Threshold dynamics of vegetation and their management implications in a Mongolian shrubland

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Introduction

The concept of ecological threshold has spurred important advances in understanding the nonlinear behavior of ecosystems to various disturbances (Groffman *et al*. 2006, Suding and Hobbs 2009). Studies on lakes, coral reefs, and arid grasslands have shown that structural attributes of ecosystems can change abruptly along a disturbance gradient (Scheffer and Carpenter 2003, Mumby *et al*. 2007, Sasaki *et al*. 2008). Yet, such nonlinear response patterns are implicitly assumed to reflect the modification of system feedbacks and interactions. We know little about mechanistic linkages between nonlinear response patterns and underlying feedback mechanisms, and the irreversibility of nonlinear responses. Consequently, in many applied settings, the threshold concept is being adopted without sufficient evaluation of evidence. Here, we present initial work towards the understanding of threshold dynamics of vegetation in a Mongolian shrubland. Our study should enhance the conceptual development of ecological threshold as well as human decision-making.

Methods

Identifying pattern-based threshold along the grazing gradient

For identifying pattern-based threshold, we used a grazing gradient approach. Livestock density and grazing intensity are usually highest close to gradient sources such as livestock camps or water sources. Along the gradient, we set survey plots from near the source to the reference distance where grazing impacts are considered minimal. Using these data, we fitted a piecewise regression model to the relationship between shrub cover and the distance from the gradient source, a relationship that represents a spatial gradient in the accumulated impact of long-term exposure to livestock.

Identifying process-based threshold contributing to the occurrence of pattern-based threshold

We examined whether a switch from dominance of negative to positive feedbacks between shrub cover and wind erosion contributed to the nonlinear change in shrub cover along the grazing gradient. To search for the process-based threshold, we measured wind erosion rates at 13

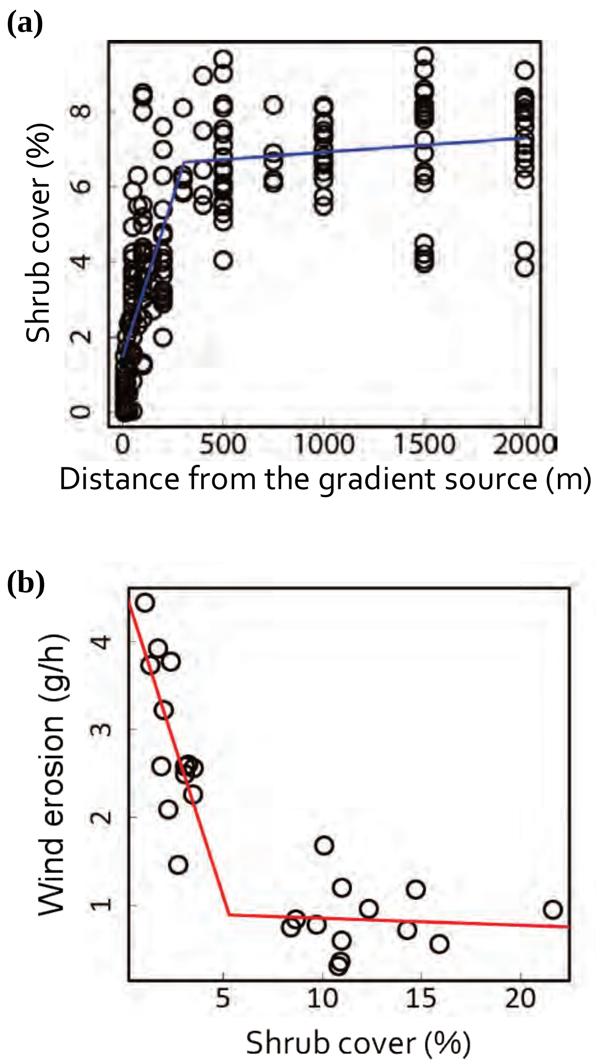

Figure 1. (a) The change in shrub cover along the grazing gradient from high intensity (0 m) to low intensity(2000 m). (b) The change in wind erosion rate as a function of shrub cover. The correspondence of process-based threshold (the shrub cover of 5.3 % in panel b) with pattern-based threshold (the shrub cover of 6.6 % in the panel a) suggests that a feedback switch contributed to the occurrence of pattern-based threshold.

paired plots differing in the cover of dominant shrub *Caragana microphylla*, at 13 sites. We then fitted a piecewise regression model to the relationship between shrub cover and wind erosion rate.

Testing irreversibility of threshold dynamics of vegetation to grazing

Finally, at the same shrubland area where we determined pattern-based and process-based thresholds, we tested the irreversibility of threshold dynamics of vegetation through a restoration experiment. Each exclosure was established in the summer of 2004 at a location with either a post pattern-based threshold state or a pre pattern-based threshold state. We examined general patterns of temporal change in vegetation for the permanent plots inside and outside each exclosure at each site between 2005 and 2010.

Results and Discussion

Along the grazing gradient, shrub cover decreased gradually to 6-7%, and then decreased rapidly, indicating the presence of pattern-based threshold (Fig. 1a). The rate of wind erosion did not change above the shrub cover of 5-6%, after which it increased rapidly (Fig. 1b), indicating the presence of process-based threshold. This suggests a switch from dominance of negative to positive feedbacks between shrub cover and wind erosion. The process-based threshold was thus tightly coupled with the pattern-based threshold. The level of shrub cover corresponding to pattern and process thresholds can serve as an ecological indicator to avoid reducing ecosystem restorability and to promote preventive management actions. Finally, we observed that vegetation state which crossed the pattern-based threshold did not reach its target community for restoration, indicating the lack of restorability despite livestock exclusion. In conclusion, a complementary understanding of threshold dynamics should thus enhance the conceptual development of ecological threshold theory as well as human decision-making**.**

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