Postprint: Plant Community Succession and Species Diversity During Gangue Remediation in Shuanglonggou

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Abstract

To investigate plant community succession and species diversity during coal gangue reclamation, this study employed the space-for-time substitution method, selecting coal gangue sites under reclamation for different durations (2 years, 5 years, 10 years) and unreclaimed coal gangue as control (CK) plots in Shuanglonggou, Tianzhu Tibetan Autonomous County, Gansu Province. Through vegetation surveys, we analyzed the characteristics of plant community succession and species diversity, and revealed their changing patterns with increasing reclamation duration, providing a scientific theoretical basis for coal gangue reclamation, ecosystem restoration, and ecological environment construction in Shuanglonggou of the eastern Qilian Mountains and similar regions. The results showed that: (1) During the coal gangue reclamation process in Shuanglonggou, a total of 55 plant species belonging to 40 genera and 24 families were recorded across the four plots, among which 15 families were monotypic (single family, single genus, and single species). The species count of Asteraceae, Poaceae, and Rosaceae reached 28, accounting for 12.5% of the total families and 50.91% of the total species. The species composition was characterized by: most species belonging to a few families, with the majority of plant species being monotypic. (2) With increasing reclamation duration, the community dominant species gradually shifted from annual or perennial herbaceous plants to perennial herbaceous plants and shrubs. The number of plant species increased from 11 in the control (CK) to 28 at 5 years of reclamation, then decreased to 18 at 10 years of reclamation. Finally, Elymus nutans, Poa annua, and Hippophae rhamnoides became the dominant species in the plot, with the sum of importance values of these three plants reaching 48.107. (3) With increasing reclamation duration, species number, Shannon diversity index, and Margalef richness index gradually increased from CK to

5 years of reclamation, reaching maximum values of 28, 3.506, and 2.877, respectively. The Pielou evenness index exhibited a “decrease-increase-decrease” trend with minor fluctuations. The Simpson dominance index showed an “increase-decrease-increase” trend, reaching a maximum value of 0.359 at 10 years of reclamation. (4) Reclamation duration had significant effects on plant population quantitative characteristics. Plant height increased significantly from CK to 2 years and to 10 years ($P<0.05$), coverage increased significantly from CK to 5 years and 10 years of reclamation ($P<0.05$), and plant individual number increased significantly from CK to 10 years of reclamation ($P<0.05$). In summary, during the coal gangue reclamation process in Shuanglonggou of the eastern Qilian Mountains, reclamation duration had significant effects on vegetation succession and species diversity under artificial intervention, with plant communities gradually becoming simpler and more stable.

Full Text

Abstract

To investigate plant community succession and species diversity during gangue treatment processes, this study employed a space-for-time substitution approach in Shuanglonggou, Tianzhu Tibetan Autonomous County, Gansu Province. Sample plots representing different gangue treatment durations (2, 5, and 10 years) and an untreated control (CK) were established to analyze vegetation community succession characteristics and species diversity patterns. The results revealed several key findings. First, a total of 55 plant species belonging to 40 genera and 24 families were identified across all sample plots. Among these, 15 families were represented by single families, single genera, and single species. The Asteraceae, Poaceae, and Rosaceae families collectively contained 28 species, accounting for 12.5% of total families and 50.91% of total species, demonstrating that most species belonged to a few families while most families contained single species. Second, as treatment duration increased, community dominant species gradually shifted from annual or perennial herbs to perennial herbs and shrubs. Species richness increased from 11 species in the control plot to 28 species after 5 years of treatment, then decreased to 18 species after 10 years. Ultimately, *Elymus nutans*, *Poa annua*, and *Hippophae rhamnoides* became the dominant species, with their combined importance values reaching 48.107. Third, species number, Shannon diversity index, and Margalef richness index increased progressively from CK to 5 years of treatment, reaching maximum values of 28, 3.506, and 2.877, respectively. The Pielou evenness index exhibited a “decrease-increase-decrease” pattern with relatively small overall variation, while the Simpson dominance index showed an “increase-decrease-increase” trend, peaking at 0.359 after 10 years of treatment. Fourth, treatment duration significantly affected plant population quantitative characteristics, with plant height, coverage, and density all showing significant increasing trends ($P < 0.05$). In conclusion, under artificial intervention, gangue treatment duration significantly influences vegetation succession and species diversity in

Shuanglonggou of the eastern Qilian Mountains, with plant communities gradually becoming simpler and more stable.

Keywords: Shuanglonggou; gangue treatment; plant community succession; importance value; species diversity

Introduction

The Qilian Mountains constitute a critical ecological barrier and water source conservation area in western China. The region's alpine ecosystems harbor some of the most concentrated and diverse species richness in high-altitude ecosystems. The eastern Qilian Mountains, particularly Shuanglonggou, were historically covered by extensive meadow steppe and secondary shrublands that contributed significantly to ecosystem stability and security. However, intensive mining activities have severely damaged riverbeds, destroyed surrounding forest and grassland vegetation, reduced water conservation capacity, degraded ecological functions, diminished species diversity, and compromised ecosystem stability. The substantial gangue produced by mining operations has caused particularly severe ecological damage, inhibiting plant growth and triggering soil contamination and erosion.

Vegetation restoration directly influences biogeochemical cycling in damaged ecosystems and effectively reduces soil bulk density, improves soil porosity, increases soil fertility, and alters spatial heterogeneity, thereby ameliorating soil physicochemical properties. As a primary measure for gangue ecological restoration and soil environment improvement, vegetation restoration has been widely applied in gangue hill soil quality improvement and has become an important research direction in abandoned mine ecological reconstruction. Previous studies have demonstrated the critical importance of vegetation recovery for open-pit mine ecosystem restoration, with key technologies including plant species selection, seedling planting, community construction, and vegetation maintenance. Species diversity serves as an objective indicator of biological resource richness within a given area, reflecting the complexity of community internal structure and spatial distribution patterns. Consequently, research on plant community succession and species diversity holds profound significance for gangue hill ecological restoration and mining area environmental protection.

While numerous studies have examined Qilian Mountain vegetation in relation to soil physicochemical properties, microbial characteristics, climatic factors, and geographic location, research on plant community succession and species diversity during gangue treatment in Shuanglonggou remains limited. This study investigated typical vegetation types in Shuanglonggou using space-for-time substitution methods to examine changes in plant community succession and species diversity across different treatment durations (0, 2, 5, and 10 years). The objectives were to elucidate the patterns of vegetation community succession and species diversity during gangue treatment and provide scientific theoretical foundations and technical support for ecosystem restoration in this region and

similar areas.

1.1 Study Area Overview

The study area is located in Shuanglonggou, Haxi Town, Tianzhu Tibetan Autonomous County, Wuwei City, Gansu Province [Figure 1: see original paper]. The region has experienced frequent anthropogenic mining activities, resulting in severe vegetation and landform destruction, reduced water conservation capacity, and diminished ecological service functions. Over the past two decades, the Shuanglonggou mining area has implemented multiple restoration projects, primarily involving backfilling of mining pits and trenches, stabilization of sand piles, river channel regulation, and artificial restoration through planting *Hippophae rhamnoides* and *Elymus nutans*. The relocation of most herders has provided ideal conditions for studying the effects of gangue treatment duration on plant community succession and species diversity.

The study area features a south-high, north-low topography with crisscrossing gullies, situated at 37°18 –37°25 N, 102°17 –102°33 E, with elevations ranging from 2400 to 4800 m. The western and southern parts border Qinghai Province. The region has a mean annual temperature of 3.3°C, $ $10°C accumulated temperature of 108°C, average annual sunshine of 2547 hours, average frost-free period of 128 days, mean annual precipitation of 400 mm (concentrated in July–September), mean annual evaporation of 1677 mm, and average relative humidity of 52.7%. During the Late Pleistocene and early Holocene, glacial meltwater and complex chemical reactions formed typical ice-water accumulation-terrace type placer gold deposits in the Shuanglonggou watershed, yielding abundant mineral resources including placer gold, copper, iron, and coal.

The watershed contains 2486.1 hm^2 of forest land, 245 hm^2 of sparse forest land, 537.5 hm^2 of shrubland, 4445.1 hm^2 of grassland, and 24.4 hm^2 of water bodies. Vegetation is dominated by forests and grasslands, with *Picea crassifolia* as the constructive tree species, mixed with small amounts of *Sabina przewalskii*, *Betula albosinensis*, and *Populus davidiana*. Shrubs are dominated by *Salix cupularis*, *Rhododendron simsii*, and *Caragana sinica*, while artificial forests consist mainly of *Hippophae rhamnoides*, *Potentilla fruticosa*, and *Potentilla glabra*. Herbaceous species are dominated by *Elymus nutans*, *Potentilla anserina*, *Potentilla multicaulis*, *Plantago asiatica*, and *Carex licum*.

1.2 Sample Plot Establishment and Vegetation Survey

Field investigations were conducted from July to August 2021. Using the space-for-time substitution method, we selected sample plots within contiguous gangue treatment areas with similar natural environments, minimal microtopographic variation, and uniform plant growth. Treatment durations of 2, 5, and 10 years were selected, with untreated gangue serving as control (CK). Following the methods of Ren Jizhou (1998), three 10 m × 10 m quadrats were established in each plot to measure shrub species composition, species number, height, cov-

erage, and crown width. Additionally, three 1 m × 1 m sub-quadrats were established diagonally within each large quadrat to measure herbaceous species composition, species number, height, and coverage. GPS was used for positioning, and detailed records were made of community dominant species, geographic coordinates, and elevation .

1.3 Calculation Methods

1.3.1 Important Value Calculation Based on surveyed community characteristic data, the important value (IV) of each species in each plot was calculated to determine community composition and dominant species:

$$\mathrm{IV} = (\mathrm{RH} + \mathrm{RC} + \mathrm{RF}) \times 100\%$$

where RH is relative height, RC is relative coverage, and RF is relative frequency, calculated as:

$$\mathrm{RH} = \left(\frac{\text{Height of species } i}{\text{Total height of all species}} \right) \times 100\%$$

$$\mathrm{RC} = \left(\frac{\text{Coverage of species } i}{\text{Total coverage of all species}} \right) \times 100\%$$

$$\mathrm{RF} = \left(\frac{\text{Frequency of species } i}{\text{Total frequency of all species}} \right) \times 100\%$$

1.3.2 Diversity Index Calculation The following diversity indices were used to measure plant communities across different treatment durations:

Shannon diversity index:

$$H = -\sum_{i=1}^{S} P_i \ln P_i$$

Simpson dominance index:

$$C = \frac{\sum_{i=1}^{S} N_i(N_i - 1)}{N(N-1)}$$

Pielou evenness index:

$$E = \frac{H}{\ln S}$$

Margalef richness index:

$$D_{\mathrm{MG}} = \frac{S-1}{\ln N}$$

where P_i is the relative frequency of species i, N_i is the individual count of species i, S is the number of species, and N is the total individual count of all species.

1.4 Data Processing and Analysis

Experimental data were first organized using Excel 2013. Statistical analyses were performed using SPSS 18.0. One-way ANOVA was used to test for significant differences in plant population quantitative characteristics among different treatment durations, with significance set at $P < 0.05$.

Results and Analysis

2.1 Plant Community Species Composition

During the gangue treatment process in Shuanglonggou, 55 plant species were identified across all sample plots, distributed among 24 families and 40 genera . The species composition revealed that most species belonged to a few families while most families contained single species. Specifically, 15 families (62.5% of total families) were single families with single genera and single species. The Asteraceae, Poaceae, and Rosaceae families contained 28 species, representing 50.91% of total species while comprising only 12.5% of total families. Other families including Ranunculaceae, Caryophyllaceae, Primulaceae, Amaranthaceae, Plantaginaceae, Mazaceae, Brassicaceae, Plumbaginaceae, Lamiaceae, Cyperaceae, Onagraceae, Rubiaceae, Orobanchaceae, Geraniaceae, Gentianaceae, Papaveraceae, Polygonaceae, Elaeagnaceae, Salicaceae, Caprifoliaceae, and Iridaceae collectively accounted for 14.55% of total species.

2.2 Effects of Treatment Duration on Species Importance Values

Comprehensive analysis of species composition and importance values across different treatment durations revealed distinct patterns . In the untreated control (CK), 11 species were present, dominated by annual or perennial herbs including *Artemisia hedinii*, *Crepis rigescens*, *Ranunculus tanguticus*, *Saussurea japonica*, and *Elymus nutans* with importance values of 0.238, 0.134, 0.098, 0.089, and 0.087, respectively. After 2 years of treatment, species richness doubled to 22, with herbaceous species increasing by 8 and shrub species by 3. The importance values of *Artemisia hedinii*, *Crepis rigescens*, and *Ranunculus tanguticus* decreased by 4.1, 2.6, and 2.2 times, respectively, while *Artemisia hedinii*, *Androsace mariae*, *Potentilla chinensis*, and *Microgynoecium tibeticum* disappeared entirely. Concurrently, artificially planted *Elymus nutans*, *Potentilla anserina*, and *Hippophae rhamnoides* emerged as new dominants with importance values of 0.112, 0.089, and 0.087, respectively.

After 5 years of treatment, species richness reached 28, with most being newly emerged herbaceous species. Shrub species *Hippophae rhamnoides* and *Comarum salesovianum* showed increased importance values of 0.184 and 0.087,

respectively, while *Potentilla glabra* reached its maximum importance value of 0.204. The liana *Clematis tangutica* appeared for the first time with a high importance value of 0.092. After 10 years of treatment, species richness decreased to 18, with herbaceous species declining to 13. The community became dominated by *Poa annua*, *Elymus nutans*, and *Hippophae rhamnoides* with importance values of 0.184, 0.179, and 0.148, respectively. The combined importance value of these three species reached 48.107, indicating a simplified but stable community structure.

2.3 Effects of Treatment Duration on Species Diversity

During the 0–10 year gangue treatment chronosequence, species number and Margalef richness index increased from CK to 5 years of treatment, reaching maxima of 28 species and 2.877, respectively, before declining . The Shannon diversity index followed a similar pattern, increasing from 1.476 at CK to 3.506 at 5 years, then decreasing to 2.039 at 10 years. The Pielou evenness index exhibited a "decrease-increase-decrease" pattern, with minimal overall variation. In contrast, the Simpson dominance index showed an "increase-decrease-increase" trend, peaking at 0.359 after 10 years of treatment. These patterns indicate that plant community species gradually developed toward a simpler, more stable state during natural succession.

2.4 Effects of Treatment Duration on Plant Population Quantitative Characteristics

Treatment duration significantly affected plant population quantitative characteristics . Plant height increased significantly from 3.170 cm at CK to 100.585 cm after 10 years ($P < 0.05$). Coverage increased significantly from 22.551% at CK to 89.562% after 10 years ($P < 0.05$). Plant density increased significantly from 157.037 individuals/m^2 at CK to 425.061 individuals/m^2 after 10 years ($P < 0.05$). These results demonstrate that artificial intervention substantially promoted ecological restoration compared to natural recovery.

Discussion

Artificial vegetation introduction enhanced vegetation diversity and facilitated community construction in the abandoned mining area of Shuanglonggou. The species composition analysis revealed that Asteraceae, Poaceae, and Rosaceae played crucial roles in vegetation succession during gangue treatment, accounting for 50.91% of total species. This pattern of "most species belonging to few families, few species belonging to most families, and most species being single-family, single-genus" aligns with findings from other restored ecosystems in the region.

The important value index, which integrates relative height, coverage, and frequency, effectively quantifies species relative importance in communities. During treatment, dominant species transitioned from annual herbs (*Artemisia he-*

dinii, *Crepis rigescens*, *Ranunculus tanguticus*) to perennial herbs (*Elymus nutans*, *Potentilla anserina*) and shrubs (*Hippophae rhamnoides*). After 10 years, the community became dominated by artificially planted *Elymus nutans*, *Poa annua*, and *Hippophae rhamnoides*. The persistence of *Elymus nutans* and *Potentilla glabra* across all treatment stages demonstrates continuity in community succession, consistent with general vegetation recovery patterns.

Species diversity indices revealed distinct temporal patterns. The "increase-decrease-increase" trend in Simpson dominance index indicates progressive simplification and stabilization of community structure. The contrasting pattern in Pielou evenness index compared to studies in semi-arid steppe and desert oasis margins likely reflects differences in environmental conditions, topography, soil properties, and climate among study regions. The initial increase in Shannon diversity and Margalef richness indices from CK to 5 years reflects the positive effects of artificial intervention (soil covering, fertilization) on species establishment. The subsequent decline after 5 years suggests that as the artificially planted shrub *Hippophae rhamnoides* grew vigorously, shading intensified and limited light availability, suppressing understory herbaceous species through competition for resources.

Plant population quantitative characteristics showed significant increases in height, coverage, and density with treatment duration, indicating that artificial intervention ("*Hippophae rhamnoides* + *Elymus nutans*" planting model) substantially accelerated ecological restoration compared to natural recovery. This finding is consistent with studies from other mining areas demonstrating the effectiveness of artificial planting in promoting vegetation recovery.

In summary, gangue treatment duration significantly influences plant community succession and species diversity in the eastern Qilian Mountains. The vegetation recovery process represents a mutualistic relationship between vegetation and soil environment. Future research should investigate correlations between plant communities and soil factors, including physical and chemical properties, enzyme activities, and microbial communities.

Conclusion

During gangue treatment in Shuanglonggou, 55 plant species from 24 families and 40 genera were recorded. Asteraceae, Poaceae, and Rosaceae accounted for 50.91% of total species, while 15 families (62.5%) were single families with single genera and species. As treatment duration increased, community dominants transitioned from annual/perennial herbs to perennial herbs and shrubs. Species number, Shannon diversity index, and Margalef richness index increased from CK to 5 years of treatment before declining. Pielou evenness index exhibited a "decrease-increase-decrease" pattern, while Simpson dominance index showed an "increase-decrease-increase" trend, peaking after 10 years of treatment. Treatment duration significantly affected plant population characteristics, with height, coverage, and density all showing significant increasing trends.

Under artificial intervention, gangue treatment duration substantially influences vegetation succession and species diversity, with plant communities gradually becoming simpler and more stable.

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