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Original Research

Long-Term Overgrazing-Induced Changes in Topsoil Water-Retaining Capacity in a Typical Steppe☆

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ABSTRACT

Understanding changes in topsoil water balance induced by grazing is of great interest for both theoretical and applied reasons. It can elucidate the processes involved in grassland degradation and is of practical importance to enhancing ecosystem functions. Unfortunately, the lack of studies on how litter and soil in grazed grassland affect soil water evaporation leaves a major gap in our understanding of the mechanisms underlying water availability and vegetation dynamics. Here, we report controlled experiments conducted to determine the impact of long-term overgrazing on topsoil water-retention capacity and evaporation rates in semiarid grasslands. Additional consideration is given to grassland ecosystem composition (i.e., litter, soil structure, and presence of plant roots). The data used correspond to typical steppe ecosystems in Inner Mongolia, northern China, where the grassland utilization consists of long-term grazing and long-term enclosure (since the 1980s). We examined soil from grazed and ungrazed land under three experimental treatments (litter exclusion, structural soil damage, and root exclusion) and a control treatment (undisturbed soil). Water capacity of the grassland soil decreased significantly (by 23.53%) after long-term overgrazing. Litter exclusion, structural soil damage, and root exclusion, however, had no effects on water-retaining capacity compared with undisturbed soil. Additionally, long-term-grazed soil had significantly lower water-retaining capacity compared with ungrazed soil. Litter exclusion, soil damage, and root exclusion significantly increased evaporation rates relative to undisturbed soil. Relative to the litter treatment, soil structure and roots had reduced effects on water-retaining capacity. The relative evaporation rate was significantly increased by temperature and wind speed and decreased by relative humidity. However, of all external meteorological factors, temperature most strongly governed grassland soil water evaporation. Overall, the combined effects of overgrazing and climate warming on soil water evaporation will accelerate soil water loss in grassland regions. This has significant implications for the management of degraded grasslands.

Introduction

Determining the relationship between topsoil water balance and human land use is of great interest for understanding the processes involved in global changes. It is also of practical importance in predicting the effect of human-induced vegetation productivity declines, biodiversity loss, and the rapid depletion of natural resources (Chen et al., 2008; Liancourt et al., 2012). Grassland occupies approximately 40.5% of the world's land area (excluding Antarctica and Greenland). In addition, grassland is, by area, the largest terrestrial ecosystem in China (Shan et al., 2011). The degradation of grassland caused by overgrazing is a major ecological challenge globally but especially in Inner Mongolia, northern China (Xu et al., 2014). Numerous studies have examined the mechanisms of grassland degradation from various perspectives (i.e., landscape, ecosystem, community, population, plant traits, etc.). In general, human activity (mainly livestock grazing) is the primary cause of grassland degradation globally (Sanderson et al., 2004; Wilsey et al., 2014).

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Long-term overgrazing likely alters the functioning of grassland ecosystems directly through its effect on plant growth and indirectly via its effects on the soil microenvironment; moreover, it may have an impact on the global carbon budget, water balance, and nutrient cycling (Hassani et al., 2008; Wu et al., 2010). Understanding the effect of grazing-induced changes on soil water balance (e.g., the water-retaining capacity of the soil and evaporation rate of the grassland ecosystem) is a fundamental problem. Such studies are essential for clarifying the causes of grassland degradation, which is characterized by productivity declines, biodiversity loss, and retrogressive succession of communities (Paruelo et al., 2000). In semiarid and arid regions of the world, water primarily affects the structure and function of grassland ecosystems (Bai et al., 2004). To date, little is known about the pattern of change in grassland water processes impacted by long-term overgrazing. Therefore, there is an urgent need to study the effects of long-term overgrazing on grassland soil water-retaining capacity and evaporation rate.

Numerous experiments have demonstrated that grazing-induced degradation of grasslands can cause a switch in the pattern of dominant water loss from transpiration to direct evaporation (Li et al., 2015). This grazing-induced switch between evaporation and transpiration in grasslands is mediated by changes in living plants, ground litter, and soil prosperities (Veldhuis et al., 2014). However, there is also an ongoing controversy concerning grazing-induced responses in evaporation rates (Odriozola et al., 2014). In contrast with this view commonly described by many reports, some studies have found that soil moisture limitation in grazed grasslands can significantly constrain evaporation rates (Wu et al., 2014). Accordingly, the in situ — only measurements of soil evaporation that are traditionally employed make it difficult to clearly identify the processes that change water content through overgrazing.

In this study, the effects of long-term overgrazing (for > 30 yr continuously) on grassland soil water-retaining capacity and evaporation rate are examined using controlled experimental conditions. The aim is to clarify the relationship underlying topsoil water change and grazing, as exemplified, to some extent, by typical steppe ecosystems (in Xilinhot, Inner Mongolia, China). We aimed to disentangle the cause of the interactions among soil, vegetation, and water resources by comparing four treatments (i.e., undisturbed soil, soil with litter excluded, soil with structural damage, and soil with roots exclusion) using two paired experimental groups (with and without grazing). Accordingly, our main hypotheses in this study are as follows: 1) long-term overgrazing significantly reduces the ability of topsoil to hold water in semiarid grassland ecosystems; 2) the different treatments (litter exclusion, soil structural damage, and root exclusion) decrease the water-retaining capacity of the grassland soil compared with undisturbed soil under both the with- and without-grazing treatments; 3) the rate of evaporation of soil water increases with litter exclusion, soil structural damage, and root exclusion, and there is decreased grassland soil water-retaining capacity compared with undisturbed soil, especially in long-term overgrazed grassland; and 4) the rate of evaporation of grassland soil water is governed by meteorological factors (e.g., temperature, relative humidity, wind speed) to various degrees.

Methods

Study Site

The study site is located at the Inner Mongolia Grassland Ecosystem Research Station (IMGERS, 43°38′N, 116°42′E) in the Xilin River catchment, China, at an altitude of approximately 1 200 m above sea level. The semiarid continental climate of the site is characterized by a mean annual precipitation of 236 mm and a mean annual temperature of 0.7°C (1998–2012). As a result of the interannual variability, the coefficient of variation of precipitation is 22%. Typically, the maximum precipitation coincides with the highest temperatures (i.e., in June, July, and August). For perennial plants, the growing season lasts approximately 150 d from April or May to September or October. Annual plants, however, do not typically germinate until July, following the period of highest rainfall. The perennial rhizome grass *Leymus chinensis* and bunch grass *Stipa grandis* dominate the typical steppe communities. The major soil types of this region are calcic chestnut and calcic chernozem.

Experimental Design and Measurements

In 1983, grazing exclusion plots (i.e., land to be left ungrazed) were established nearby the long-term free-grazing plots by IMGERS and Inner Mongolia University for long-term ecological observation and research on typical and meadow steppes. The grazing plots, which covered > 200 ha in area, had been grazed by > 900 sheep and goats year-round for > 30 yr. Therefore, the stocking rate in this region is about 4.5 sheep per ha. This is significantly higher than the standard stocking rate of local grazing practices (1.5 sheep per ha).

Field sampling was carried out at the beginning of April 2014, corresponding to the time before the grassland landscape of Xilinhot, Inner Mongolia turned green. Following the principles of replication, randomization, etc., > 30 cubical, undisturbed soil samples measuring 45 cm × 45 cm × 50 cm (length × width × height) were sampled regularly using soil sampling methods in the long-term overgrazed and long-term ungrazed plots. Undisturbed soil samples were carefully transferred back to a laboratory located at the National Forage Improvement Center of China in the Shaerqin Farming-pastoral Ecotone Experimental Station (SFEES) of the Institute of Grassland Research, Chinese Academy of Agricultural Sciences (40°36′N, 111°45′E). All the undisturbed soil was air-dried naturally and completely in a ventilated laboratory room for about 60 d (up to early June 2014).

In order to explore the roles of different soil compositions (e.g., vegetation litter, soil structure, soil roots) in determining the water-retaining capacity of the grassland soil and the evaporation rate, four pairs of experimental treatments (undisturbed soil, litter excluded, soil with structural damage, and root-excluded soil) were imposed on grazed and ungrazed soil. Four replications were included for each treatment using replicate pots. Two land use treatments (nongrazing and grazing), four soil treatments, and four replications of each combination of soil and land use treatments were examined in our research. Therefore, 32 pots were involved in the whole experiment. Before the four experimental soil treatments were applied, all the cubic soil blocks were oven-dried for 48 hr. Then the four treatments were conducted sequentially (from undisturbed soil to root-excluded) using the following steps: 1) A knife was used to lightly prune the shape all of the undisturbed soil to fit within each pot; 2) In the litter exclusion

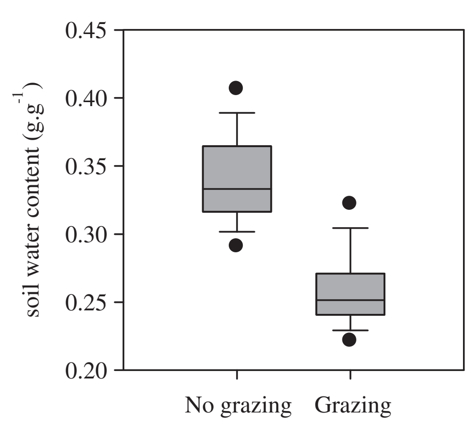

Figure 1. Effects of long-term grazing on the water-retaining capacity of grassland soil. After adequate irrigation in the laboratory (10 hr), there were significant differences in the water-retaining capacity of the soil from the grazed and ungrazed grassland, on the whole, according to an analysis of variance ($F = 66.82$, $P < 0.001$).