Simulating self-organized spatial patterns induced by overgrazing

Yichun Xie[1] and Ting Ma[1]

[1]Department of Geography and Geology
Eastern Michigan University
Ypsilanti, Michigan 48917, USA
E-mail: yxie@emich.edu, tma@emich.ed

1. Introduction

Dryland ecosystems and their services are highly sensitive to exogenous stresses caused by intensifying human activities and changing climate. It is very critical to study the processes of grassland degradation and consequent desertification in response to intensified grazing pressures and severe climate events. Understanding these processes is a prerequisite for determining best practices of balancing the conflicts between the intensifying grazing pressure due to growing human population and economic desire and the increasing awareness of sustainable use of dryland ecosystems (Reynolds *et al*. 2007; Gillson 2007; Smith *et al*. 2007). However, it is difficult and also controversial to identify an equilibrium between vegetation productivity and herbivore consumption because of the complexity and uncertainty of coupled natural and human ecosystems (Gillson 2007; Liu *et al*. 2007). Complicated behaviors of degraded ecosystems at multiple spatiotemporal scales can not be simply inferred from evolution equations. Hence, a new approach interpreting emergent landscape patterns as direct outcomes of vegetation degradation could potentially contribute to a comprehensive understanding of the evolutions of dyland ecosystems affected by anthropogenic pressures and environmental variables.

Recent studies concerning arid and semiarid ecosystems suggest that the emergence of spatial landscape patterns is likely linked to the transitions of grassland degradation states induced by external pressures and local disturbances (Rietkerk *et al*. 2004; Kéfi *et al*. 2007). Intensifying grazing pressure was found to significantly affect plant growth and its spatial pattern through the analysis of satellite-derived normalized difference vegetation index (NDVI) (Kawamura *et al*. 2005). .

Our field survey as well as image analysis has confirmed the occurrence of self-organized landscape patterns in the dryland ecosystems of Xilingol Steppe in Inner Mongolia. Our analysis indicates that the size distributions of both degraded and vegetated patches fit to the power law (Fig. 1). Changes in the scaling parameters (including the fitting slopes and intercepts) directly reflect the dynamic transitions of emerging patterns of self-organized patches under various grazing pressures, climate variables, and resources availabilities.

2. Materials and Methods

We are constructing an agent model on the basis of a discrete lattice composing of N cells, and each cell represents a discrete land cover site. There is a single type of agent in this model, called herdsman agents who practice animal husbandry randomly across a simulate grassland and cause grazing pressure as the primary reason of degradation. The physical environmental resources of this simulated grassland are determined by two natural elements, vegetation and soil. The environmental factors such as climate change and water condition are indirectly contained in the mathematical descriptions of these two elements. The vegetation element is formulated as two interdependent components, grass

(G_i) and root (R_i), which are impacted by habitat and grazing factors with logistic growth (adapted from Anderies *et al*. 2002 and Williams & Albertson 2006):

$$\begin{aligned} \frac{dG_i}{dt} &= (1-\frac{G_i}{G^*})[(\gamma_{g\to g}G_i+\gamma_{r\to g})R_i-\varsigma_g G_i]-C_i \\ \frac{dR_i}{dt} &= (\gamma_{g\to r}G_i-\varsigma_r R_i)+<R_i>\{1-\exp[-\alpha(1-\frac{R_i}{<R_i>})]\} \end{aligned} \tag{1}$$

If the grazing effect C_i and the spatially local interaction (the last item in the root and the soil evolution equations, respectively) were not taken into consideration, the entire vegetation system would have stable and uniform intrinsic growth rate γ and mortality rate ς. Hence it could reach a nontrivial equilibrium point (*12*), in which G_i equals the potential grass biomass G^* that depends on the soil and climate conditions. This equilibrium status, however, becomes increasingly fragile with the escalation of spatial heterogeneity of natural resources or environmental conditions induced by exogenous pressures and corresponding endogenous responses (Schlesinger *et al*. 1990; Rietkerk *et al*. 2004). Furthermore, Equation 1 describes the spatially local interaction of the root component as a function of the gradient of root biomass between R_i and its neighboring sites $<R_i>$, of which every site owns more root biomass than itself, according to the exponential law.

The dynamics of soil agents S_i are closely related to corresponding R_i, which prevents soil resource loss from wind and water erosion. While the local facilitation with adjacent soil sites is treated as the way as R_i is, the dynamic behavior of soil agents is given by:

$$\frac{dS_i}{dt} = -\tau\exp(-\frac{R_i}{R_0})S_i+<S_i>\{1-\exp[-\beta(1-\frac{S_i}{<S_i>})]\} \tag{2}$$

Parameters α and β, which are positively related to the soil moisture and nutrients, represent the intensity of local facilitation. Lower τ and higher α and β values are usually associated with better soil and environmental conditions, which are better resistant to exogenous disturbances. Over spatially heterogeneous vegetation and soil communities, the growth and mortality rates of plant are varied across the whole grassland depending on local habitat or environmental conditions. Hence, our model assumes that $\gamma_i(t) = \gamma(0)S_i(t)$ and $\varsigma_i(t) = \varsigma_i(0)(2 - S_i(t))$ while the quantity of S_i is scaled within the range, 0 to 1. Grazing in semiarid grassland has long been one of the leading causes of three reciprocal processes, such as spatio-temporal heterogeneity of environmental resources, desertification, and invasive plant intrusion (Schlesinger *et al*. 1990; Kéfi *et al*. 2007). These processes lead to self-organized patterns of patchy landscape followed by grassland ecosystem degradation in both structures and functions (Rietkerk *et al*. 2004). The herdsman agents are introduced in this agent model to simulate the dynamic features of grassland degradation. A stochastic grazing algorithm was incorporated to portray the behaviors of herdsmen, which will generate random external disturbances and spatial heterogeneity of vegetation and soil resources. A herdsman randomly chooses one of the neighboring sites as the initial pasture for grazing. When all adjacent sites have been visited over a given time, the herdsman has to choose another site that is surrounded with abundant unvisited sites as the new settlement site to continue grazing until the forage in the neighboring cells is almost consumed. The allowed grass consumption at grazing cites is pre-determined as a fixed proportion of the forage. The amount of forage consumption is determined by the simulation time, and the consumption status is called the grazing pressure. This random grazing behavior and Herdman's random settlement constrained by the available forage resource simulates uneven degradation of grassland starting with an initially homogeneous structure.

The agent model is implemented on a grid lattice of 160×160. Every cell is set to represent a homogeneous grassland surface with actual size of 100m×100m. Every cell has three interwoven status parameters including grass biomass, root biomass and soil condition. The status of grid cells is determined by an external grazing pressure and the status of adjacent cells (von Neumann Neighborhood). We assumed that herdsman agents live in this simulated rangeland and practice stochastic grazing activities. The number of herds depends upon the available amount of forage which approximately equals the product of the total grass biomass and the pre-defined grass pressure (from 0 to 1). In every simulated time step, the followings are executed: (1) estimate the forage amount based on the total grass biomass and the grazing pressure; (2) determine the number of herds; (3) move randomly for grazing in the simulated rangeland; (4) update the grass biomass on the basis of the animal's consumption; (5) calculate the natural growth for grass-root system and (6) update soil conditions for all cells.

3. Preliminary Results

The simulation results with various parameter values exhibit diverse relationships among the degradation process (expressed as simulate time steps), the habitat and climate-related variables (α, β and G^*) and grazing pressure. As shown in Fig. 2, all simulated rangelands are sensitive to the increase of grazing pressure and extremely vulnerable to heavy grazing pressure. For instance, low grazing pressure is often associated with a slow degradation process (Fig. 2a), and all simulated rangelands are total degraded in fewer than 30 simulated steps when the grazing pressure exceeds 0.7.

An interesting finding is that when the grazing pressure is moderate (around 0.5 in this case), the rangelands with better habitat conditions (better soil quality and environmental conditions) illustrate an enhanced resistance to degradation (Fig. 2b). Moreover, the simulated grassland with better habitat and climate conditions, in general, illustrates a stronger resilience to the degradation process (Fig. 2a, 2b, and 2c).

In brief, the simulated results demonstrate that continuous pasturing (i.e., increasing grazing pressure) is probably the most important factor to cause inconspicuous degradation of grassland even under lower grazing pressure. Varied degradation curves at different time steps in simulation and with various combinations of impact factors also imply that no single stable equilibrium status can be found for rangeland ecosystems. Hence, best practice of rangeland management should avoid excessive grazing practice either duration or in intensity so as to sustain recurring use of rangeland. A systematic approach and a comprehensive plan should be taken to balance all aspects of a grazing ecosystem, such as the coordination of the "carrying capacity" with the livestock rate and the grassland productivity.

4. References

1. Gillson, L. & Hoffman, M.T. (2007). Rangeland ecology in a changing world. *Science*, 315, 53-54.
2. Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O. & Wang, S. (2005). Quantifying grazing intensities using geographic information systems and satellite remote sensing in the Xilingol steppe region, Inner Mogolia, China. *Agric. Ecosyst. Environ.*, 107, 83-93.

3. Kéfi, S., Rietkerk, M., Alados, C.L., Pueyo, Y., Papanastasis, V.P., EIAich, A. & de Ruiter, P.C. (2007). Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature*, 449, 213-217.
4. Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E. *et al*. (2007). Complexity of coupled human and natural systems. *Science*, 317, 1513-1516.
5. Reynolds, J.F., Smith, D.M.S., Lambin, E.F., Turner II, B.L., Mortimore, M., Batterbury, S.P.J. *et al.* (2007). Global desertification: building a science for dryland development. *Science*, 316, 847-851.
6. Rietkerk, M., Dekker, S.C., de Ruiter, P.C. & van de Koppel, J. (2004). Self-organized patchiness and catastrophic shifts in ecosystems. *Science*, 305, 1926-1929.
7. Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L. F., Jarrell, W.M., Virginia, R.A. *et al*. (1990). Biological feedbacks in global desertification. *Science*, 247, 1043-1048.
8. Smith, D.M.S., McKeon, G.M., Watson, I.W., Henry, B.K., Stone, G.S., Hall, W.B. & Howden, S.M. (2007). Learning from episodes of degradation and recovery in variable Australian rangelands. *Proc. Natl. Acad. Sci*, 104, 20690-20695.

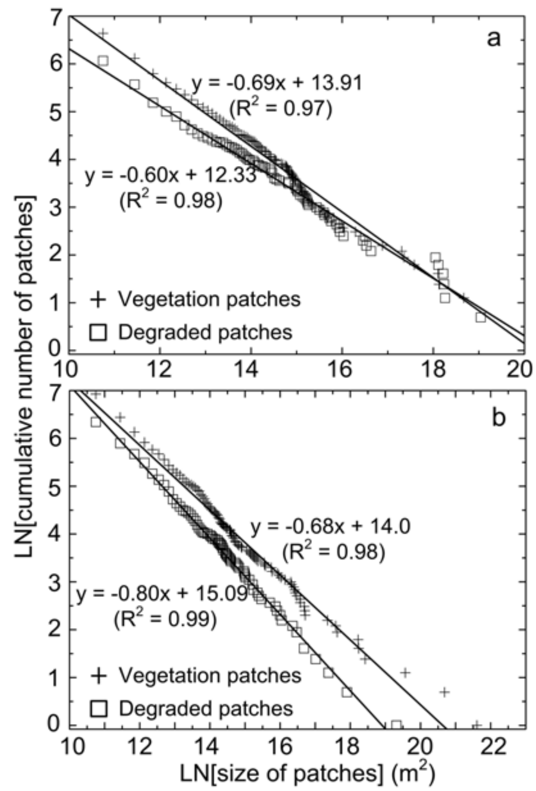

Figure 1 Rank-size distributions of grassland patches in July, 2001 (a) and 2005 (b) in Baiyinxile Rangeland (Xilingole Steppes, Inner Mogolia, China). The grassland patches are derived from MODIS NDVI data according to the classified fractional vegetation cover (*FC*) index. The definition of *FC* is $(NDVI - NDVI_{\min})/(NDVI_{\max} - NDVI_{\min})$. The classification rules for different types of pixels are as follows: severe degraded ($FC \leq 0.1$), medium degraded ($0.1 < FC \leq 0.3$), slight degraded ($0.3 < FC \leq 0.5$) and non-degraded ($0.5 < FC$). The degraded patches in the rank-size diagram are composed by the severe and medium degraded patches. The slight and non-degraded patches are treated as the vegetation patches. *P*-value is less than 0.001 for all linear fittings.

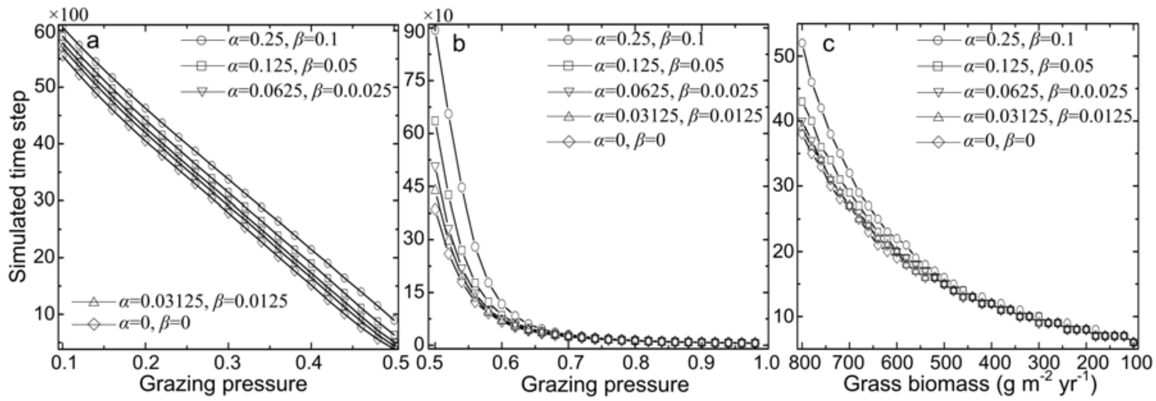

Figure 2 The simulated time steps against grazing pressure and potential grass biomass, under various environment-related local interactions. Initial model parameter values are: $G(0) = G^* = 800$ $gm^{-2}yr^{-1}$ (for a and b), $R(0) = 240$ $gm^{-2}yr^{-1}$, $r_{g\rightarrow g} = 0.03$, $r_{r\rightarrow g} = 0.03$, $\varsigma_g = 0.5$, $r_{g\rightarrow r} = 0.15$ and $\varsigma_r = 0.5$. After grazing pressure increases over 0.7, all simulations are finished within 30 simulated time steps (b). While the potential grass biomass is less than 500 $gm^{-2}yr^{-1}$, all rangeland systems are totally degraded in no more than 15 simulated steps with a constant grazing pressure of 0.65 (c)**.**