Postprint: Physicochemical Properties and Composite Shear Strength of Alpine Grasslands at Different Degradation Levels in the Yellow River Source Region

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Abstract

To investigate the impacts of alpine grassland degradation on soil physicochemical properties and root-soil composite shear strength in the Yellow River source region, this study examined alpine grasslands in Henan County, Qinghai Province, within the Yellow River source region. Through field sampling and laboratory testing of grasslands at varying degradation levels, indices and variation characteristics of soil density, water content, particle size distribution, soil nutrient elements, and plant root-soil composite shear strength were obtained. The results revealed that: (1) Under identical degradation levels and sampling depths, the average soil density in the Nanqicun experimental area was 1.02~1.29 times that of Qilong Ranch, while soil water content exhibited a decreasing trend with intensifying grassland degradation; soil organic matter, total nitrogen, and total phosphorus in both experimental areas decreased with intensifying grassland degradation. (2) The shear strength of root-soil composites in the region decreased with intensifying grassland degradation, with reduction amplitudes in the upper layer (0~10 cm) and lower layer (10~20 cm) of Qilong Ranch and Nanqicun experimental area being 72.05%, 48.77% and 77.26%, 81.37%, respectively; further research indicated that the root number and root dry weight contained in root-soil composites showed a gradual decreasing trend with intensifying grassland degradation, with reduction amplitudes of root number in root-soil composites in the upper and lower layers of Qilong Ranch and Nanqicun experimental area being 79.28%, 75.93% and 92.48%, 39.59%, respectively. (3) According to results from the WWM model and Pearson correlation analysis, reductions in root number and nutrient element content had a significant decreasing effect on the shear strength of root-soil composites. The findings of this study provide practical guidance for the rational prevention and control of grassland degradation, as well as for disasters such as soil erosion and shallow landslides in alpine grasslands of the Yellow River source region.

Full Text

Study on Physical and Chemical Properties and Shear Strength Characteristics of Root-Soil Composite System with Different Degradation Degrees of Alpine Grassland in the Source Region of the Yellow River

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Abstract

This study investigated the effects of alpine grassland degradation on soil physicochemical properties and the shear strength of root-soil composite systems in the source region of the Yellow River. The alpine grassland in Henan County, Qinghai Province, served as the research area. Through field sampling and laboratory testing of grasslands at different degradation stages, variations in soil density, water content, particle size distribution, nutrient elements, and shear strength indicators of plant root-soil composites were obtained. The results showed that under the same degradation level and sampling depth, the average soil density in the Nanqi Village test area was 1.02–1.29 times that of the Qilong Pasture area. Soil water content decreased as grassland degradation intensified. Soil pH values increased with degradation, while organic matter, total nitrogen, and total phosphorus contents decreased. Consequently, the shear strength of root-soil composite systems decreased with worsening degradation. In the Qilong Pasture and Nanqi Village test areas, the shear strength reduction in the upper (0–10 cm) and lower (10–20 cm) layers reached 72.05% and 48.77%, and 77.26% and 81.37%, respectively. The root quantity and dry weight in the root-soil composite system also decreased gradually with degradation. In Qilong Pasture and Nanqi Village, root numbers in the upper and lower layers decreased by 79.28% and 75.93%, and 92.48% and 39.59%, respectively. Based on the WWM model and Pearson correlation analysis, the reduction in root quantity and nutrient element content significantly decreased the shear strength of root-soil composite systems. These findings provide practical guidance for the rational prevention

and control of grassland degradation, soil erosion, and shallow landslides in the source region of the Yellow River.

Keywords: source region of the Yellow River; grassland degradation; physical and chemical properties; root-soil composite system; shear strength; correlation analysis

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1 Introduction

The source region of the Yellow River is located in the northeastern Tibetan Plateau, covering parts of Qinghai, Sichuan, and Gansu provinces, with a total area of approximately 12.2×10^{4} km^{2}. In recent years, due to both anthropogenic and natural factors, alpine grasslands in the source region have experienced varying degrees of degradation, affecting the ecological balance of the region. To date, grassland degradation continues to occur at different levels. Research by Li Xuqian et al. [4] indicates that degraded grassland area in Qinghai accounts for 74.70% of the total natural grassland area, with lightly degraded grassland comprising 31.45%, moderately degraded 19.14%, and severely degraded 24.11%. Further studies show that grassland degradation in the region has triggered a series of ecological problems, including changes in surface plant communities, reduced forage quality and yield, conflicts between livestock and forage resources, decreased grassland carbon storage, increased greenhouse gas emissions, reduced species diversity, and frequent extreme weather events [1-3]. Therefore, scientific and effective prevention and control of grassland degradation in the Yellow River source region is an urgent task.

Numerous scholars have conducted various studies on grassland degradation in the Yellow River source region, yielding rich research findings [5-7]. Regarding the basic physicochemical properties of alpine grassland soils and grassland degradation management, substantial research results have also been obtained [8-10]. Li Xuqian et al. [11] studied the effects of alpine meadow degradation on vegetation types, soil physicochemical properties, and microbial communities in Maqin County, Qinghai, finding that vegetation coverage decreased from 100% to 20% from non-degraded to severely degraded grasslands, with soil total nitrogen and other nutrients showing decreasing trends and soil density increasing by 16.67%. Li Shixiong et al. [12] investigated plant community characteristics and soil physicochemical properties during alpine steppe degradation in Maduo County, Yellow River source region, revealing that plant species richness decreased by 39.66%, diversity decreased by 40.58%, and aboveground biomass decreased by 39.66% as degradation intensified. Further analysis showed that from non-degraded to severely degraded grasslands, dominant species transitioned from *Stipa purpurea* and *Kobresia humilis* to forbs, and finally to psammophytes.

In terms of research on the mechanical mechanisms of root-soil composite systems in alpine grasslands of the Yellow River source region, some studies have been conducted [13-15]. Shen Ziyan et al. [16] examined the physicochemical properties and shear strength characteristics of different soil depths in alpine grasslands in Henan County, upper Yellow River, finding that soil water content decreased with depth by 42.88% and 22.23% in grassland and degraded bare land, respectively, while soil density increased by 18.31% and 20.66%, and root-soil composite shear strength decreased by 59.55% with depth. Liu Changyi et al. [17] studied the shear strength characteristics of root-soil composite systems in alpine grasslands in Henan County, Yellow River source region, from non-degraded to severely degraded stages, showing that both composite shear strength and root content decreased with degradation, with cohesion c values decreasing by 73.52% and root content decreasing from 0.74% to 0.18%.

Comprehensive analysis reveals that research on alpine grassland degradation in the Yellow River source region has primarily focused on ecological structure, degradation causes, plant composition, and succession processes. However, research findings on the mechanical strength of root-soil composite systems remain relatively limited, particularly regarding the mechanical strength characteristics of soils in alpine grasslands at different degradation stages and their interaction relationships with grassland degradation. Based on this, the present study integrates the basic physicochemical properties of alpine grassland soils with shear strength characteristics of root-soil composite systems to further explore the degradation patterns of alpine grasslands in the region. The results provide theoretical support and practical guidance for scientifically and effectively preventing grassland degradation and associated soil erosion and shallow landslide disasters.

2 Study Area Overview

The study area is located in Henan Mongolian Autonomous County, Huangnan Tibetan Autonomous Prefecture, Qinghai Province, including the Nanqi Village and Qilong Pasture test sites. The Qilong Pasture test site is located at 101°50 08 E, 34°35 12 N, with an average elevation of 3600 m. The Nanqi Village test site is located at 101°27 54 E, 34°51 32 N, with an elevation of 3580 m. The distance between the two test sites is 45 km. The region belongs to a plateau sub-frigid humid climate zone with complex terrain and monsoon influence, characterized by a plateau continental climate [18]. The annual average temperature ranges from 9.2 to 14.6°C, relative humidity is 62-66%, annual rainfall is 597.1-615.5 mm, and annual evaporation is 1349.70 mm. Plant distribution types are closely related to altitude and slope aspect. Below the snow line to 4200 m, moss and cushion vegetation are distributed. At 3600-4200 m, *Kobresia pygmaea*, *Kobresia humilis*, and *Kobresia capillifolia* dominate. At 3500-3650 m, *Kobresia* species are predominant, accompanied by *Carex rigescens* and *Poa annua* [19].

3 Materials and Methods

3.1 Field Investigation and Sampling

This study selected Nanqi Village and Qilong Pasture as test sites. Based on herbaceous plant growth conditions and surface vegetation coverage, grasslands in the region were classified into four degradation levels: non-degraded, lightly degraded, moderately degraded, and severely degraded [20]. Using the quadrat survey method, aboveground biomass was obtained. Subsequently, in-situ samples were prepared from the four degradation-level grasslands for indoor nutrient element testing, water content, density, particle size analysis, and root-soil composite shear tests. Specifically, three sampling points were established for each degradation level, and samples were prepared in layers at 0–10 cm (upper layer) and 10–20 cm (lower layer) below the surface. During sampling, water content samples (200 g), nutrient element samples (500 g), particle size samples (500 g), and root-soil composite direct shear samples (four groups per layer, also used for density tests) were prepared at each sampling position.

3.2 Herbaceous Plant Types and Growth Characteristics Survey

Herbaceous plant biomass surveys in the test areas employed the quadrat method, with three 50 cm × 50 cm quadrats arranged sequentially in each degradation-level grassland. Dominant herbaceous plant species, vegetation coverage, and other biomass indicators within each quadrat were recorded. The four degradation-level grasslands and plant growth conditions are shown in Figure 2.

3.3 Soil Physical Properties

Soil density, water content, and particle analysis tests for the grasslands in both test areas were conducted using the ring knife method, drying method, and sieving method, respectively.

3.4 Soil Nutrient Elements

Soil nutrient elements were tested for different degradation-level grasslands in both Nanqi Village and Qilong Pasture. Test indicators included total nitrogen, total phosphorus, total potassium, alkali-hydrolyzable nitrogen, available phosphorus, and available potassium. Specific test methods are listed in Table 1.

3.5 Root-Soil Composite Direct Shear Test

Root-soil composite samples were subjected to indoor direct shear tests using a strain-controlled direct shear apparatus. During testing, plants at the sampling position were trimmed to be parallel with the surface soil, and a ring knife (6.18 cm in diameter and 2 cm in height) was vertically pressed into the soil until fully inserted. The soil on both sides of the ring knife was trimmed with scissors, and immediately placed in a ring knife box, labeled, and sealed with tape to prevent water evaporation [21]. Using this method, shear strength indicators (cohesion c value and internal friction angle ϕ value) of root-soil composites were obtained through indoor direct shear tests. After testing, the root-soil composite in each group of four ring knife samples was washed to remove soil particles while retaining the root system. The root surface moisture was then dried, and root number, dry weight, and average root diameter were measured [22].

4 Results and Analysis

4.1 Distribution Characteristics of Herbaceous Plants in Four Degradation Types

The survey results of herbaceous plants in the four degradation-level grasslands are shown in Table 2. Vegetation coverage decreased with intensifying grassland degradation, with particularly significant reductions in severely degraded areas. In Qilong Pasture, vegetation coverage decreased from 100.00% to 20.0%, and plant height decreased from 11.02 cm to 4.00 cm. In Nanqi Village, vegetation coverage decreased from 98.20% to 36.67%, and plant height decreased from 29.20 cm to 6.60 cm. Further analysis revealed that the succession process in the four degradation-level grasslands showed a transition from native plants (*Kobresia humilis*, *Stipa purpurea*, *Poa annua*) to secondary plants (*Elsholtzia densa*, *Saussurea pulchra*, *Gentiana straminea*), indicating that as degradation intensified, the biomass of weedy plants increased.

In Qilong Pasture, the non-degraded area was dominated by *Kobresia humilis*, with some *Stipa purpurea* and *Poa annua*, and secondary species including *Medicago falcata*, *Carum carvi*, and small amounts of *Gentiana straminea*, *Potentilla discolor*, and *Saussurea pulchra*. The lightly degraded area was still dominated by *Kobresia humilis*, but *Stipa purpurea* and *Poa annua* decreased while *Elymus nutans* increased. Secondary plants were mainly *Medicago falcata*, with increasing *Ajania tenuifolia* and *Saussurea pulchra*. The moderately degraded area featured a combination of *Kobresia humilis* and *Ajania tenuifolia*, with significantly reduced native species and secondary plants dominating. Native species were mainly *Kobresia humilis* and *Poa annua*, while secondary plants were dominated by *Ajania tenuifolia*, accompanied by *Elsholtzia densa*, *Potentilla discolor*, and *Medicago falcata*, showing significantly reduced herbaceous diversity. The severely degraded area also showed significantly reduced diversity, dominated by secondary plants, primarily *Elsholtzia densa*, accompanied by *Aconitum gymnandrum*, *Microula tibetica*, and *Artemisia hedinii*, with most areas degraded to bare land.

In Nanqi Village, the non-degraded area was dominated by a combination of *Kobresia humilis* and *Elymus nutans*, with native herbs *Poa annua* and *Stipa purpurea*, and secondary plants including *Saussurea pulchra*, *Taraxacum mongolicum*, *Ligularia virgaurea*, and *Gentiana straminea*. The lightly degraded area was dominated by *Kobresia humilis*, with significantly increased *Elymus nutans* and decreased *Poa annua* and *Stipa purpurea*, while secondary plant species and quantities decreased. The moderately degraded area featured a combination of *Kobresia humilis* and *Elymus nutans*, with increased *Potentilla anserina* as a major type, and decreased *Poa annua* and *Stipa purpurea*. Secondary species also included *Ligularia virgaurea*, *Saussurea pulchra*, *Gentianopsis paludosa*, and *Elsholtzia densa*. The severely degraded area was dominated by *Elsholtzia densa*, with most areas degraded to bare land except for small amounts of *Stellaria alaschanica*.

4.2 Physical Properties of Soils in Four Degradation-Level Grasslands

4.2.1 Soil Density and Its Variation Characteristics As shown in Table 3, soil density in both Qilong Pasture and Nanqi Village test areas generally exhibited lower layer > upper layer. The increase amplitude of soil density under the same degradation level in both test areas ranged from 3.88% to 16.82% and 3.50% to 14.04%, respectively. Further analysis revealed that soil density in Nanqi Village was greater than that in Qilong Pasture at the same position, with the non-degraded grassland in Nanqi Village showing the maximum density, increasing by 10.45% in the upper layer and 10.85% in the lower layer compared to Qilong Pasture. Meanwhile, as grassland degradation intensified, soil density in both test areas showed a decreasing then increasing trend.

4.2.2 Soil Water Content and Its Variation Characteristics Table 3 shows that the upper layer water content was greater than the lower layer in both test areas (except for the upper layer of non-degraded area in Nanqi Village), and Qilong Pasture had greater water content than Nanqi Village at the same degradation level. The most significant differences between upper and lower layer water content occurred in the lightly degraded areas of both test areas, with reduction amplitudes of 21.88% in Qilong Pasture and 15.98% in Nanqi Village. Further analysis indicated that water content in both test areas decreased gradually with intensifying degradation (except for the lower layer of severely degraded area in Nanqi Village), with Nanqi Village showing a relatively larger reduction amplitude of 41.80% compared to 36.34% in Qilong Pasture.

4.2.3 Soil Particle Size Distribution and Its Variation Characteristics Figure 3 shows that soil particle sizes in the region are mainly 0.1–2 mm, with most distributed in the 0.1-1 mm range. For particles >0.1 mm, Qilong Pasture showed a decreasing trend with intensifying degradation. In Nanqi Village, the moderately degraded grassland had the highest content of 2–0.1 mm particles at 76.01%. Table 4 indicates that the uniformity coefficient Cu of Qilong Pasture soil decreased then increased, ranging from 0.90 to 1.15, reflecting poorly graded sandy soil in the upper layer. Nanqi Village soil uniformity coefficient Cu showed an increasing then decreasing trend, ranging from 0.71 to 1.10, also indicating poorly graded sandy soil. The curvature coefficient Cc of Qilong Pasture soil increased with degradation, with an increase amplitude of 61.63%, reflecting decreasing fine particle content. Nanqi Village showed a similar pattern, with

Cc increasing by 44.33%, indicating that fine particle content in the upper layer decreased gradually with grassland degradation.

4.3 Soil Nutrient Element Characteristics

Table 5 and Table 6 present test results of nutrient element content in soils of different degradation-level grasslands. In Qilong Pasture, soil organic matter content was relatively high and decreased with intensifying degradation. From non-degraded to severely degraded grassland, the average organic matter content in the upper layer decreased by 51.48%, and the lower layer by 50.19%. In Nanqi Village, the reduction amplitudes were 72.05% in the upper layer and 77.26% in the lower layer. Total nitrogen content in Qilong Pasture was highest in the lightly degraded upper layer at 3.83 $g \cdot kg^{-1}$, with an overall decreasing trend as degradation intensified. The contents of total nitrogen, total potassium, and total phosphorus were all >1.00 $g \cdot kg^{-1}$, while alkali-hydrolyzable nitrogen, available potassium, and available phosphorus were relatively low at <1.00 $g \cdot kg^{-1}$. Under the same degradation condition, upper layer contents of alkali-hydrolyzable nitrogen and available potassium were significantly greater than the lower layer (except for severely degraded area in Qilong Pasture).

4.4 Shear Strength Characteristics of Plant Root-Soil Composite Systems

Table 7 shows that the cohesion c value of root-soil composite systems decreased gradually with intensifying grassland degradation, while the internal friction angle ϕ value increased. In Qilong Pasture, compared with the non-degraded area, the average cohesion c value of the upper layer root-soil composite decreased by 25.35%, 74.16%, and 81.37% under lightly, moderately, and severely degraded conditions, respectively, while the lower layer decreased by 50.71%, 79.28%, and 75.93%, respectively. In Nanqi Village, the upper layer decreased by 68.64%, 78.12%, and 92.48%, respectively, while the lower layer decreased by 48.77% and 39.59% under moderate and severe degradation, respectively. Correspondingly, the root quantity, root dry weight, and average root diameter in root-soil composite samples showed consistent variation patterns with the cohesion c value (except for the lower layer in Nanqi Village), decreasing gradually with intensifying degradation. The root quantity and dry weight in the upper layer of Qilong Pasture were greater than those in the lower layer. Combined with the variation pattern of cohesion c values, these results reflect that as grassland degradation intensifies, the significant reduction in plant root quantity reduces the shear strength of root-soil composite systems.

4.5 Analysis and Evaluation

To further explain and evaluate the significant influence of roots on root-soil composite shear strength, the WWM (Waldron and Wu Model) was adopted to evaluate the reinforcement effect of plant roots on shear strength. According to established formulas for unsaturated root-soil composite strength [34–36], the shear strength increase value S provided by plant roots is proportional to the average root tensile strength and root area ratio. That is, more roots result in a larger root area ratio, thereby increasing the shear strength increment of the root-soil composite. Conversely, reduced root quantity decreases this increment, leading to significantly reduced shear strength. Pearson correlation analysis using SPSS 19.0 was conducted on the influence degree of root quantity, root dry weight, and other five indicators on root-soil composite cohesion in Nanqi Village. Table 9 shows the correlation analysis results between cohesion and root quantity in the upper layer (0–10 cm) of Nanqi Village. Cohesion showed positive correlations with root quantity, root dry weight, and organic matter, and a significant positive correlation with density ($R^2 = 0.974$, $P < 0.01$).

5 Discussion

Current research on grassland degradation both domestically and internationally has mainly focused on basic soil properties such as density, water content, and nutrient element distribution [37–39]. In this study, as grassland degradation intensified, plant types transitioned from native herbs to secondary plants, with significantly reduced root content in soils. The results show that water content in both test areas decreased gradually with intensifying degradation. Under the same depth conditions, the reduction amplitude was more significant when comparing severely degraded with non-degraded areas. This conclusion aligns with Wang Ting et al. [40] and Mu Junpeng et al. [41], who found that soil water content decreased significantly with grassland degradation in Maduo County, Qinghai, and Hongyuan County, Sichuan. Additionally, soil density in the four degradation-level grasslands showed a decreasing then increasing trend, mainly attributed to the influence of root systems on soil nutrient distribution, which further affected soil properties and structure [42]. Soil pH values were weakly alkaline and increased with degradation, while organic matter, total nitrogen, and total phosphorus contents decreased. This conclusion is consistent with Zhang Zhenchao [43], who found that nitrogen, phosphorus, and other soil nutrient element contents decreased with grassland degradation in Hongyuan County, Sichuan, and Shenzha County, Tibet. Under the same degradation condition, upper layer contents of organic matter, total nitrogen, and other nutrient elements were significantly greater than the lower layer, reflecting the surface accumulation phenomenon of soil nutrients [44–46], where nitrogen, phosphorus, potassium, and other nutrient elements accumulate in areas with more roots below the surface. The decreasing trend of soil nutrient element content with intensifying degradation is mainly caused by soil erosion induced by wind and water erosion and other natural and anthropogenic factors.

The shear strength indicators of plant root-soil composite systems in the study area showed an overall decreasing trend with intensifying degradation. The average cohesion c value of the upper layer root-soil composite was significantly greater than the lower layer (except for non-degraded grassland in Qilong Pasture). The main reason is that as grassland degradation intensifies, the root quantity in root-soil composite samples gradually decreases, demonstrating the reinforcing effect of roots on shear strength. This result is consistent with Liu Changyi et al. [17], who found that shear strength of root-soil composite systems in alpine grasslands in Henan County, Yellow River source region, gradually decreased with degradation, and that reduced root content significantly decreased composite shear strength.

In summary, there is a correlation between basic physicochemical properties of alpine grassland soils and shear strength of root-soil composite systems under four degradation levels in the study area. This study shows that shear strength of root-soil composite systems is positively correlated with nutrient elements and root content, decreasing gradually with intensifying degradation. This indicates a positive correlation between shear strength and nutrient element content. The main reason is that soil nutrient element content affects plant growth and development—higher nutrient content promotes faster plant growth and more developed root systems, resulting in more significant reinforcement of root-soil composite shear strength [47-49]. Meanwhile, grassland degradation caused by wind and water erosion, rodents, and grazing leads to the loss of various soil nutrient elements, affecting soil physicochemical properties and root distribution, resulting in decreased shear strength of root-soil composite systems. Consequently, the reduced shear strength of degraded grassland soils further increases the probability of soil erosion and shallow landslides, which requires further investigation.

6 Conclusions

1. Under the same position, soil density in Nanqi Village test area was generally greater than that in Qilong Pasture. In the same test area, lower layer soil density was greater than the upper layer. Fine particle content in the upper layer of both test areas decreased gradually with intensifying degradation.

2. Soil pH values in the four degradation-level grasslands increased with degradation, while soil organic matter, total nitrogen, and total phosphorus decreased. Under the same degradation condition, nutrient element content in the upper layer of Nanqi Village was generally greater than in the lower layer.

3. Shear strength indicators of plant root-soil composite systems in both test areas decreased gradually with intensifying degradation, with reduction amplitudes of 72.05% and 48.77% in Qilong Pasture, and 77.26% and 81.37% in Nanqi Village for upper and lower layers, respectively. Root quantity, root dry weight, and average root diameter in root-soil composite systems showed similar variation patterns, decreasing by 79.28% and 75.93% in Qilong Pasture, and 92.48% and 39.59% in Nanqi Village for upper and lower layers, respectively. This reflects that more developed root systems within the optimal root content range provide greater shear

strength enhancement.

4. In the upper layers of Qilong Pasture and Nanqi Village test areas, soil cohesion showed positive correlations with root quantity, root dry weight, density, and organic matter. In Nanqi Village, soil cohesion showed a significant positive correlation with density ($R^2 = 0.974$, $P < 0.01$).

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