University of Alberta

Spatial patterns of vegetation and soil fertility along a grazing gradient in a desert steppe in Inner Mongolia, China

by

Yang Lin

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Examining Committee

Dr. Scott Chang, Renewable Resources

Dr. Fangliang He, Renewable Resources

Dr. James Cahill, Biological Sciences

Dr. Edward Bork, Agricultural, Food and Nutritional Science

ABSTRACT

Spatial heterogeneities of vegetation and soil can strongly affect ecological processes in arid and semi-arid ecosystems. However, little is known about how those spatial patterns respond to grazing intensity in such systems. I studied how grazing intensity affect the spatial patterns of vegetation and soil nutrients at scales ranging from 0.1 to 18.7 m in a desert steppe in Inner Mongolia, China. Vegetation patches were more fragmented and homogeneous under higher grazing pressure. Heavy grazing also destroyed the spatial aggregation of plant species richness. Spatial heterogeneity of soil water and organic matter contents decreased along the gradient of increasing grazing intensity, while that of soil mineral N was first increased and then decreased along the grazing gradient. Both percent plant cover and power-law modeling could be used to indicate the risk of desertification associated with increasing grazing pressure.

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1. Introduction

Degradation and desertification has been a global threat to conservation, management and development of arid and semi-arid ecosystems (Schlesinger et al. 1990, Dodd 1994, Reynolds et al. 2007). Up to 73% of rangelands in these ecosystems have experienced some forms of degradation, including long-term reduction of productivity and biodiversity, loss of soil fertility through wind and water erosion, reduced water resources and, in some cases, salinization (Lund 2007). Due to the fragility of arid and semi-arid ecosystems, human utilization can easily surpass the natural carrying capacity of those ecosystems and lead to land degradation. To address the challenge of degradation and desertification, the interaction between human activities and ecosystem processes should be better understood.

Spatial patterns of vegetation and soil resources have been emphasized in recent studies because of their strong relationship with ecosystem functions (Schlesinger et al. 1996, Schade and Hobbie 2005, Maestre et al. 2006, Coppedge et al. 2008). Spatial vegetation patterns have been suggested to indicate desertification processes (Kefi et al. 2007). However, it is still unclear how human disturbances would change those spatial patterns. In this chapter, I will review the current understanding about the formation and functions of spatial patterns of distribution of vegetation and soil nutrients and their responses to grazing, which is the major land use type in arid and semi-arid ecosystems. I will also describe the research objectives and hypotheses of this M.Sc. thesis.

1.1 Spatial patterns in arid and semi-arid ecosystems

The distribution of plants, soil nutrients and animals commonly forms spatial patterns in natural ecosystems. For example, regularly isolated clusters of trees and shrubs are typical traits of savanna ecosystems, and tree lines and snow deposition can form striped patterns in sub-alpine forests (Rietkerk and van de Koppel 2008). Grazed arid and semi-arid ecosystems cover nearly 30% of the earth's terrestrial surface (HilleRisLambers et al. 2001). In these systems, plant communities can often be considered as two-phased mosaics consisting of a high-cover phase and a low-cover phase (bare land) (Aguiar and Sala 1999). Thus, the vegetation will be characterized by different patches at multiple scales. Vegetation patches vary in form, ranging from irregular mosaics to regular shape (such as "stripes", "labyrinths" and "spots"), and in sizes, changing from less than a meter to several hundred meters (see HilleRisLambers et al. 2001 for a review, Rietkerk et al. 2002). In these ecosystems, soil nutrients could also form spatial patterns at scales varying from the individual plant to landscape feature (Afzal and Adams 1992, Jaramillo and Detling 1992, Frank and Groffman 1998, Augustine and Frank 2001).

There are several major hypotheses explaining the formation of vegetation patterns in arid and semi-arid ecosystems. Some mechanisms emphasize the impact of disturbances such as fire, ungulate grazing and termite. For example, Bromley et al. (1997) suggested that vegetation mosaics started from complete cover and were formed by disturbances, which changed vegetation cover and created bare land. Other scientists attributed vegetation patterns to patterns of soil nutrients and properties (Boaler and Hodge 1962, Belsky 1986). All the above mechanisms are primarily based on conceptual models. In recent years, more and more studies prefer to use the so-called “scale-dependent feedbacks” mechanism to explain vegetation pattern formation based on simulation models (Lejeune et al. 1999, HilleRisLambers et al. 2001, Rietkerk et al. 2004, Rietkerk and van de Koppel 2008). This mechanism claims that localized facilitation among plants and competition for resources over a long range are able to generate regular or random vegetation patterns in arid and semi-arid ecosystems.

Vegetation patterns can significantly affect the spatial distribution of soil nutrients and other soil properties. Plants, especially shrubs and trees, have a strong positive effect on soil nutrients to form islands of fertility where nutrient availabilities are higher than in the surrounding bare land (Schlesinger et al. 1996, Reynolds et al. 1999). Multiple mechanisms explain the positive impact of plant coverage on soil properties, including deposition of litter in local area, root sequestration, unbalanced distribution of water caused by roots and symbiotic nitrogen-fixing bacteria in roots (Schlesinger and Pilmanis 1998). As a result of positive plant impacts, soil properties can show spatial patterns similar to that of vegetation (Schlesinger et al. 1996, Rietkerk et al. 2000, Schade and Hobbie 2005). Augustine and Frank (2001) found that ungrazed grasslands in Yellowstone National Park exhibited a high degree of patchiness in the distribution of soil N and N-mineralization rates (94 and 77% of total variation could be explained spatially, respectively) at small spatial scales (0.1-2 m). Rietkerk et al. (2000) proved that the variations of soil moisture content could be spatially explained (86%) in a savanna in West Africa. Overall, these studies suggest that the impact of vegetation on soil nutrient distribution mainly takes place at small scale (several meters or less), although other abiotic factors such as landscape position, precipitation and parent material also affect the spatial distribution of soil properties at larger scales (Belsky 1994).

Geostatistics have been widely applied to study the spatial variation of vegetation and soil variables (Schlesinger et al. 1996, Augustine and Frank 2001, Gallardo et al. 2006). Spatial patchiness of single variable could be studied by semivariance analysis, which examines the variance between measurements taken at increasing distance from each other and provides useful information with regard to the average size of patches and the degree of heterogeneity (Augustine and Frank 2001, Lane and BassiriRad 2005). Cross-correlogram that study the spatial correlation between two dependent variables provides an useful tool to examine how vegetation patches affect the spatial distribution of soil variables (Rietkerk et al. 2000). Near-surface aerial photos with high resolution have been recently used to construct maps of vegetation patches to study the spatial pattern of vegetation (Bar Massada et al. 2008). Compared to geostatistical methods, which require extensive sampling in a regular or fixed sampling matrix, photography method is more time-efficient in studying the vegetation patches.

Given that ecological processes are closely related to spatial patterns in arid and semi-arid ecosystems, the functions of natural spatial patterns have been recently emphasized in ecological research. Spatial vegetation patterns can influence seedling establishment (Tirado and Pugnaire 2003), pollination (Aguilar et al. 2006) and plant community composition (Facelli and Brock 2000, Joshi et al. 2006, Lopez et al. 2009). Vegetation patches serve as important habitats for animals such that changes in vegetation patchiness can greatly alter the community structure of soil biota and birds (Housman et al. 2007, Coppedge et al. 2008). Vegetation patches are more effective in trapping water and sediments than bare ground, protecting ecosystems from wind and water erosion (Reid et al. 1999, Puigdefábregas 2005, Descheemaeker et al. 2006).

It is well documented that spatial heterogeneity of soil nutrients can affect the coexistence of plant species, plant community structure and productivity (Day et al. 2003, Hutchings et al. 2003, Lundholm 2009). Therefore, localized nutrient accumulation under vegetation patches may provide important feedback to plant populations and communities. Spatial heterogeneity of soil nutrients can change soil microbial composition (Herman et al. 1995) and functions (Bennett and Adams 1999, Schade and Hobbie 2005, Gonzalez-Polo and Austin 2009). For example, Schade and Hobbie (2005) found higher net N mineralization, net nitrification and microbial biomass in islands of fertility than those in surrounding bare ground in Sonoran Desert, Arizona, USA. Spatial patterns of soil nutrients and microbial activities can have strong impacts on the C stock and greenhouse gas emission and influence the feedback of arid and semi-arid environment on climate change (Maestre and Reynolds 2006).

1.2 Grazing and spatial patterns of vegetation and soil

Due to the importance of the biotic and abiotic spatial patterns on ecological functions, there is an increasing body of literature documenting how disturbances, such as grazing, fire and climate change, affect those spatial patterns (Reynolds et al. 1999, Golodets and Boeken 2006, Coppedge et al. 2008). Livestock grazing is the main land use in arid and semi-arid rangelands and strongly modifies the properties and functions of ecosystems, such as forage production, diversity, community composition and soil fertility (Hobbs 1996, Marìa and Martìn 2001, Han et al. 2008). Contradicting results are usually reported with respect to the effects of grazing on the above properties and functions of ecosystems. For example, grazing has been shown to increase (Loeser et al. 2007, Olofsson et al. 2008), maintain (Stohlgren et al. 1999), or decrease rangeland plant diversity (Kruess and Tscharntke 2002). Grazing has also been shown to increase (Pineiro et al. 2009), maintain (Tracy and Frank 1998, Cui et al. 2005), or decrease soil organic carbon concentration (Su et al. 2005, Steffens et al. 2008).

Similarly, grazing has been found to present contrasting effects on the spatial patterns of vegetation in arid and semi-arid ecosystems (Berg et al. 1997, Adler et al. 2001, Olofsson et al. 2008). Grazing impacts can have great variation spatially based on the regime of grazing and properties of ecosystems (Hobbs 1996), and it can strongly affect the direction of change of spatial vegetation pattern (Adler et al. 2001). Rietkerk (2000) suggested that grazing intensity affected the spatial distribution of grazing and subsequently changed the spatial patterns of vegetation. However, few studies have examined the responses of spatial vegetation pattern to grazing intensity.

Grazing has been shown to increase (Afzal and Adams 1992, Rietkerk et al. 2000) or decrease (Augustine and Frank 2001, Wiesmeier et al. 2009) spatial heterogeneity of soil properties in arid and semi-arid ecosystems. Grazers have direct impacts on soil properties by tramping and wallowing, which can cause soil compaction (Knapp et al. 1999), and by adding excreta to change nutrient availabilities (Tolsma et al. 1987). Grazers can also indirectly affect spatial distribution of soil properties through changing substrate input through plant roots and litter, altering the spatial distribution of plant species composition and/or affecting the spatial patterns of other organisms such as insects (Augustine and Frank 2001). The interaction between spatial patterns of vegetation and soil is important in understanding the role of grazing on arid and semi-arid ecosystems; however, most previous studies only focused on one aspect of the interaction. Moreover, few studies have attempted to understand how grazing intensity affects this interaction.

Spatial patterns of vegetation and soil can also affect grazing behavior. For example, Hester et al. (1999) found that sheep prefers small-size grass patches in a heather moorland in Scotland. Grazers can create patches that maintain a higher forage quality and plant growth rate. These patches, known as "grazing lawns", have a higher possibility to attract grazers to feed on them again (Dutoit 1990). Forming grazing lawns can provide positive feedback between grazing and re-grazing. In contrast, this feedback can become negative when grazers destroy the spatial patterns of vegetation and soil. If grazing intensities induce different patterns of vegetation and soil distribution, the feedback between grazing and re-grazing is likely to change accordingly. Therefore, understanding the relationship between grazing intensity and spatial patterns is essential for sustainable management of arid and semi-arid ecosystems.

Recent studies have suggested that changes in vegetation pattern can have direct application in rangeland management to indicate suitable grazing intensities and warning signals for desertification (Schlesinger and Reynolds 1990, Kefi et al. 2007). Kefi et al. (2007) found that the sizes and numbers of vegetation patches follow a power-law distribution under low grazing pressures in three different Mediterranean arid and semi-arid ecosystems, but the patch-size distribution would deviate from standard power law under higher grazing pressures. Based on this phenomenon and model simulation results, they suggested that the deviation from power-law distribution could serve as a predictor of early desertification. However, Maestre and Escudero (2009) did not observe such deviation along a gradient of increasing desertification; instead they found that percent plant cover could be used as an indicator for desertification. Studying the impacts of grazing intensity on spatial vegetation pattern can provide an opportunity to test the suitability of these predictors.

The Inner Mongolia Steppe is the main part of the Central Eurasian Steppe region and the biggest continuous grassland in China. Overgrazing has caused severe land degradation and eventually desertification in this region (Su et al. 2005, Zhao et al. 2005, Zheng et al. 2005). Compared to other types of grasslands, desert steppe accounts for 39% of total native grassland in Inner Mongolia and has a higher susceptibility to overgrazing (Li et al. 2000). Thus, desert steppe is a great model ecosystem to study the grazing-induced desertification. Choosing a suitable grazing intensity and identifying early signals for desertification are extremely important for sustainable rangeland management in this type of desert steppe.

1.3 Research objectives

As discussed above, there is still a knowledge gap regarding how disturbances (such as grazing) affect spatial distributions of vegetation and soil resources in arid and semi-arid ecosystems. Little is known about the role of grazing intensity in modifying the influences of livestock grazers on those spatial patterns. The performance of spatial vegetation patterns as a desertification indicator has not been tested in a wide range of ecosystems.

The central research question of this M.Sc. thesis is how grazing intensity affects the spatial patterns of vegetation and soil fertility in a desert steppe in Inner Mongolia, China. The specific research objectives are:

1) To determine how vegetation characteristics (such as aboveground biomass and height) and soil nutrient availability (such as soil organic carbon and mineral nitrogen) change along a grazing gradient (Chapter 2)

2) To determine how the characteristics of vegetation and soil patchiness change along the grazing gradient (Chapter 2 & 3)

3) To determine the spatial correlations between vegetation metrics and soil nutrient availabilities and their responses to grazing intensities (Chapter 2), and

4) To determine whether percent plant cover and the patch-area distribution of vegetation can indicate the desertification process associated with increasing grazing pressure (Chapter 3)

For the above objectives, I hypothesized that:

1) Increasing grazing intensity decreases biomass and height of the vegetation and soil nutrient availability
2) Grazing intensities have different impacts on patchiness of the vegetation and soil properties. Compared to ungrazed exclosures, heavy grazing decreases spatial heterogeneity of the studied variables, while light grazing would maintain those spatial heterogeneity
3) Spatial distributions of soil nutrients are correlated with those of vegetation metrics under no or light grazing pressure and heavy grazing weakens these correlations, and
4) Patch-area distribution of vegetation is suitable for detecting signs of desertification

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