potential, the order is: woodland > shrubland > open woodland > other woodland. (3) From the perspective of current development trends in Shanxi Province, land use patterns are unsustainable. We maintain a cautious attitude toward large-scale afforestation in Shanxi Province. Moreover, under the constraints of farmland protection red lines, implementing the ecological conservation scenario development model in Shanxi Province may face difficulties.

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