Effects of Different Stocking Rates on Soil in Stipa breviflora Desert Steppe (Postprint)

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Abstract

This study was conducted in the Stipa breviflora desert steppe in Ulanqab, Inner Mongolia Autonomous Region, to investigate the effects of grazing on soil physicochemical properties through a 9-year long-term experiment, aiming to reveal the processes and mechanisms of grassland soil degradation under different stocking rates and to inform reasonable grazing management measures for curbing grassland degradation and promoting sustainable development of grassland livestock production. The experiment was established with 4 stocking rate levels, with 3 replicates, using adult Mongolian wether sheep as the grazing livestock. Plot grazing experiments were initiated in 2004, with the grazing period each year from early June to late November and daily grazing duration from 06:00 to 18:00. Following the conclusion of the grazing experiment in 2012, analysis of grassland soil physicochemical properties yielded the following principal findings: After 9 years of continuous grazing, surface soil moisture content decreased significantly with increasing stocking rate ($P<0.05$); the effects of stocking rate on soil mechanical composition, pH, and available phosphorus and available potassium contents were not significant ($P>0.05$); soil organic matter content in the 0-10 cm soil layer was significantly lower under heavy grazing treatment compared to other treatments ($P<0.05$); soil bulk density decreased by 17.25% over the grazing period; with increasing grazing intensity, soil sand content exhibited an increasing trend while clay content decreased; soil available phosphorus and available potassium contents decreased with increasing stocking rate; in 2012, heavy grazing reduced soil respiration rate ($P<0.05$). Based on the analysis of the stocking rate × year interaction, after 9 years of continuous grazing, grazing in the Stipa breviflora desert steppe had not fundamentally induced severe degradation of grassland soil physicochemical properties; however, based on soil organic matter content, the soil exhibited a certain degree of degradation.

Full Text

Effect of Stocking Rate on Stipa breviflora Desert Steppe Soil Properties

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Abstract

Grassland grazing ecosystems represent one of the most efficient consumption systems in terrestrial ecosystems. However, few studies have examined the long-term effects of stocking rate on grazing ecosystem stability. Using the Stipa breviflora desert steppe in Ulanqab, Inner Mongolia as a case study, we conducted a nine-year stationary experiment to investigate grazing effects on soil physical and chemical properties. The study aimed to elucidate the processes and mechanisms of soil degradation under different stocking rates to inform reasonable grazing management measures and promote sustainable development of grassland animal husbandry. A randomized complete block design was established with four stocking rate treatments and three replicates. The treatments included control [non-grazed enclosure (CK)], light grazing (LG), moderate grazing (MG), and heavy grazing (HG). Adult Mongolian wether sheep were used in a continuous grazing system from June to November each year from 2004–2012. The stocking rates were 0 sheep$\cdot$hm^{-2} (CK), 0.91 sheep$\cdot$hm^{-2} (LG), 1.82 sheep$\cdot$hm^{-2} (MG), and 2.71 sheep$\cdot$hm^{-2} (HG). Soil physical and chemical properties were measured in 2004 and again in 2012 after nine years of grazing.

The results showed that soil water content in the topsoil decreased significantly with increasing stocking rate after nine years of continuous grazing. Soil bulk density decreased by 17.25% with extended grazing time ($P < 0.05$), but did not change significantly with stocking rate. The stocking rate had no significant influence on soil mechanical composition, pH, or contents of available phosphorus and potassium. However, soil organic matter in the 0–10 cm layer was significantly lower under HG treatment compared with other treatments ($P < 0.05$). With increasing stocking rate, the sand content in soil increased while clay content decreased. Additionally, HG treatment significantly decreased soil respiration rate in 2012. Based on statistical analysis of stocking rate, grazing year, and their interactions, the soil physical and chemical conditions of the S. breviflora desert steppe did not change significantly over the nine-year grazing period. However, organic matter showed apparent degradation. Due to the resilience, hysteresis, and complexity of natural soil systems, we recommend that studies on stocking rate effects on soil bulk density be conducted over longer time periods.

Keywords: Stipa breviflora desert steppe; Stocking rate; Soil system; Physical property; Chemical property

Introduction

In grazing ecosystems, the "grass-soil-livestock" components form an intimately connected and inseparable whole. As the most important substrate for grassland biomass production, soil stores substantial nutrients and serves as the primary site for decomposition and material cycling, forming the foundation for forage and livestock production. During grazing, livestock reduce ecosystem biomass and alter plant canopy structure and community composition through grazing, trampling, and excretion behaviors. These activities modify the chemical composition of litter inputs to soil, increase excrement deposition, alter plant root exudates, and affect soil microclimate, thereby directly or indirectly influencing soil physicochemical properties and soil microorganisms. Therefore, investigating the effects of different stocking rates on soil physicochemical characteristics and exploring the processes and mechanisms of grassland soil degradation are crucial for curbing grassland degradation and ensuring sustainable development of grassland livestock production.

Previous studies have demonstrated that grazing reduces aboveground biomass, increases soil temperature, and decreases soil moisture. As stocking rate increases, surface litter coverage declines, organic matter cycling weakens, soil fertility gradually decreases, surface soil erosion and compaction intensify, and grassland degradation accelerates. However, these studies have primarily focused on short-term grazing effects. Chinese scholars have conducted research on various grassland types, consistently showing that soil bulk density increases with stocking rate and soil depth. Conversely, some studies have reported that surface soil compaction and bulk density actually decrease under heavy grazing. Regarding grazing effects on soil organic matter, findings have been inconsistent: some report no effect, others show increased organic matter, while some demonstrate decreased content. Similarly, studies on soil available nutrients responses to grazing intensity have yielded divergent results due to environmental factors and soil properties.

In summary, although numerous scholars have investigated grazing intensity effects on soil, inconsistent results arise from differences in regional grassland types, grazing systems, grazing pressure gradients, grazing duration, soil conditions, and livestock types. Moreover, few studies have examined these effects over medium to long-term time scales in desert steppe regions. Therefore, this study selected the Stipa breviflora desert steppe as the research object. Located in an ecologically fragile arid and semi-arid transition zone between grassland and desert, this ecosystem has weak resistance and resilience to disturbance, with poor and unstable soil substrates. Through nine years of continuous monitoring, we investigated the effects of different stocking rates on soil physicochemical properties to understand grazing response patterns and provide scientific basis for determining appropriate grazing intensities and rational grassland utilization.

1.1 Study Area Description

The experimental site is located at Wangfu Team 1, Siziwang Banner, Ulanqab City, Inner Mongolia (41°47 17 N, 111°53 46 E) at an elevation of 1,450 m. The region has a typical mid-temperate continental climate with mean annual precipitation of 280 mm, characterized by dry, windy springs and hot summers. Evaporation is 7-10 times precipitation, with humidity of 0.15-0.3. The soil wind erosion modulus is 2,000-9,147 $t \cdot km^{-2} \cdot a^{-1}$, representing moderate erosion intensity. Soils are light chestnut.

The area belongs to the Stipa breviflora desert steppe, which accounts for 11.2% of the total temperate desert steppe area. Average vegetation height is 8 cm with sparse cover of 5%-18%. The plant community comprises approximately 20 species, with S. breviflora as the constructive species, Artemisia frigida and Cleistogenes songorica as dominant species, and major companion species including Convolvulus ammannii, Heteropappus altaicus, Neopallasia pectinata, Kochia prostrata, and Calagana stenophylla.

1.2 Experimental Design

The grazing experiment began in June 2004 using a randomized complete block design. The fenced grazing area was divided into three random blocks as replicates. Each block contained four treatments: control (CK, stocking rate 0), light grazing (LG, 0.91 sheep units $\cdot hm^{-2}$), moderate grazing (MG, 1.82 sheep units $\cdot hm^{-2}$), and heavy grazing (HG, 2.71 sheep units $\cdot hm^{-2}$), arranged randomly. Each experimental plot measured 4.4 hm^2.

Experimental sheep were adult Mongolian wethers. The grazing period each year extended from early June to late November (six months), with daily grazing from 6:00 to 18:00.

1.3 Sampling and Measurement Methods

Soil sampling employed completely random sampling within plots. For soil water content, three sampling points were established in each plot, with samples taken at 10 cm intervals from the surface to 20 cm depth, repeated three times. A 2 cm diameter soil auger was used to collect samples, which were weighed wet, then dried at 105 °C for 24 h to constant weight and weighed dry. Sampling occurred monthly from June to October each year, with average values calculated as soil water content. Soil bulk density was measured using soil rings ($V = 100\ cm^3$) to collect 5 cm surface soil samples, which were placed in aluminum boxes, brought to the laboratory, and oven-dried at 105 °C to constant weight for bulk density calculation.

Soil chemical properties were sampled in August using a 2 cm diameter auger at two depths (0–10 cm and 10–20 cm). Three samples were collected per plot, with each sample being a composite of three sampling points. Soil samples were air-dried indoors and sieved through 0.15 mm and 2 mm meshes. Fine soil was used for soil organic matter (SOM) determination via the potassium dichromate volumetric method with external heating. Coarse soil was used for mechanical composition and available nutrient (available potassium, available phosphorus) analysis. Mechanical composition was determined by the hydrometer method, available phosphorus by the 0.5 $\mathrm{mol \cdot L^{-1}}$ $NaHCO_3$ method, and available potassium by NH_4OAc extraction with flame photometry.

Soil respiration rate was measured using a LI-6400 (LI-COR, USA) connected to a soil respiration chamber (LI-6400-09, LI-COR, USA). Measurements were taken in August during clear weather. PVC tubes (10.5 cm diameter, 8 cm height) were installed 24 h prior to measurement in each plot, extending 2 cm above the surface, with three replicates per plot. Plants and litter inside the tubes were removed before measurement. The infrared gas analyzer in the chamber automatically recorded soil respiration rate and relative humidity data, which were imported to computer for analysis after measurement.

Soil physicochemical properties were sampled in 2004 and again in 2012 after nine years of grazing.

1.4 Data Processing and Analysis

Microsoft Excel 2010 was used for data compilation and chart construction. The SAS 9.0 software package was employed for statistical analysis, including ANOVA and regression analysis modules to test differences among treatments, years, and their interactions.

2.1 Effects of Different Stocking Rates on Grassland Soil Water Content

Analysis of stocking rate effects on soil water content (Table 1) revealed that in 2004 at the beginning of grazing, the 0–10 cm layer water content in the LG treatment was significantly higher than in CK and HG, with no significant difference between MG and HG. In the 10–20 cm layer, LG and MG were significantly higher than CK but not significantly different from HG. In 2012, the 0–10 cm layer water content in HG was significantly lower than CK but not significantly different from LG and MG. Similarly, the 10–20 cm layer water content in HG was significantly lower than CK but not significantly different from LG and MG. Stocking rate significantly affected soil water content, as did the interaction between stocking rate and year. In 2012, the 0–10 cm layer water content in HG decreased by 13.62% compared with CK, while the 10–20 cm layer decreased by 12.16%.

2.2 Effects of Different Stocking Rates on Soil Bulk Density and Mechanical Composition

Livestock trampling affects soil bulk density. Stocking rate effects on soil bulk density are shown in Figure 1 [Figure 1: see original paper]. Neither the interaction between stocking rate and year nor stocking rate alone significantly affected soil bulk density. In 2004, no significant differences existed among treatments. After nine years of grazing, soil bulk density showed a decreasing trend with increasing stocking rate, though the change was not significant. The average soil bulk density in 2012 was 1.36 $g \cdot cm^{-3}$, compared with 1.64 $g \cdot cm^{-3}$ in 2004, representing a 17.25% decrease.

Stocking rate effects on soil mechanical composition are presented in Table 2 . Stocking rate did not significantly affect surface soil mechanical composition. All treatments and the control showed the highest proportion of sand, followed by silt and clay, reflecting the parent material properties of the regional soil. In 2004 at the beginning of grazing, surface soil (0-10 cm) in all treatments was classified as sandy loam. After nine years of grazing in 2012, surface soil sand content showed an increasing trend while clay content decreased, though not significantly, with the surface soil remaining sandy loam.

2.3 Effects of Different Stocking Rates on Soil pH and Organic Matter Content

Soil pH results (Table 3) showed that in 2004, from CK through LG to HG, pH in both 0-10 cm and 10-20 cm layers first decreased then increased, with HG showing the highest pH and LG the lowest, though differences were not significant. The 10-20 cm layer pH was slightly higher than the surface (0-10 cm) soil. In 2012, CK showed the lowest pH while HG remained highest, but differences remained non-significant.

For grassland ecosystems, soil organic matter content changed under different stocking rates and soil depths over several years of grazing. Table 3 shows that in 2004 (the first grazing year), soil organic matter content decreased with increasing stocking rate, but differences between HG and other treatments were not significant. In 2012, the 0-10 cm soil organic matter content in HG was significantly lower than other treatments, while LG showed the highest content. In the 10-20 cm layer, LG had significantly higher organic matter than other treatments, with HG showing the lowest content.

After nine years of grazing, soil organic matter content decreased in both MG and HG plots. The trend was not significant in the surface layer but was significant in the 10-20 cm layer. Average organic matter content in 2004 was 24.71 $g \cdot kg^{-1}$ in the 0-10 cm layer and 20.92 $g \cdot kg^{-1}$ in the 10-20 cm layer, decreasing to 23.62 $g \cdot kg^{-1}$ and 18.97 $g \cdot kg^{-1}$ respectively in 2012, representing declines of 4.41% and 9.32%.

2.4 Effects of Different Stocking Rates on Soil Available Nutrients

Data analysis (Table 4) revealed that year and depth significantly affected soil available phosphorus content ($P < 0.05$), while interactions between depth and year, stocking rate and depth, stocking rate and year, and the three-way interaction did not significantly affect available phosphorus. Soil available potassium content differed significantly only among soil layers, with no significant effects from stocking rate or year.

In 2004, no significant differences in 0–10 cm available phosphorus existed among treatments. In the 10–20 cm layer, HG was not significantly different from LG but was significantly higher than other treatments ($P < 0.05$), while CK, LG, and MG showed no significant differences. In 2012 after nine years of grazing, surface available phosphorus in HG was significantly lower than CK and LG ($P < 0.05$) but not significantly different from MG. In the 10–20 cm layer, HG was not significantly different from MG but significantly lower than other treatments, with no significant differences among the remaining three treatments.

In 2012, available phosphorus content in CK and MG at both depths and in LG at 0–10 cm was higher than in 2004, while both layers in HG were lower than in 2004 ($P < 0.05$). The decreases in HG were 46.90% in the 0–10 cm layer and 46.39% in the 10–20 cm layer.

Table 4 shows that in 2004, CK had the highest available potassium content in both layers, with MG slightly lower but not significantly different. Both CK and MG were significantly higher than the other two treatments. In 2012, the 0–10 cm available potassium content was lowest in HG, though not significantly different from other treatments. In the 10–20 cm layer, LG and MG differed significantly, with MG showing the lowest content but not significantly different from CK and HG. The average surface available potassium content in 2012 was 147.36 $\mathrm{mg \cdot kg^{-1}}$, a 23.75% decrease from 2004, while the 10–20 cm layer average of 146.29 $\mathrm{mg \cdot kg^{-1}}$ represented a 76.36% increase. The difference between LG and HG in the 10–20 cm layer reached significance ($P < 0.05$).

2.5 Effects of Different Stocking Rates on Soil Respiration Rate

Soil respiration rate measurements (Table 5) showed significant effects from year and stocking rate ($P < 0.05$). In 2004, LG was higher than other treatments, but ANOVA indicated no significant differences ($P > 0.05$). In 2012, soil respiration rate under heavy grazing was significantly reduced ($P < 0.05$), with respiration rate decreasing as stocking rate increased. Between years, the average soil respiration rate in 2012 was 1.57 $\mathrm{\mu mol \cdot m^{-2} \cdot s^{-1}}$, a 25.6% increase from 2004.

Discussion

In grazing ecosystems, soil serves as the substrate intimately linked with forage and livestock, interacting with both the history and future trajectory of the ecosystem. Soil water content is a crucial indicator of soil firmness and permeability. Grazing livestock alter leaf area through defoliation while trampling affects soil permeability and consequently water content. As stocking rate and grazing duration increase, continuous trampling reduces surface soil porosity, impedes water movement to the surface, significantly increases soil firmness, and decreases water retention capacity, leading to reduced soil water content. These findings align with previous research.

Stocking rate did not significantly affect soil bulk density, which decreased by 17.25% in 2012 compared with 2004. This may be attributed to the low organic matter content in sandy soils, where heavy grazing intensity reduces organic matter content, decreases soil aggregate structure and stable aggregates, increases sand content, and reduces clay content, thereby decreasing bulk density. In this study, surface soil organic matter content decreased significantly with increasing stocking rate, consistent with research on the Xilin River grassland ecosystem. This occurs because grazing reduces surface vegetation and litter, increases surface soil temperature, and enhances mineralization of surface organic matter.

Soil available nutrients represent the most direct and rapid nutrient source for grassland plants. Available phosphorus content varies with soil type, climate, management level, and utilization intensity. Our results showed that stocking rate did not significantly affect available nutrients, though available phosphorus and potassium tended to decrease with increasing stocking rate. This contrasts with some studies showing increased available phosphorus under long-term heavy grazing due to reduced above- and below-ground biomass and return. In our study, high stocking rates likely increased nutrient export from the system through frequent defoliation, reducing available nutrient content.

Based on current soil physicochemical conditions, grazing has not fundamentally altered the grassland soil system. When soil water content is high, trampling compacts soil, increases surface runoff, and causes root hypoxia. When water is scarce, trampling creates a "hoof-tillage" effect that loosens surface soil, increases wind erosion risk, and reduces evaporation by cutting capillary action. Both compaction and hoof-tillage damage soil and plants, ultimately harming the entire ecosystem. Therefore, stocking rate effects on soil require integration with livestock trampling effects, though few studies have addressed this. Given the resilience, hysteresis, and complexity of soil systems, longer-term studies on stocking rate effects on soil bulk density are needed.

Conclusion

From 2004 to 2012 (nine years of grazing), different stocking rates significantly affected soil water content in the Stipa breviflora desert steppe, but did not significantly affect soil mechanical composition, pH, available phosphorus, or available potassium ($P > 0.05$). Soil bulk density decreased by 17.25% with extended grazing time. Heavy grazing significantly reduced soil organic matter content in the 0-10 cm layer ($P < 0.05$). With increasing grazing intensity, soil sand content increased while clay content decreased. Soil available phosphorus and potassium content decreased with increasing stocking rate. In 2012, heavy grazing reduced soil respiration rate ($P < 0.05$).

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