Formation Mechanisms and Remediation Techniques for Low-Efficiency Artificial Shelter Forests on the Chinese Loess Plateau (Postprint)

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Date: 2022-10-13T00:00:00+00:00

Abstract

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Full Text

Preamble

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Abstract: The construction of artificial shelter forests (ASFs) has generated substantial ecological, economic, and societal benefits for the Chinese Loess Plateau (CLP). However, the health and benefits of these forests are increasingly threatened by the formation of low-efficiency artificial shelter forests (LEASFs). This study systematically analyzes LEASFs on the CLP in terms of their status, formation mechanisms, and developmental obstacles, and summarizes key restoration techniques and schemes to improve their quality and efficiency. LEASFs arise through relatively complex mechanisms, primarily driven by poor habitat conditions, improper tree species selection, mismatch between stands and habitat, extensive forest management practices, and human interferences. The restoration and improvement of LEASFs are hindered by water deficits, stand-habitat mismatch, single-purpose management, and low efficiency. LEASFs are becoming more complex due to their extensive distribution, restoration challenges, and insufficient technological measures. Key techniques for improving LEASFs include basic forest tending methods, near-natural restoration, multifunction-oriented improvement, and systematic restoration. Understanding the formation mechanisms of LEASFs and adopting a scientific restoration approach are urgently needed and critical for ecological protection and high-quality development of ASFs on the CLP. Based on these analyses, we recommend strengthening monitoring and supervision of LEASFs, considering regional water resource carrying capacity, implementing multiple restoration techniques, promoting multifunction-oriented ecological development, and exploring new management concepts to achieve sustainable ASF development on the CLP.

Keywords: near-natural forestry; Three-North Shelter Forest; Chinese Loess Plateau; low-efficiency artificial shelter forests; restoration; forest management; multifunctional forestry

Citation: WANG Yaobin, SHANGGUAN Zhouping. 2022. Formation mechanisms and remediation techniques for low-efficiency artificial shelter forests on the Chinese Loess Plateau. Journal of Arid Land, 14(8): 837–848. https://doi.org/10.1007/s40333-022-0069-x

1 Introduction

The Chinese Loess Plateau (CLP), known as the birthplace of Chinese civilization (Zhu et al., 2018), is home to over 1.0$\times10^{8}$ people (Fu et al., 2017). The survival and well-being of these residents are closely linked to the health of the CLP's natural environment. Through implementation of national restoration programs (Wang et al., 2018), large areas of artificial shelter forests (ASFs) have been established on the CLP, serving as important ecological barriers (Zhu et al., 2004) that provide immense ecological, economic, and societal benefits to local communities (Xiao et al., 2019; Zhu and Zheng, 2019). Consequently, improving the quality and efficiency of ASFs has become a key issue for achieving ecologically sound development on the CLP.

To address long-standing problems such as low vegetation coverage, severe soil erosion, and ecosystem degradation, major projects including the "Three-North Shelter Forest," "Natural Forest Protection," and "Grain for Green" have been implemented (Liu et al., 2017; Wang et al., 2018). These initiatives have achieved remarkable outcomes, including effective ecological environment improvement (Jiao et al., 2005), continuous increases in forest coverage (Liu et al., 2017), significant reductions in soil erosion and Yellow River sediment transport (Wang et al., 2015), and substantial carbon emission reductions (Deng et al., 2014, 2019). However, these restoration projects have also created new challenges, particularly regarding ASFs. On one hand, expanding ASF areas has substantially reduced watershed runoff (Yu et al., 2009) and increased forest water consumption. On the other hand, large ASF areas exhibit growth problems such as poor stand stability (Hao, 2012), unsuitable forest structures, and lack of understory regeneration (Ahmad et al., 2018). Furthermore, large areas of inefficient or degraded forests—termed low-efficiency artificial shelter forests (LEASFs)—have emerged in recent years (Guo et al., 1998). These forests experience gradual but severe functional decline (Wang, 2010) due to poor ecological conditions, unscientific management practices, global climate change, and mature stand physiology (Guo et al., 1998).

LEASFs compromise the ecological restoration achievements of ASFs, threatening both human life and property protection and the goal of ecologically sound CLP development. Since 2015, China's National Forestry and Grassland Administration has conducted extensive work on LEASFs, including investigations of degraded shelter forest status, construction of experimental areas, and formulation of technical specifications for their transformation. Numerous related studies have examined concepts, definitions, formation mechanisms, and restoration techniques for LEASFs (Li et al., 2009; Liang, 2019; Bi and Hou, 2021). Improving the quality and efficiency of LEASFs has thus become an important component of forestry development and ecological construction on the CLP.

Systematic efforts based on LEASF experiences on the CLP are urgently needed to provide valuable theoretical support for future sustainable ASF development. This study systematically analyzes LEASFs on the CLP from the perspectives of formation mechanisms, current status, restoration advances, future challenges, and key restoration techniques or models. We also offer scientific recommendations for LEASF remediation and ASF improvement, providing scientific and technological support for ecological management and high-quality development of the CLP.

2 Influencing Factors and Formation Mechanisms of LEASFs on the CLP

LEASF formation on the CLP is driven by many interrelated factors (Zhu, 2013) that can be categorized into four groups: human interferences, habitat conditions, stand conditions, and disasters (Fig. 1 [Figure 1: see original paper]). These factors cause LEASFs with unbalanced structure and stability to enter recession stages prematurely or transition rapidly to recession, ultimately resulting in tree death, poor growth, and functional decline. Consequently, ASF functions such as carbon sequestration, windbreak, sand fixation, and water conservation deteriorate or cease altogether.

2.1 Poor Habitat Conditions, Improper Tree Species Selection, and Stand-Habitat Mismatch

Poor habitat conditions constitute a major factor in LEASF formation on the CLP. Plant survival and growth require essential resources including water, light, temperature, and nutrients. Soil nutrient conditions critically affect stand health, yet most protective forest plantations on the CLP occupy abandoned farmland or marginal lands with poor soil quality, making soil fertility deficiencies a significant challenge for healthy tree growth. Additionally, most ASFs are located in semi-arid regions receiving approximately 400 mm average annual precipitation. Insufficient water availability not only prevents natural regeneration (Zhu et al., 2006) but also stunts tree growth, creating "little old trees" (Jiang et al., 2006). Improper species selection further exacerbates LEASF formation. Approximately 40.00% of new arbor forests are distributed in Three-North Shelter Forest areas receiving less than 400 mm annual precipitation, with unhealthy forests accounting for 26.40% of total afforestation area in the project (Xiao et al., 2019; Zhu and Zheng, 2019). Planting afforestation species in climatically unsuitable conditions contributes to LEASF formation. For example, growth decline in poplar species—the main afforestation trees in early CLP forest management—is primarily caused by insufficient water supply in planting areas.

2.2 Extensive Forest Management and Frequent Human and Natural Interferences

Extensive forest management promotes LEASF formation through both afforestation techniques and forest tending. During initial project implementation on the CLP, most plantations were established at densities of 10,000 trees/hm^2 or 6,700 trees/hm^2. Such high stand density inevitably causes intense competition among adjacent trees for nutrients and growing space, strongly affecting forest growth and potentially causing degradation. Large areas of single-species, even-aged artificial forests exhibit low biodiversity and poor growth. Inappropriate post-afforestation management also affects forest health. In Wutai Mountain (Shanxi Province), extensive management has created large areas of low-functioning *Larix principis-rupprechtii* forests (Zhang et al., 2007).

Frequent extreme weather events—including high temperatures, drought, climate anomalies, and successive years of drought and precipitation—also harm vegetation restoration on the CLP (Wang et al., 2017; Sun et al., 2020). On windward slopes, frequent strong winds cause crown deviation, while cold, dry winter conditions can cause frostbite or freeze-induced tree mortality. Frequent logging, grazing, and land reclamation destroy the structure and nutrient status of protected forest lands, with severe soil erosion and nutrient loss representing main human-driven LEASF factors. Rodents and rabbits frequently damage *Pinus tabulaeformis*, *Larix gmelinii*, and *Pinus armandii* forests in Gansu Province, seriously harming forest growth.

2.3 Unreasonable Stand Structure and Physiological Maturity

Proper stand composition and structure are essential for forest function; improper composition and structure cause poor tree growth, insufficient benefits, and functional degradation, phenomena exacerbated by human and natural conditions (Jiang et al., 2006; Song et al., 2009). In the 1990s, second-generation forests in Ningxia Hui Autonomous Region were destroyed by cattle (National Forestry and Grassland Administration of China, 2017). Furthermore, almost all farmland shelterbelt species from the early Three-North Shelter Forest project consist of poplar trees, with scarce shrubs and herbaceous understory also contributing to low functional benefits.

Physiological maturity is the main reason for large-scale ASF degradation on the CLP. The Three-North Shelter Forest project began in 1978, with first-stage forests preserved for approximately 40 years and second-stage forests for over 25 years. In maturity or recession stages, stand quality and physiological functions decline rapidly. In northern Shanxi Province, large areas of *Populus simonii* forests have entered natural maturity periods (Yan et al., 2021). In the Three-North Shelter Forest area, shrub forests comprising 43.00% of the total have shorter growth cycles than tree-dominated forests, with 40% of farmland shelter forests requiring restoration (National Forestry and Grassland Administration of China, 2017). Unreasonable afforestation measures and unsuitable natural conditions can also accelerate ASF physiological maturity.

3 Achievements and Restoration Status of LEASFs on the CLP

LEASFs are widely distributed across large areas on the CLP, with complex formation mechanisms, multiple types, and increasingly difficult restoration. A survey by the National Forestry and Grassland Administration of China (2017) indicated that approximately 14.52% of shelter forests on the CLP were degraded (Fig. 2 [Figure 2: see original paper]). Shaanxi Province had the highest proportion of degraded forests at approximately 19.70% of the total degraded forest area on the CLP, while Inner Mongolia Autonomous Region had the largest degraded forest area at approximately 62.22$\times10$ˆ{4}$ hm^2. Qinghai Province showed the most extensive LEASF formation among degraded forests on the CLP (Fig. 2e). The areas of severely, moderately, and mildly degraded forests on the CLP were 65.09$\times10^{\{4\},\,79.09\times10}\{4\}, and 58.50\times10$ˆ{4}$ hm^2, respectively (Fig. 2e), accounting for 32.12%, 39.01%, and 28.88% of total forest area (Fig. 2a). Statistics show the five major causes of degraded forests on the CLP are physiological maturity, habitat conditions, tree species selection, disasters (diseases, pests, and rodents), and improper human interferences. Species selection and physiological maturity were the dominant factors, accounting for 28.17% and 28.03% of degradation, respectively (Fig. 2d), while improper human interferences accounted for the lowest proportion at 9.91% (Fig. 2d). Regarding main shelterbelt types, farmland shelterbelt forests covered 19.36$\times10$ˆ{4}$ hm^2, soil and water conservation forests covered 121.54$\times10$ˆ{4}$ hm^2, and windbreak and sand fixation forests covered 61.79$\times10$ˆ{4}$ hm^2 (Fig. 2c). Overall, forest degradation remains severe and varies considerably among CLP regions. In northern Shaanxi Province, 117.35$\times10$ˆ{4}$ hm^2 of young- and middle-aged plantations account for 54.80% of total plantation area (Yan et al., 2021). Substantial work remains to restore LEASFs on the CLP.

4.1 Water Resource Deficiency and Conflicts with Forestry Development

As ecological restoration advances, the antagonistic relationship between water supply and forest water consumption has become increasingly prominent. Poorly planned afforestation results in high water consumption that exceeds vegetation carrying capacity, causing water deficits and severe soil layer drying (Wang et al., 2012). Coordinating forest-water resource relationships has become a primary condition for CLP forestry development. Although precipitation on the CLP is low and unevenly distributed, it represents the only water source for plant growth. Consequently, under warming and drying climate trends, growing forests—especially those with high evapotranspiration rates—face difficulty meeting their water demands (Yang, 2018). Additionally, unreasonable allocation of water for domestic, production, and ecological purposes, plus unbalanced water use and distribution in river upper and lower reaches, further exacerbates water deficits for CLP forests.

4.2 Mismatch Between Stands and Habitat

Stand-habitat mismatch is particularly prominent on the CLP, gradually causing adverse consequences that hinder forestry development. This mismatch reduces stand growth and quality while limiting natural regeneration, resulting in inefficient or degraded stands. Undesirable distributions of trees, shrubs, and grasses also increase water consumption and cause soil degradation. Beyond violating plant geographical distribution laws, vegetation-microclimate mismatches occur. For example, early poplar species selection for Huajialing Mountain was unsuitable for high-altitude climates, where frequent windy conditions and poor soil quality are unsuitable for tree growth, causing low survival rates and large-scale growth recession.

4.3 Single Management Purpose and Insufficient Forest Benefits

Early CLP forest management initiatives established ASFs with single-purpose objectives of soil and water conservation, wind protection, or sand protection. This narrow focus on single ecological functions and goals challenges efforts to maximize forest benefits. Consequently, fast-growing species like poplar and locust were selected to pursue short-term benefits, and pure forests with high initial density were chosen over natural forest structures to maximize timber benefits, resulting in insufficient late-term development. The single development goal of large-scale ecological public welfare forests with low efficiency cannot meet current socioeconomic development and livelihood needs. Broadening industry perspectives and considering diverse economic, social, and other benefits have become key requirements for new-era forestry development.

5.1 Optimizing Stand Structure and Composition via Precise Implementation of Forest Tending Measures

Adopting appropriate forest tending measures for different LEASF types (by degradation degree, growth indicators, forest type, and influencing factors) is key to restoring and improving ecosystem functions and benefits. Six restoration types have been outlined for LEASFs: replacement restoration, selective cutting and replanting, tending restoration, gradual restoration, enclosed restoration, and comprehensive restoration. These reference measures have been flexibly applied according to habitat conditions (Zhang, 2017; Song, 2020; Yu et al., 2020). We recommend reforesting severely degraded forests, replanting moderately degraded forests, and applying appropriate pest control measures to mildly degraded forests.

5.2 Promoting "Near-Natural Forestry" Concepts

Natural restoration, artificial-assisted restoration, and ecological engineering represent three common traditional ecological restoration methods (Ren et al., 2019). The near-natural forestry (NNF) concept was initially proposed in Germany in the 19th century and rapidly expanded throughout Europe and the United States (Remeš, 2018). Studied and applied since the 1990s, NNF has become mainstream ideology in the new era (Shao, 1991; Liu et al., 1996; Zhang et al., 1996; Gao, 1999). Promoting NNF restoration techniques is crucial for LEASF restoration.

Nature-based solutions, consistent with NNF recovery concepts (He et al., 2020), focus on sustainable development to simultaneously meet human and natural environment goals (Mussinelli et al., 2018). NNF emphasizes forest ecosystem stability, biodiversity, multifunctionality, and buffering capacity based on natural processes. Main technical characteristics include selective cutting and natural regeneration, with forest structures that mimic natural forests through multispecies, multilevel, and different-aged compositions to create mixed forests for sustainable, efficient management. Lu et al. (2017) proposed a logical framework for near-natural restoration decision-making across four artificial forest types: broadleaf, coniferous, mixed coniferous-broadleaf, and even-aged coniferous forests. This approach understands and respects natural laws by prioritizing natural recovery supplemented with reasonable human intervention, achieving increased ecological functions and growth rates through continuous stand structure optimization. Wang et al. (2021) evaluated the near-natural state of five forest stands using 10 indicators related to stand structure, species composition, age, and dead wood, proposing remediation measures through combined qualitative and quantitative methods. He et al. (2020) identified seed multiplication, assembly, and supplementary sowing of native grassland species as bottlenecks in alpine grassland near-natural restoration, proposing that combined soil nutrient augmentation and microbial regulation are essential supplementary measures. Exploring inefficient or degraded forest remediation based on near-natural management theories is therefore highly significant.

5.3 Function-Oriented Restoration Under Multifunctional Forestry Concepts

Forest management objectives have gradually transitioned from single-objective to comprehensive consideration of forests' multidimensional functions and benefits. Based on near-natural management theory and approaches, multifunctional forestry management can meet social and economic development needs by balancing and improving various ecosystem products and services. Multifunctional forestry management operates at two scales: stand level and regional forest level. Developing multifunctional forestry at both stand (Ahmad et al., 2018) and regional scales (Wang et al., 2011) involves trade-off decision-making related to functions such as carbon fixation, oxygen release, water supply, and species protection (Carpentier et al., 2017; Strengbom et al., 2018). Overall optimization meets dominant function needs while considering other important functions (Wang et al., 2015). Balancing competing forest functions requires in-depth, quantitative understanding of potential ecosystem services and trade-offs supported by site conditions (Bennett et al., 2009; Dade et al., 2019; Resende et al., 2018). Forest structure adjustment is necessary to achieve multifunctional forestry management goals (Lu et al., 2017). Hao (2012) and Tian (2019) explored multifunctional forestry management decision-making using *Larix principis-rupprechtii* in the Liupan Mountains as a case study. Huang (2020) reported transitioning degraded poplar forests to *Rhus typhina* and *Forsythia suspensa* landscape forests and *Armeniaca vulgaris* economic forests in Yunzhou District, Datong City, Shanxi Province.

5.4 Application of Biological Regulation, Chemical Regulation, and Soil Dry Layer Regulation

Systematic restoration effectively realizes sustainable plantation development. Restoring LEASFs should consider soil ecosystem restoration through exogenous substance addition, biological regulation, and soil dry layer regulation. Soil nutrient conditions and forest health can be improved by enhancing soil physical and chemical properties. Nitrogen addition (Yu et al., 2010), biochar amendment, exogenous mycorrhizal fungus addition (Ren et al., 2014), and humic acid addition (Li et al., 2020) have improved forest soil conditions and promoted growth. Solving dry soil layer problems is crucial for stand transformation and functional improvement. Soil moisture can recover naturally to some extent (Wan et al., 2008), but this process is slow (Cheng et al., 2004). Fortunately, artificial recovery can accelerate soil moisture restoration. Soil water deficit regulation can be achieved by increasing water supply and reducing consumption through population density regulation, land-use change, plant replacement, and adjusting biological and physical coverage. Straw or grass mulching has effectively increased precipitation infiltration, reduced surface runoff, and inhibited soil moisture evaporation in farmland and economic forest applications (Huang et al., 2009; Cai et al., 2011), offering important references for forest ecological protection (Wang and Guo, 2020). Combining engineering land preparation measures with three-dimensional shrub-grass configurations can also regulate soil moisture and promote rapid shrub-grass vegetation restoration. Additionally, suitable understory planting and breeding industry development can promote nutrient cycling and improve site conditions.

6 Suggestions for Quality and Efficiency Improvement of LEASFs

Continuous advancement of ecological restoration projects has greatly improved vegetation coverage on the CLP, alleviating ecosystem degradation to some extent. However, reduced available land and increased risks of exceeding vegetation carrying capacity have become main obstacles for CLP ecological restoration (Wang et al., 2021). Optimizing existing LEASFs has now become the focus of CLP ecological construction projects. A framework diagram for LEASF quality and efficiency improvement on the CLP is shown in Figure 3 [Figure 3:

see original paper]. We propose suggestions for improving LEASF quality and efficiency in four categories.

6.1 Strengthening Monitoring and Supervision of LEASFs

Improving LEASF quality and efficiency on the CLP requires obtaining adequate, reliable basic data through field surveys and remote sensing monitoring to guarantee accurate scientific analysis and decision-making. We advocate: (1) formulating scientifically reasonable criteria and investigation methods for LEASFs under unified accreditation standards; (2) investigating background data of LEASFs across CLP regions, including low-efficiency function types, spatial distribution, main influencing factors, and degradation degrees; and (3) establishing representative long-term experimental plots to monitor LEASF restoration. Advanced techniques should monitor spatiotemporal LEASF variation to establish an air-space-ground coordinated monitoring network using multisource remote sensing, ecosystem observation stations, and field sampling surveys. This effort will solve current problems of insufficient and unreliable data, enabling real-time control of LEASF development trends and achieving accurate restoration and quality improvement.

6.2 Fully Considering Regional Water Resource Bearing Capacity

Water resource shortage is a common and major obstacle to high-quality ecological protection on the CLP. Vegetation restoration and ecological development face problems including soil moisture decline, deep soil dry layer formation, and excessive groundwater consumption. For reasonable water resource utilization, efforts should: (1) identify vegetation water resource carrying capacity in different regions; (2) clarify water cycling and consumption in different forest types; (3) reduce water resource wastage by optimizing stand structure and species composition; (4) fully utilize precipitation resources by building forest reservoirs and gully dams; and (5) explore trade-offs between vegetation water utilization and ecological protection functions. Overall, greater attention must be paid to water resource consumption for ecological restoration and regional water resource bearing capacity, exploring more techniques and methods to balance water utilization and ecological development.

6.3 Scientifically Implementing Forest Management Measures and Rehabilitation Techniques

Lack of necessary management has damaged growth and functions of some CLP forests, requiring evaluation of restoration techniques. We suggest: (1) increasing special fund investment in forest tending and management to strengthen LEASF quality and efficiency improvement efforts; (2) assessing effectiveness of existing restoration techniques and regional extension feasibility; (3) establishing rehabilitation demonstration plots in typical degraded areas to identify transformation techniques and development directions for different LEASF types; (4)

actively promoting "structure-based forest management" on the CLP; (5) establishing suitable local vegetation pools and cultivating good target tree species; and (6) replacing original species with native or suitable species and transforming pure forests into mixed forests. LEASFs can be restored through precise implementation of these forest tending measures.

6.4 Promoting Multifunctional-Oriented Construction and Coordinated Development of Service Benefits

To achieve high-quality, sustainable vegetation restoration on the CLP, we recommend: (1) fully assessing ASF carbon sequestration potential and value contribution to meet China's emission peak and carbon neutrality goals; (2) fully considering other ecological regulation services (economic product supply, ecotourism value, forest health care) during restoration; (3) balancing ecological, social, and economic benefits during forest development; (4) adopting near-natural forestry and multifunctional-oriented management during LEASF quality and efficiency improvement; and (5) exploring new multi-investment and multi-operation mechanisms for ecological projects with government-led social participation and multiple societal inputs. In summary, we hope these efforts will achieve high-quality LEASF development on the CLP and coordinate ecological protection with economic development.

7 Conclusions

This study identifies complex formation mechanisms of LEASFs on the CLP, including poor habitat conditions, improper species selection, stand-habitat mismatch, extensive management practices, and human interferences. Water deficits, stand-habitat mismatch, single-purpose management, and low efficiency constitute main obstacles for current and future LEASF restoration and improvement. Given the increasingly complex status and restoration challenges of LEASFs, we identify basic forest tending methods, near-natural restoration, multifunction-oriented improvement, and systematic restoration as key restoration techniques. Finally, to optimize existing LEASFs and prevent new ones from forming, future work must strengthen LEASF monitoring and supervision, consider regional water resource bearing capacity, scientifically implement forest management measures and rehabilitation techniques, and promote multifunctional-oriented forest development.

Acknowledgements This work was supported by the Science and Technology Innovation Program of the Shaanxi Academy of Forestry (SXLK2022-02), the National Natural Science Foundation of China (42077452), and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA23070201).

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Note: Figure translations are in progress. See original paper for figures.