Vegetation–Soil System Characteristics and Stability Assessment of Poplar Plantations across Degradation Gradients in the Heilaigou Watershed

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Abstract: Clearing up the interactive nature of the vegetation-soil system during consecutive degradation of the Populus simonii plantation. Poplar plantations in the Engebei Demonstration Area were used as model systems whereby stands were divided into four categories of degradation depending on the amount of dieback observed; non-degraded (<10%), mildly degraded (10-20%), moderately degraded (20-60) and severely degraded (>60).The vegetation community attributes, soil physicochemical properties and fine-root functional traits of all grades have been systematically measured. ANOVA, principal component analysis (PCA) and entropy-weighted TOPSIS were used to analyze the data and build a composite stability assessment. As the degradation increased, the height of the trees, the diameter of the trees at the breast height (DBH) and the crown area decreased by 24.6, 59.9 and 67.7 percent, respectively, whereas the rate of dieback increased by 7.80-65.30 percent. The shrub-herb layer cover and its biomass were represented by a unimodal trend of rise-then-fall with maximum values reached in the stage of moderate degradation - as an under-story compensation response. The peaks of both SRL and SRA shifted upwards in the soil layer of 80-100 cm to that of 20-60 cm, this indicates that the approach was changed to use deeper water resources than to engage in opportunistic rooting behavior in less deep horizons. The soil sand content was over 88 per cent in heavily degraded stands; total nitrogen (TN) dropped by half, that is, to 0.12 g/kg, and the C/N ratio increased twofold, reaching 42. Total N, AP, C/N, EC, and SWC were selected to be the main driving factors. The stability ranking derived by both PCA and TOPSIS analyses was the same: non-degraded > mildly degraded > moderately degraded > severely degraded. It is also important that the transition between minor and intermediate damage is an inflection point, or an instable state change, which marks the final chance to fix it. The most common deterioration process is the water-salinity-nutrient coupling link. The moderate degradation stage is the final operational opportunity to act on the remediation. Even though a tiered control system is recommended: prevention of unhealthy state of intact stands and silvicultural thinning of poorly lit stands, restorative measures in lightly degraded areas, and complete refurbishment of heavily degraded stands.

Keywords: Poplar Plantation; Degradation Gradient; Vegetation–Soil System; Fine-Root Functional Traits; Principal Component Analysis; Stability Assessment

1. Introduction

Poplar (Populus spp.) is the backbone species of the Three-North Shelterbelt Programme in northern China providing important ecosystem services such as windbreaks and sand fixation, soil and water conservation and climate regulation at regional level [1]. Nevertheless, over recent decades there has been a large-scale degradation of poplar plantations due to many interacting stressors such as increased climatic aridity, stand senescence and long-term monoculture management. The total area of degraded plantations has reached 3.23 million hectares [2-4], severely compromising the ecological service capacity of these shelterbelts [5,6]. The decline of degraded forest land has become a prominent problem restricting the stability of ecological barrier in the north. Until now, most of the research has been carried out in degradation with one-dimensional perspectives [7]; comprehensive, multi-gradient analyses that at the same time reflect changes in vegetation communities, environmental changes in soil, and functional response of roots systems, translating them into a consistent framework of stability assessment are still extremely rare. In this paper, we created four degradation gradients by applying poplar plantations in the Engebei Demonstration Area, systematically described the response trajectories of the vegetation-soil system, determined the most important environmental drivers and developed a quantitative stability assessment framework. The aim is to provide theoretical support and practical reference for the implementation of differentiated graded restoration and management of degraded protection forests in arid and semi-arid areas.

Within forest ecosystems, soil serves as the central medium underpinning material cycling, energy flow, and hydrological regulation. It supplies trees with water, mineral nutrients, and physical anchorage, while profoundly shaping regional species composition, community structure, and the successional trajectory of ecological functions — thus acting as an indispensable environmental driver [8]. Concurrently, vegetation returns organic matter and nutrients to the soil through litter decomposition, root exudation, and rhizodeposition, establishing a bidirectional, dynamically equilibrated vegetation–soil coupling system characterized by continuous material exchange and co-evolutionary feedbacks [9].The two restrict and feedback each other, and jointly determine the long-term development trend of forest ecosystem.

The fundamental principle of the degradation of forest land is the overall external appearance of the synchronized degradation of the vegetation and soil coupling system. The changes in soil quality over time and space are inherently associated with the processes of forest community succession and degradation of stands. The temporal trends in soil physicochemistry and ecological stoichiometry (C: N: P) not merely offer information about the underlying dynamics that lead to forest succession or failure but are the foundation of a number of important diagnostics in evaluating ecosystem health [10]. The physicochemical properties of soils and the C:N:P stoichiometric proportions are direct indicators of soil fertility levels and types of nutrient limitation and thus represent an important benchmark in estimating soil quality and supporting plantation productivity as well as guaranteeing the consistency in the provision of ecosystem services [11,12]. There is a large body of research demonstrating that environmental heterogeneity, including the level of degradation, type of vegetation, topography (elevation, slope position and aspect), among others can significantly affect the pattern of soil nutrients and their ratios. Among all this complexity, it has been a major challenge to identify the main environmental factors that determine vegetation-soil co-evolution in response to degradation because it is essential when developing efficient adaptive management and restoration plans [13].

2. Materials and Methods

2.1 Study Area

The study was conducted in the Engebei Ecological Demonstration Area, Dalad Banner, Inner Mongolia Autonomous Region (109°30′–109°50′ E, 40°10′–40°25′ N). The region experiences a temperate continental semi-arid climate, with a mean annual temperature of 6.5 °C, annual precipitation of 250–350 mm, and annual potential evaporation of approximately 2,200 mm. Soils are predominantly aeolian sandy soils with a coarse texture. The poplar plantations, which are mainly made up of the Populus simonii (Simon poplar) species, were planted in the 1970s1980s and have been showing the signs of wide-scale degradation ever since.

2.2 Experimental Plot Design

Four degradation grades were delineated based on canopy dieback rate (Table 1). The three 20 m x 20 m replicate plots per degradation grade produced a total of 12 plots.

2.3 Measurement Protocols

Vegetation parameters: In the tree layer, we measured tree height, diameter at breast height (DBH), crown area, dieback rate, and canopy light transmittance. At the shrub-herb level, the survey of species composition, coverage, density, and aboveground biomass was done by means of 1 m x 1 m quadrats. Roots of fine size (2 mm or less) were taken in five soil depths (0-100 cm profile) to measure specific root length (SRL), specific root area (SRA), root tissue density (RTD), and root mean diameter (RMD).Soil parameters: Five different depths were used to obtain samples of soils that would be analyzed in terms of particle-size distribution (mechanical composition), bulk density, porosity, gravimetric water content, pH, electrical conductivity, total nitrogen (TN), total phosphorus (TP), soil organic matter (SOM), available phosphorus (AP), available potassium (AK), and C:N:P stoichiometric ratios. Data analysis: One-way analysis of variance (ANOVA), Pearson correlation analysis, principal component analysis (PCA), and the entropy-weighted Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) were employed for statistical evaluation and integrated stability ranking.

Table 1. Classification Criteria for Poplar Plantation Degradation Grades

Degradation Degree	Dieback Rate/%	Leading Feature
ND	<10	The trees grow vigorously, the canopy is complete, and the undergrowth vegetation is well developed.
LD	10～20	Growth slowed down, the canopy was slightly sparse, and the understory vegetation began to increase.
MD	20～60	The Bgrowth declined significantly, the canopy was obviously sparse, and the withered shoots were common.
SD	>60	The growth is basically stagnant, the canopy is seriously incomplete, and the number of dying trees increases.

3. Results and Analysis

3.1 Vegetation Community Characteristics

With progressive degradation, tree-layer growth exhibited sustained decline across all metrics (Table 2, Figure 1): tree height decreased from 6.80 m to 5.13 m (a 24.6% reduction), DBH from 19.27 cm to 7.72 cm (a 59.9% reduction), and crown area from 4.83 m² to 1.56 m² (a 67.7% reduction). Dieback rate escalated from 7.80% to 65.30%.. The growth indexes of each tree showed significant gradient differences with the degradation gradient, and the distinguishing characteristics between groups were obvious. On the contrary, the shrub–herb layer showed a highly non-linear response (Table 3): species richness decreased from 8 to 4 species, while coverage and aboveground biomass showed an unimodal trend – first increasing, then reaching maximum in the intermediate degradation class (60.20% cover;(239.86 g/m² biomass) and then decreasing. Compared with the non-degraded stage, peak values at moderate degradation were approximately 42% and 68% higher, respectively, indicating a pronounced compensatory growth response of the understory vegetation during mid-degradation. By the severe degradation stage, however, progressive soil deterioration ultimately overrode the positive effects of increased light availability, driving understory decline.

Table 2. Tree-Layer Growth Metrics across Degradation Grades in Poplar Plantations

Degradation Degree	Tree Height/m	Diameter at Breast Height/cm	Chcanopy/m²	Dieback Rate/%
ND	6.80±0.45a	19.27±1.82a	4.83±0.51a	7.80±1.25d
LD	6.32±0.38ab	16.43±1.55b	3.71±0.44b	15.40±2.10c
MD	5.78±0.41b	11.28±1.36c	2.48±0.37c	38.60±3.45b
SD	5.13±0.36c	7.72±0.94d	1.56±0.28d	65.30±4.80a

Table 3. Shrub–Herb Layer Community Characteristics across Degradation Grades

Degradation Degree	Species Richness	Coverage/%	Density/(plant·m⁻²)	Biomass/(g·m⁻²)
ND	8	42.35±4.20c	209.33±22.5b	142.78±15.6c
LD	7	52.18±5.15b	254.67±26.8ab	187.45±20.3b
MD	6	60.20±5.80a	288.00±30.2a	239.86±24.8a
SD	4	33.52±3.85d	306.00±31.5a	128.30±14.2c

3.2 Fine-Root Functional Traits

Fine-root (≤2 mm) functional traits exhibited pronounced vertical differentiation across degradation gradients (Figure 2). The zones of highest SRL and SRA progressively migrated upward from the 80–100 cm depth layer in non-degraded stands to the 20–60 cm layer in severely degraded stands, reflecting a strategic reconfiguration from deep-profile water extraction toward rapid resource foraging in the mid-to-surface soil layers. In contrast, root tissue density (RTD; 0.01–0.23 g/cm³) and root mean diameter (RMD; 1.05–2.88 mm) fluctuated only modestly across degradation grades, suggesting that structural root traits are relatively phylogenetically conserved and less responsive to environmental deterioration.

3.3 Soil Physicochemical Properties

With intensifying degradation, soil sand content increased persistently while silt and clay fractions declined; in severely degraded stands, sand content reached 88.02%–97.29% throughout the entire soil profile (Table 4, Figure 3). Gravimetric water content dropped from 10.52% to 4.35%, total nitrogen from 0.30 g/kg to 0.12 g/kg (a 60% reduction), and soil organic matter from 3.63 g/kg to 1.58 g/kg (a 56.5% reduction). The C/N ratio soared from 12.10 to 42.15, indicating severe impairment of nitrogen mineralization — a stoichiometric signature of ecosystem-level nitrogen limitation and disrupted microbial decomposition pathways.

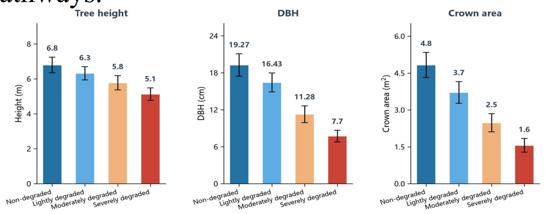

Figure 1. Tree-Layer Growth Indices and Shrub–Herb Layer Community Characteristics across Degradation Grades

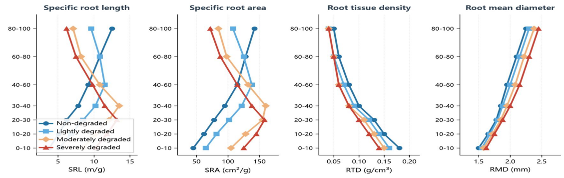

Figure 2. Vertical Profile Variation of Fine-Root Functional Traits across Degradation Grades

Table 4. Surface Soil (0–20 cm) Physicochemical Properties across Degradation Grades

Index	ND	LD	MD	SD
Grit/%	67.45±5.2d	75.83±6.1c	82.56±7.3b	91.20±8.5a
Volumetric Weight/(g·cm⁻³)	1.28±0.05d	1.38±0.06c	1.47±0.07b	1.58±0.08a
Water content/%	10.52±1.5a	7.84±1.2b	5.96±0.9c	4.35±0.7d
Total Nitrogen/(g·kg⁻¹)	0.30±0.03a	0.24±0.03b	0.18±0.02c	0.12±0.02d
Organic Matter/(g·kg⁻¹)	3.63±0.35a	2.85±0.30b	2.10±0.25c	1.58±0.20d
C/N	12.10±1.2d	18.45±1.8c	28.32±2.5b	42.15±3.8a

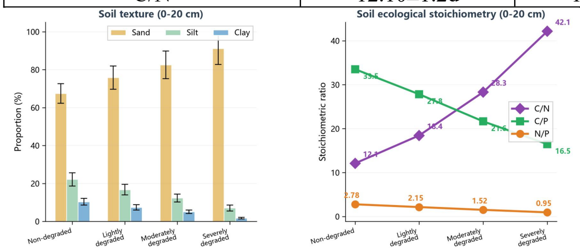

Figure 3. Soil Particle-Size Distribution and Stoichiometric Signatures across Degradation Grades

3.4 Comprehensive Stability Evaluation

PCA extracted three principal components with a cumulative variance contribution of 78.5%. Five variables — total nitrogen (loading: 0.70), available phosphorus (0.57), C/N ratio (0.53), electrical conductivity (0.47), and soil water content (0.45) — were identified as the dominant driving factors of system variation. Stability evaluation (Table 5, Figure 4) yielded consistent results across both independent methods: PCA composite scores ranked non-degraded (0.87) > mildly degraded (0.74) > moderately degraded (0.25) > severely degraded (−0.30), and TOPSIS relative closeness coefficients ranked 0.30 > 0.27 > 0.23 > 0.20, respectively. It is worth noting that the drop of PCA scores from the mild degradation state to the moderate degradation state was up to 66.2% , suggesting that the moderate degradation stage is a critical failure boundary for the stable operation of systems – i.e., it is where the possibility of recovering decreases significantly.

Table 5. Vegetation–Soil System Stability Assessment

Degradation Degree	PCA	TOPSIS
ND	0.87	0.30
LD	0.74	0.27
MD	0.25	0.23
SD	-0.30	0.20

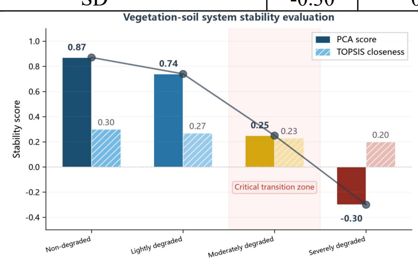

Figure 4. System Stability Evaluation Based on PCA and TOPSIS Methods

4. Discussion

The compensatory understory effect observed at moderate degradation — manifested as elevated shrub–herb coverage and biomass — arises from the confluence of two transiently favorable conditions: enhanced light penetration through a thinning, senescing canopy, and the persistence of partially intact soil nutrient pools that have not yet been fully exhausted. This phenomenon should not, however, be misinterpreted as indicative of forest health. Severe soil degradation may lead to a gradual deterioration of the soil (coarsening texture, reduced water holding capacity and nitrogen depletion) which eventually overcomes any beneficial effect of increased understory irradiance and results in the collapse of the shrub-herb layer. The upward movement of the high-SRL root zone is in line with the hypothesis of Zierdie·Baheti et al. that it is a case of water-use strategy shift [5]: the root depth is shifted upward into surface and sub-surface soils due to reduced water availability at greater depths of the soil profile; this enhances the short term foraging capacity but it also makes trees susceptible to more frequent droughts - hence less adaptable in periods of higher drought frequency. The increase in the soil C/N ratio by a factor of 35 (with a value of 73.97 reached in the 10-20 cm layer of severely degraded stands) is much greater than the national soil average of 11.9 [7] it means that nitrogen mineralization has been nearly halted. The extreme stoichiometric imbalance is an indication that carbon and nitrogen cycles have been decoupled - organic inputs are still coming in through litterfall and root turnover but microbial nitrogen transformation has been heavily impaired due to coarsening texture, reduction in moisture and limitation of substrates. These five features (total N, AP, C/N, EC and SWC) are the primary drivers of the formation of the chain of hydro-salino-nutrient coupling degradation. The evidence that PCA (a variance maximization and data-driven ordination method) and TOPSIS (a distance-based MCDM method) give the same stability order; on top of the identification of a moderately degraded regime as the critical transition area is strong evidence of this conclusion. The concordance of the two methods in question places moderate degradation at the end of the actionable window of restoration: thereafter, soil degradation is self-reinforcing and recovery paths grow exponentially, making intervention more expensive and unpredictable.

5. Conclusions

(1) The tree-layer increase was found to decrease monotonically as the degradation progressed, but the shrubherb layer showed a unimodal rise-then-fall nonlinear growth pattern due to transient compensatory dynamics. The high-SRL root zone moving upwards across the deep to mid-surface soil layer is a sign of adaptable reorganization of water uptake strategy under the growing drought stress.

(2) Degradation was accompanied by an increase in soil sand content, a rise in the bulk density, a decrease in water-holding capacity and nutrients stocks as well as a sharp increase in the C/N ratio, and the nitrogen deficiency became the major edaphic limitation to ecosystem recovery.

(3) The main environmental drivers were total nitrogen, accessible phosphorus, C/N ratio, electrical conductivity, and moisture content of the soil; the degradation process is defined by the dominance of the "water-salinity-nutrient coupling" nexus.

(4) System stability declined monotonically across degradation gradients. The middle stage of degradation is the critical breaking point and the final chance to provide an effective remedial intervention. Our advice is the implementation of hierarchical management system with degradation stratification including prevention of damage to non-degraded stands, silvicultural treatment of slightly damaged stands, selective ecological rehabilitation of moderately damaged stands, and radical reconstruction of heavily damaged stands.

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(2) Soil and water conservation ecological product price of check dam controlled watershed Value accounting method and case analysis (202601010402A)

(3) 'Guidelines for the Measurement of Soil

Loss' and 'Production Construction project soil and water conservation plan preparation' course Deep fusion (JGYB2026032)
(4) Preparation of soil and water conservation plan for production and construction projects (PX-32619)

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