Ecological Threshold Estimation for Changes in Vegetation and Soil Characteristics During Alpine Grassland Desertification: A Postprint

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Abstract

Grassland desertification represents a critical environmental issue that significantly impacts forage production and the living environment of residents. Current research on grassland desertification primarily focuses on changes in vegetation characteristics and soil properties during the desertification process; however, studies on selecting sensitive indicators to track this process and quantifying its ecological thresholds remain scarce. This study employs a space-for-time substitution approach, selecting five desertification gradients in a semi-arid alpine grassland region as research subjects to systematically investigate changes in plant, soil, and microbial characteristics during desertification and to estimate the ecological thresholds of this process. The results demonstrate that with intensifying desertification, community coverage and both aboveground and belowground biomass exhibit significant declining trends; soil water content gradually decreases while soil bulk density progressively increases, and the gravel content in extremely severely desertified grasslands is significantly higher than in other gradients. Analysis of soil nutrient content reveals that total carbon and total nitrogen in surface soil (0–10 cm) gradually decrease, while the carbon-to-nitrogen ratio in extremely severely desertified grasslands is significantly higher than in other gradients. During grassland desertification, the ecological threshold for vegetation occurs at the mild-to-moderate desertification gradient, whereas those for soil and soil microorganisms occur at the moderate-to-severe gradient. Threshold estimation indicates that plant responses are more sensitive than soil responses, making changes in plant community characteristics more scientifically robust indicators of grassland desertification degree. Furthermore, the mild-to-moderate desertification gradient represents a critical period in the desertification process, underscoring the importance of early prevention and control measures for desertified grasslands.

Full Text

Estimation of Ecological Thresholds for Vegetation and Soil Characteristics during the Desertification Process in Alpine Grasslands

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Abstract

Grassland desertification represents a critical environmental challenge with significant impacts on forage production and human livelihoods. While existing research has primarily focused on changes in vegetation characteristics and soil properties during desertification, there remains a knowledge gap regarding which sensitive indicators best signal this process and how to quantify the ecological thresholds that define regime shifts. Using a space-for-time substitution approach, we selected five desertification gradients in a semi-arid alpine steppe region to systematically investigate changes in plant communities, soil properties, and microbial characteristics, and to estimate ecological thresholds for the desertification process. Our results demonstrate that community coverage, aboveground biomass, and belowground biomass decreased significantly with intensifying desertification. Soil moisture content showed a gradual decline, while soil bulk density increased progressively. Gravel content in extremely severely desertified grasslands was significantly higher than in other gradients. Analysis of soil nutrient content revealed that total carbon and nitrogen concentrations in surface soils (0–10 cm) decreased gradually, with the carbon-to-nitrogen ratio in extremely severely desertified areas significantly exceeding other gradients. Ecological thresholds for vegetation occurred between lightly and moderately desertified stages, whereas thresholds for soil properties and soil microorganisms appeared between moderately and severely desertified stages. These findings indicate that plant communities respond more sensitively than soil systems, making vegetation characteristics more scientifically robust indicators of grassland desertification status. Moreover, the transition from light to moderate desertification represents a critical period in the desertification process, underscoring the importance of early intervention and prevention strategies.

Keywords: alpine grassland; desertification gradient; vegetation characteristics; soil properties; soil microorganisms; ecological threshold

Introduction

Grassland desertification has become a global environmental issue, referring to the degradation process where native vegetation and community structure are altered, soils become eroded and sandy, water content declines, nutrients are lost, and grassland productivity diminishes, resulting in sand-dominated landscapes in previously non-desert areas. Under combined natural and anthropogenic pressures, alpine grassland ecosystems have experienced severe desertification in recent years, transitioning from patchy distribution to extensive fully desertified areas and active sand dunes. This desertification not only threatens pastoral production and living environments but also compromises regional ecological security and sustainable economic development.

Previous studies have extensively documented changes in vegetation community characteristics, biomass, soil physicochemical properties, nutrient content, soil microorganisms, and enzyme activities during grassland desertification. Generally, intensifying desertification leads to reduced vegetation cover, decreased species diversity, and lower productivity. Soil surface water content and nutrient concentrations decline sharply, soil pH decreases, surface particles coarsen, soil enzyme activity diminishes, and soil microbial community composition changes significantly. While aboveground vegetation changes are most 直观, research also suggests that soil properties and microbial community composition represent the most sensitive indicators of ecosystem change. However, no consensus exists regarding which metrics best indicate grassland desertification, and few studies have quantified ecological thresholds for this process.

Ecological thresholds represent discontinuous changes in ecological factors, marking critical values of independent variables when systems shift from one stable state to another. Common methods for determining thresholds include statistical analysis (using statistical models and piecewise regression) and model simulation (process models, system dynamics models, conceptual models), both requiring extensive field data. Nonlinear dynamics form the theoretical foundation of ecological thresholds, with identification relying on detecting inflection points in ecosystem dynamic processes. Statistical methods quantify thresholds by describing experimental data to generate simple statistical models consistent with ecological principles, then establishing thresholds through model simulation. In the context of desertification, ecological thresholds represent critical values where vegetation or soil properties abruptly shift between desertification gradients. Quantifying these thresholds is crucial for understanding ecosystem structure and function and has potential applications for ecosystem management and early desertification prevention.

The Tibetan Plateau, highly sensitive to global climate change, is particularly vulnerable to desertification due to its fragile ecological environment, abundant sand sources, and unique high-wind conditions. Recent statistics indicate that total desertified land area in Tibet exceeds 20×10^{4} km^{2}, representing 16.8% of the plateau area. Large-scale grassland desertification and ecological degradation directly threaten sustainable development of alpine pastoralism and human habitats, adversely affecting water conservation and soil erosion control, with significant negative impacts on economic development and ecological protection in this critical region.

This study employs a space-for-time substitution approach across five desertification gradients in a semi-arid alpine steppe region. By measuring vegetation community characteristics, soil properties, and microbial community features, we identify sensitive indicators of desertification and quantify ecological thresholds. These findings provide important guidance for indicator selection during desertification and have practical significance for early prevention, vegetation restoration, and rehabilitation of desertified grasslands.

1. Materials and Methods

1.1 Study Area The study was conducted approximately 40 km north of Baingoin County, Tibet Autonomous Region (31°26 N, 90°02 E, elevation 4678 m), located in the hinterland of the northern Tibetan Plateau. The region experiences a semi-arid continental plateau climate with a mean annual temperature of -1.2 °C (ranging from -17.5 °C to 14.7 °C) and annual precipitation of 335 mm. Annual potential evapotranspiration ranges from 1993.4 to 2104.3 mm, yielding an aridity index (potential evapotranspiration to precipitation ratio) of 6.0–6.3. Soils are alpine steppe soils with relatively low fertility, depths of 0.3–0.5 m. Dominant species include *Stipa purpurea*, *Leontopodium leontopodioides*, and *Heteropappus bowerii*.

1.2 Experimental Design Following the classification standards of Dregne and Li Sen et al., alpine grassland desertification severity can be categorized based on bare ground area and vegetation coverage. Using a space-for-time substitution approach, we selected five desertification gradients in the alpine steppe region: native grassland (bare area <5%, vegetation coverage >60%), lightly desertified (bare area 5-15%, vegetation coverage 45–60%), moderately desertified (bare area 15–30%, vegetation coverage 30–45%), severely desertified (bare area 30–45%, vegetation coverage 15–30%), and extremely severely desertified (bare area >45%, vegetation coverage <15%). Local grassland desertification primarily results from overgrazing over recent decades, exacerbated by wind and water erosion. Dominant species across gradients were: native grassland (*Stipa purpurea*, *Potentilla multifida*, *Microula sikkimensis*); lightly desertified (*Carex montis-everestii*, *Potentilla multifida*, *Festuca ovina*); moderately desertified (*Stipa purpurea*, *Potentilla multifida*, *Poa crymophila*); severely desertified (*Stipa purpurea*, *Artemisia demissa*, *Carex montis-everestii*); and extremely severely desertified (*Microula sikkimensis*, *Axyris prostrata*).

1.3 Sample Collection and Analysis Vegetation surveys were conducted during the growing seasons of 2015-2016, with soil samples collected during the 2016 growing season. Plant community characteristics were investigated using quadrat methods during peak growth (mid-August). Five 0.5 m × 0.5 m quadrats were randomly selected in each plot, with each quadrat divided into 10 cm × 10 cm grids using fine string to determine total community coverage and individual species coverage based on grid occupancy. After survey completion, aboveground biomass was harvested by species at ground level and stored in envelopes; litter was also collected. Samples were oven-dried at 65 °C to constant weight and weighed. Belowground biomass was obtained by excavating soil blocks (20 cm × 20 cm) from each quadrat at three depths (0–10 cm, 10-20 cm, 20–40 cm). Roots were washed clean of soil and sand, then oven-dried at 65 °C to constant weight and weighed.

Soil samples were transported in portable coolers to the laboratory, where roots and stones were removed before sieving and splitting into two subsamples: one stored at -20 °C for microbial analysis and the other air-dried for physicochemical analysis. Air-dried samples were ground using a ball mill and passed through a 100-mesh sieve. Soil bulk density was measured using the core method; soil water content was determined by oven-drying at 105 °C to constant weight; gravel content was measured by sieving and weighing; and total carbon and nitrogen contents were analyzed using an elemental analyzer.

1.4 Soil Bacterial Community Composition Analysis Soil microbial analysis was performed at Sichuan Bobaite Biotechnology Co., Ltd. For each plot, five surface soil cores (0–10 cm) were collected from random locations and mixed. DNA was extracted using the Power Soil DNA Isolation Kit (MO BIO Laboratories, CA, USA). Bacterial 16S rRNA V4–V5 regions were amplified using universal primers (GTGCCAGCMGCCGCGG and CCCCGYCAATTCMTTTRAGT). Each 25 L PCR reaction contained 1×PCR buffer, 2.5 mM $MgCl_2$, 0.4 M each primer, 0.5 U Ex Taq polymerase (TaKaRa), and 10 ng template DNA. The amplification program included initial denaturation at 95 °C for 5 min, followed by 30 cycles of 95 °C for 30 s, 56 °C for 30 s, and 72 °C for 40 s, with a final extension at 72 °C for 10 min. Each sample was amplified in duplicate, with negative controls included. Amplicons were pooled and sequenced on the Illumina MiSeq platform using the MiSeq Reagent Kit v3.

Raw sequences were merged using FLASH v1.2.7. Quality control was performed using Qiime v1.9.0: sequences were truncated at the first low-quality base (quality threshold <20), and tags shorter than 75% of the expected length were removed. UPARSE was used to detect chimeric sequences and obtain final clean tags.

1.5 Statistical Analysis One-way ANOVA was used to analyze desertification gradient effects on vegetation characteristics (aboveground/belowground biomass, community coverage), soil properties (bulk density, moisture, gravel content, total carbon, total nitrogen, C:N ratio), and soil microbial community composition (Shannon diversity, Chao1 richness). Nonlinear regression was applied to normalized response ratios (relative changes compared to native grassland) of all vegetation, soil, and microbial parameters to identify optimal models. Significance was set at $P < 0.05$. Statistical analyses were performed using SPSS 16.0 (SPSS Inc., Chicago, IL, USA) and OriginPro 2017 (OriginLab Corporation, Northampton, MA, USA).

2. Results

2.1 Changes in Vegetation Community Characteristics Along Desertification Gradients With increasing desertification severity, both years of community surveys revealed significant decreasing trends in aboveground biomass, from 47.5–68.6 $g \cdot m^{-2}$ in native grassland to 5.0–10.7 $g \cdot m^{-2}$ in extremely severely desertified grassland. Belowground biomass also decreased significantly, from 355.6 $g \cdot m^{-2}$ in native grassland to 2.2 $g \cdot m^{-2}$ in extremely severely desertified grassland, though significant interannual differences were observed. Community coverage declined from 55–64% in native grassland to 5.0–10.4% in extremely severely desertified grassland. Response ratio analysis indicated that aboveground biomass and community coverage responded sensitively, showing significant decreases from native to lightly desertified grassland, while belowground biomass responded more slowly, with significant changes appearing between lightly and moderately desertified stages [Figure 1: see original paper].

2.2 Changes in Soil Physicochemical Properties Along Desertification Gradients Soil bulk density, gravel content, and C:N ratio increased gradually with desertification, while soil moisture and surface (0–10 cm) carbon and nitrogen contents decreased. Soil bulk density increased from 1.34 to 1.60 $g \cdot cm^{-3}$, gravel content rose from 2.5% to 21.3%, and C:N ratio increased from 8.9 to 12.1. Conversely, soil moisture decreased from 13.8% to 2.1%, soil carbon content from 2.43% to 0.21%, and soil nitrogen content from 0.27% to 0.05%. Response ratio estimation revealed that declining soil properties showed significant changes during moderate-to-severe desertification, while increasing properties (except bulk density) showed significant changes during severe-to-extremely severe transitions [Figure 2: see original paper]. These results indicate that soil property changes lag behind vegetation responses.

2.3 Changes in Soil Microbial Community Composition Along Desertification Gradients Bacterial Shannon diversity and Chao1 richness indices increased gradually with desertification, with significant changes appearing between severe and extremely severe stages [Figure 3: see original paper]. At the phylum level, relative abundances of Actinobacteria and Crenarchaeota decreased significantly, while Proteobacteria, Acidobacteria, and Bacteroidetes increased significantly [Figure 4: see original paper]. Response ratio analysis showed that significant changes in microbial diversity occurred between severe and extremely severe desertification stages, whereas significant changes in dominant population relative abundance appeared between moderate and severe stages. This suggests that soil microbial ecological thresholds occur during moderate-to-severe desertification transitions.

2.4 Estimation of Ecological Thresholds in the Desertification Process Comprehensive analysis revealed that vegetation characteristic thresholds occurred during light-to-moderate desertification transitions [Figure 5: see original paper]. For soil properties, thresholds for increasing parameters occurred during severe-to-extremely severe transitions, while thresholds for decreasing parameters appeared during moderate-to-severe transitions. Soil microbial thresholds emerged during moderate-to-severe transitions. These findings demonstrate that vegetation responds more sensitively than soil properties, suggesting plant community characteristics serve as more appropriate indicators of desertification status. Consequently, early prevention of vegetation degradation is crucial in desertification management.

3. Discussion

Vegetation reduction and land exposure represent the most conspicuous changes during desertification. Previous research indicates that intensifying desertification drives vegetation retrogression, reducing cover, height, and biomass, ultimately causing vegetation decline. Our study corroborates these patterns, with community coverage decreasing from 50-60% to below 10% and total productivity dropping from 40-70 $g \cdot m^{-2}$ to below 10 $g \cdot m^{-2}$ as desertification progressed from potential to extremely severe stages. Desertification altered vegetation composition, replacing palatable perennial grasses with unpalatable species like *Axyris prostrata* and *Heteropappus bowerii* in extremely severely desertified areas. This vegetation shift reduces wind speed attenuation and surface erosion protection, accelerating soil exposure and desertification feedbacks.

Soil constitutes a vital component of grassland ecosystems, with desertification involving coupled vegetation-soil feedbacks. Most studies show that intensifying desertification causes severe nutrient loss, with soil carbon and nitrogen declining progressively, particularly in surface horizons. Our results confirm these trends, with soil moisture, total carbon, and nitrogen decreasing while bulk density and gravel content increased significantly in extremely severely desertified grassland. This increased surface roughness further accelerates vegetation loss and desertification progression.

Soil microorganisms regulate material cycling, and microbial biomass, though a small fraction of soil organic matter, critically controls carbon-nitrogen flows and nutrient supply. Biological parameters increasingly serve as indicators of soil quality changes. We found significant differences in bacterial communities between severe and extremely severe desertification stages, with Shannon diversity increasing significantly in extremely severely desertified plots. Dominant populations shifted markedly, with decreases in Actinobacteria and Crenarchaeota and increases in Proteobacteria, Acidobacteria, and Bacteroidetes. These microbial responses lag behind vegetation changes but precede some soil property shifts, highlighting their importance for understanding desertification mechanisms and developing biological control measures.

Ecological thresholds define conditions triggering state changes in ecosystem responses to environmental variation. While previous research documented vegetation and soil changes during desertification, few studies quantified associated thresholds. Our integrated analysis shows vegetation thresholds occur during light-to-moderate desertification, soil property thresholds during moderate-to-severe transitions, and microbial thresholds during moderate-to-severe stages. This temporal sequence confirms that vegetation responds most sensitively and should serve as the primary indicator for monitoring desertification. The light-to-moderate transition represents a critical management window, as soil properties, once degraded, are difficult to restore. Therefore, desertification control must emphasize both vegetation restoration and soil protection, with early intervention being paramount.

4. Conclusion

Using a space-for-time substitution approach across five desertification gradients in a semi-arid alpine steppe region, we systematically investigated changes in plant, soil, and microbial characteristics and estimated ecological thresholds for desertification. Our conclusions are:

1. With intensifying desertification, plant community coverage, aboveground biomass, and belowground biomass decreased significantly. Soil properties showed gradient changes: moisture declined while bulk density increased, with gravel content significantly higher in extremely severely desertified grassland. Surface soil total carbon and nitrogen decreased progressively, and C:N ratios were significantly higher in extremely severely desertified stages.

2. Fitting analysis revealed that vegetation characteristic thresholds occurred during light-to-moderate desertification, while soil and microbial thresholds appeared during moderate-to-severe transitions.

3. Plant communities responded more sensitively than soil properties, making vegetation characteristics more scientifically appropriate indicators of desertification status. The light-to-moderate desertification transition represents a critical period for alpine grasslands, emphasizing the importance of early prevention and control measures.

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