Vegetation Characteristics of Herbaceous Communities on Highway Slopes in the Loess Plateau and Their Relationships with Soil: Postprint

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Abstract

This study investigated the vegetation characteristics and species diversity of herbaceous communities established by hydroseeding mixed grass species on highway slopes in the Loess Plateau, and explored the relationships between herbaceous community characteristics, species diversity, and soil physicochemical properties. Using a space-for-time approach, we examined the characteristics of herbaceous communities, alpha species diversity, and their correlations with soil physicochemical properties via Mantel test on highway slopes in the Loess Plateau restored for 15, 12, 8, 4, and 2 years. On slopes restored for 15 years, a total of 8 families, 13 genera, and 13 species were recorded; for 12 years, 7 families, 10 genera, and 10 species; for 8 years, 3 families, 5 genera, and 5 species; for 4 years, 3 families, 5 genera, and 5 species; and for 2 years, 4 families, 6 genera, and 6 species. Patrick species richness followed the order: 15 years > 12 years > 8 years > 2 years > 4 years; Shannon-Wiener index and Simpson index followed: 15 years > 12 years > 2 years > 8 years > 4 years; Pielou evenness index followed: 15 years > 2 years > 8 years > 12 years > 4 years. Patrick species richness showed significant positive correlations with total porosity, capillary porosity, organic matter, total nitrogen, and total phosphorus ($P<0.05$), while Shannon-Wiener index showed significant positive correlations with organic matter and total phosphorus ($P<0.05$). After hydroseeding mixed grass species for different durations, the herbaceous communities were predominantly composed of perennial herbaceous plants, but differed in species composition and quantity. Patrick species richness, Shannon-Wiener index, and Simpson index exhibited an increasing trend with restoration age. Total porosity, capillary porosity, organic matter, total nitrogen, and total phosphorus were key environmental factors influencing Patrick species richness and Shannon-Wiener index.

Full Text

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Abstract

This study investigated the vegetation characteristics and species diversity of herbaceous communities established by hydroseeding mixed grass species on highway slopes in the Loess Plateau across different restoration years, and explored the relationships among community characteristics, species diversity, and soil physicochemical properties. Using a space-for-time substitution approach, we examined herb community characteristics, α-species diversity, and their correlations with soil physicochemical properties on highway slopes of the Loess Plateau after 15, 12, 8, 4, and 2 years of restoration. The survey revealed 13 species from 13 genera across 8 families in the 15-year restoration sites, 10 species from 10 genera across 7 families in the 12-year sites, 5 species from 5 genera across 3 families in both the 8-year and 4-year sites, and 6 species from 6 genera across 4 families in the 2-year sites. Patric species richness recovered in the order 15 a > 12 a > 8 a > 2 a > 4 a, while Shannon-Wiener and Simpson indices recovered in the order 15 a > 12 a > 2 a > 8 a > 4 a, and the Pielou evenness index recovered in the order 15 a > 2 a > 8 a > 12 a > 4 a. Patric species richness showed significant positive correlations with total porosity, capillary porosity, organic matter, total nitrogen, and total phosphorus ($P < 0.05$). The Shannon-Wiener index was significantly positively correlated with organic matter and total phosphorus ($P < 0.05$). After hydroseeding mixed grass species at different times, the herbaceous communities were predominantly composed of perennial herbs, though differences existed in species composition and abundance. Species richness, Shannon-Wiener index, and Simpson index exhibited upward trends with increasing restoration years. Soil total porosity, capillary porosity, organic matter, total nitrogen, and total phosphorus were identified as the key environmental factors influencing Patric species richness and the Shannon-Wiener index.

Keywords: Loess Plateau highway slope; herbaceous community; vegetation characteristics; soil

Introduction

The Loess Plateau region experiences chronic aridity and prominent water-heat contradictions. Combined with long-term human disturbance, this has caused severe soil erosion and water loss, declining vegetation ecological functions, and made it one of China's most ecologically fragile regions. In recent years, natural and anthropogenic activities including geological disasters, engineering construction, mineral resource extraction, and highway and railway construction have caused landslides, collapses, or cutting of rock and soil masses, forming unstable steep slopes that destroy vegetation, intensify soil loss, reduce soil organic matter, trigger retrogressive succession, and cause serious declines in ecological function.

Vegetation and soil represent the two most important subsystems of terrestrial ecosystems and play critical roles in the restoration and reconstruction of fragile ecosystems. The relationship between plants and soil has long been a research focus in ecology. Plant-soil interactions constitute a primary mechanism shaping plant community patterns, often accompanied by changes in community type, species diversity, and soil nutrient cycling. Plants are vital components of terrestrial ecosystems, particularly in fragile ecological zones. In arid and semi-arid desert ecosystems, most herbaceous plants possess well-developed, interwoven root systems with characteristics such as drought tolerance, salinity-alkalinity resistance, wind fixation, sand stabilization, and adaptation to adverse conditions, playing essential roles in maintaining ecological balance, preventing desertification, reducing surface runoff, and promoting degraded grassland recovery. Zuo Xiao'an et al. found that annual and biennial herbs in degraded sandy grasslands play a dominant role in maintaining community and ecosystem stability and function. Xu Wenwen et al. suggested that herbs constitute a large proportion of desert vegetation primarily due to their strong adaptability, rapid growth, and low resource requirements, with annual herbs particularly capable of completing their brief life cycles using limited precipitation in desert areas. Qiao Jingjuan et al. demonstrated that desert steppe herb communities respond and adapt to nutrient addition and disturbance through changes in dominant species and key functional traits. Fang Zhao et al. found significant correlations between herbaceous community belowground biomass and mean annual precipitation, mean annual temperature, soil organic carbon, total nitrogen, and total phosphorus content. Evidently, herbaceous plants and soil in arid and semi-arid fragile ecosystems exhibit mutual feedback mechanisms that promote community succession and improve regional ecological benefits.

However, few studies have examined the vegetation characteristics of herbaceous communities on highway slopes in the Loess Plateau and their relationship with soil. This research focuses on exposed highway slopes on the north and south mountains of Lanzhou City, analyzing vegetation characteristics and species diversity of herbaceous communities hydroseeded with mixed grass species at different times, exploring relationships among community characteristics, species diversity, and soil properties, and revealing vegetation-soil feedback

mechanisms. These findings are significant for enhancing ecological restoration capacity on steep slopes, strengthening ecosystem stability, and reducing soil erosion.

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1. Materials and Methods

1.1 Study Area Overview The study area is located along the north and south mountain highways of Lanzhou City, Gansu Province (103°21 04 – 104°0 38 E, 35°53 18 –36°33 56 N). The region has an arid climate, classified as a mid-temperate semi-arid temperate grassland climate zone within the warm temperate climate belt. The mean annual temperature is 9.1°C, the frost-free period is 180 days, mean annual precipitation is 327.7 mm, average elevation ranges from 1520–1580 m, and average slopes exceed 600 m with a relative relief of approximately 200 m. The soil is predominantly sierozem. After highway construction, the resulting slopes had sparse natural vegetation. Local ecological departments used ecological slope protection technology to hydroseed mixed grass species in 2008, 2011, 2015, 2017, and 2021. Currently, herbaceous communities on the slopes are dominated by *Medicago sativa* (alfalfa), *Agropyron cristatum* (crested wheatgrass), and *Melica przewalskyi* (Gansu melic grass).

1.2 Sample Plot Setup and Vegetation Survey In July 2023, after comprehensive field reconnaissance, we established survey plots on steep slopes along the north and south mountain highways of Lanzhou that had been hydroseeded with mixed grass species at different times. Plots were established for vegetation restored for 2, 4, 8, 12, and 15 years, with three 10 m × 10 m plots per restoration age. Within each plot, three 1 m × 1 m herb quadrats were established to measure plant species, individual numbers, average height, and coverage. Basic plot information is shown in .

1.3 Soil Survey and Measurement In each plot, three soil profiles were excavated along an "S" pattern. Undisturbed soil samples were collected from the 0–20 cm layer to determine soil water-physical properties. Soil cores were collected using an auger at the same depth, with repeated sampling. After removing stones and litter, soil samples from the same depth were thoroughly mixed, air-dried in the laboratory, and passed through a 0.1 mm sieve for analysis.

Soil measurements included: - Soil mass water content by oven-drying method (105°C) - Soil bulk density and porosity by ring knife method - Soil compaction by soil compaction meter - Soil organic matter by potassium dichromate volumetric method - Soil alkaline hydrolyzable nitrogen by alkali diffusion method - Soil available phosphorus by 0.5 $\mathrm{mol \cdot L^{-1}}$ sodium bicarbonate extraction with molybdenum-antimony-scandium colorimetry - Soil available potassium by atomic absorption flame photometry - Soil total nitrogen by semi-micro Kjeldahl

method - Soil total phosphorus by molybdenum-antimony-scandium colorimetry - Soil total potassium by atomic absorption flame photometry

Specific procedures followed standard references. Soil physicochemical properties are characterized in .

1.4 Data Statistical Processing Basic data were organized using Excel 2019. Calculations of species diversity, correlation analysis, and graphing were performed in R 4.3.1.

1.4.1 Basic Characteristics of Herbaceous Communities Based on family, genus, and species characteristics of herbaceous communities at different restoration years, we created diagrams showing the number of species per family for each community.

1.4.2 α-Species Diversity Measurement Analysis We selected Patric species richness (N_0), Shannon-Wiener index (H), Simpson index (D), and Pielou evenness index (J) to measure species richness, distribution, dominance, and diversity. One-way ANOVA was used to analyze differences in species diversity among slopes of different ages, with Duncan's multiple comparison test for mean values. Calculations were completed using the vegan package in R.

The formulas are: - **Patric species richness (N_0):** $N_0 = S$ (where S is the number of species) - **Shannon-Wiener index (H):** H = - P ln P (where P is the relative frequency of each species, P = N /N, with N being the number of individuals of species i and N being the total number of individuals of all species) - **Simpson index (D):** D = 1 - P^2 - **Pielou evenness index (J):** J = H /H = H /ln S

1.4.3 Relationship Between Herbaceous Community α-Species Diversity and Soil Physicochemical Properties The Mantel test examines correlations between two distance matrices from the same sample, assuming matrix independence and linear correlation. Based on α-species diversity indices and soil physicochemical data, we used Mantel test correlation analysis to investigate relationships between slope herbaceous community restoration succession and soil physicochemical properties. Calculations were completed using the vegan package in R.

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2. Results

2.1 Basic Characteristics of Herbaceous Communities The survey found that after hydroseeding mixed grass species at different times, herbaceous communities on the slopes were predominantly composed of perennial herbs, though community species composition and abundance differed (Table 3). The 15-year restoration community contained 13 plant species, with Poaceae

(Gramineae), Asteraceae, and Convolvulaceae having the most species (4, 3, and 2 species respectively), while Apiaceae and Amaranthaceae each had only 1 species. The 12-year community had 10 species, with Poaceae and Asteraceae having the most species (3 and 2 species respectively), while Convolvulaceae had 2 species and the remaining families each had 1 species. The 8-year community contained 5 species, with Poaceae having the most (3 species), while Fabaceae and Asteraceae each had only 1 species. The 4-year community had 5 species, with Poaceae and Asteraceae having the most species (2 each), while Fabaceae had only 1 species. The 2-year community contained 6 species, with Poaceae having the most (3 species), while Asteraceae, Fabaceae, and Amaranthaceae each had only 1 species.

2.2 α-Species Diversity Differences Analysis As shown in Figure 2, one-way ANOVA of α-species diversity indices for herbaceous communities across restoration years revealed significant differences in Patric species richness, Shannon-Wiener index, and Simpson index among communities ($P < 0.001$). Patric species richness recovered in the order: 15 a > 12 a > 8 a > 2 a > 4 a, with significant differences between the 15-year community and the 12-year, 8-year, 4-year, and 2-year communities ($P < 0.001$), but no significant difference between the 12-year and 8-year communities ($P \geq 0.05$). The Shannon-Wiener index recovered in the order: 15 a > 12 a > 2 a > 8 a > 4 a, with significant differences between the 15-year community and the 12-year, 8-year, 4-year, and 2-year communities ($P < 0.001$), but no significant difference between the 12-year and 2-year communities ($P \geq 0.05$). The Simpson index recovered in the order: 15 a > 12 a > 2 a > 8 a > 4 a, with significant differences between the 15-year community and the 12-year, 8-year, 4-year, and 2-year communities ($P < 0.001$), but no significant difference between the 12-year and 2-year communities ($P \geq 0.05$). The Pielou evenness index recovered in the order: 15 a > 2 a > 8 a > 12 a > 4 a, with no significant differences between the 15-year and 2-year communities ($P \geq 0.05$), but significant differences between the 15-year community and the 12-year, 8-year, and 4-year communities ($P < 0.001$).

2.3 Relationship Between Herbaceous Community α-Species Diversity and Soil Physicochemical Properties We used Mantel test to explore correlations between α-species diversity and soil physicochemical properties during slope vegetation restoration succession (Figure 3). Regarding physical properties, Patric species richness showed significant positive correlations with total porosity and capillary porosity ($P < 0.05$), but no significant relationships with water content, bulk density, non-capillary porosity, or compaction ($P \geq 0.05$). Shannon-Wiener, Simpson, and Pielou indices showed no significant relationships with soil physical properties ($P \geq 0.05$).

Regarding chemical properties, Patric species richness showed significant positive correlations with organic matter, total nitrogen, and total phosphorus ($P < 0.05$), but no significant relationships with total potassium, available phospho-

rus, available potassium, nitrate nitrogen, or ammonium nitrogen ($P \geq 0.05$). The Shannon-Wiener index showed significant positive correlations with organic matter and total phosphorus ($P < 0.05$), but no significant relationships with total nitrogen, total potassium, available phosphorus, available potassium, nitrate nitrogen, or ammonium nitrogen ($P \geq 0.05$). Simpson and Pielou indices showed no significant relationships with soil chemical properties ($P \geq 0.05$).

3. Discussion

When vegetation is completely destroyed in an area, natural succession generally progresses from herbaceous communities to shrubs or trees. However, due to harsh conditions including climate, soil, water, and slope, climax communities often become dominated by perennial herbs. Highway slopes are steep with poor soil and limited water. After hydroseeding mixed grass species, communities remained dominated by herbs after different restoration years (2–15 a). Plant family, genus, and species numbers initially decreased then increased with restoration age, likely because hydroseeding allowed most grasses to survive initially, but as succession proceeded with reduced human intervention, limited soil moisture and nutrients intensified competition. Some plants released allelochemicals inhibiting others, eliminating less adaptable species. As succession continued and soil properties improved, herbaceous plants gradually increased.

α-species diversity reflects plant community diversity at the species level and serves as an important indicator of community dynamics, species composition, structure, and functional complexity and stability. In this study, as slope herbaceous community succession progressed, Patric species richness, Shannon-Wiener index, and Simpson index all increased with restoration years, indicating increasingly complex species composition and structure, greater community dominance, and stronger stress resistance. This aligns with Lu Zhaohua et al.'s research on slope vegetation restoration community stability. The primary reason is that highway slopes are anthropogenically formed with initially infertile soils unsuitable for plant survival. However, hydroseeding legumes like alfalfa fixed soil nitrogen, while grasses like crested wheatgrass improved soil physical and chemical properties through their root systems, facilitating colonization by other species and gradual community stabilization shifting from structural to functional stability.

The Pielou evenness index showed no significant differences among most restoration years except between the 15-year and 2-year communities, indicating minimal impact on species distribution uniformity. This may occur because herb seeds are easily dispersed by wind and insects, resulting in relatively uniform seed distribution across the study area.

Soil physicochemical properties significantly influence plant species diversity. He Jinsheng et al. suggested that better soil fertility conditions support higher species diversity. Li Xinrong et al. and Hu Chanjuan et al. found that species di-

versity increases with restoration age as soil fertility improves on disturbed sites. In this study, soil physicochemical properties significantly affected herbaceous community α-species diversity, corresponding to increased species richness and community diversity with restoration years. This demonstrates that vegetation succession involves changes in soil physical and chemical properties, which in turn promote increased plant community species diversity. Wen Jiwen et al. proposed that vegetation succession is often influenced by one or more key environmental factors while showing weaker correlations with others. Our results align with this: total porosity and capillary porosity had the greatest influence on Patric species richness among physical properties, while organic matter, total nitrogen, and total phosphorus most strongly affected Patric species richness and Shannon-Wiener index among chemical properties. Although some Mantel test correlations were non-significant, correlation coefficients were relatively large.

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4. Conclusion

After hydroseeding mixed grass species on Loess Plateau highway slopes at different times, herbaceous communities were predominantly composed of perennial herbs, with differences in species composition and abundance across restoration years. Patric species richness, Shannon-Wiener index, and Simpson index increased with restoration years, while Pielou evenness index showed minimal variation. Soil total porosity, capillary porosity, organic matter, total nitrogen, and total phosphorus were the key environmental factors influencing Patric species richness and Shannon-Wiener index, while other physicochemical properties had non-significant effects on species diversity.

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