Desertification Emerges through Cross-scale Interaction

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Abstract

Desertification, which causes irreversible loss of productivity in drylands, is one of the most urgent global environmental threats. Desertification emerges through a complex process at the local scale, and prevails at a large scale. Complexity and largeness are difficult to understand simultaneously; therefore previous desertification studies have been separated according to scale. This study demonstrates the cross-scale nature of desertification by showing the current state of desertification at the large scale through remote sensing and examining the spatial arrangement of herders' camps and level of desertification through modeling. These two results can describe the cross-scale nature of desertification in Mongolia, i.e., a political regime change has caused herders to concentrate in specific locations, thus modifying piosphere dynamics. Such modification has caused desertification to progress, resulting in a belt-like desertification at the large scale. By understanding the cross-scale nature of this phenomenon, rangeland management plans at the national level can specifically include instructions on how the herders' day-to-day land use should be organized to prevent desertification at the large scale. This study suggests that an explicit linkage between the current activities of herders' groups and the current belt-like desertification can improve rangeland management planning in Mongolia.

Key words: animal-vegetation interaction, land degradation, Mongolia, piosphere, satellite remote sensing

1. Introduction

Desertification, which causes irreversible loss of productivity in drylands, is one of the most urgent global environmental threats (Duda & El-Ashry, 2000; Adger *et al*., 2001). The United Nations Environment Programme (1992) reported that land degradation has occurred on 10.35 million km^2, which accounts for 19.3% of the world's total drylands. The global direct annual loss has been estimated at 42.3 billion USD (Dregne *et al*., 1991). According to a report by the United Nations (1994), desertification results from both climatic and anthropogenic activities; Yoshikawa (2003) estimated that 13% of desertification is due to climatic change and 87% is caused by human activities.

Though desertification is evident on a broad scale across the world, its processes occur at a local scale (Berlow *et al*., 2002; Getzin, 2005; Dembele *et al*., 2006). Previous small-scale studies have shown that desertification was not spatially homogeneous, but rather spread heterogeneously depending on patterns of land and resource use by local people (Pickup *et al*., 1993, 1994, 1998; Pickup & Chewings, 1994; Ringrose *et al*., 1996; Harris & Asner, 2003; Getzin, 2005; Dembele *et al*., 2006). The number of livestock is one of the most popular desertification indicators, but Sneath (2003) and Fernandez-Gimenez (2002) showed that the problem of desertification and the livestock numbers are not necessarily correlated. Uemura (2003) pointed out that in addition to livestock numbers, the spatial distribution of animals affects the level of desertification. Iosifides and Korres (2002) also stressed that animal density is not the only factor in desertification. Because the relationship between herders' behavior and desertification is complex and nonlinear, various factors should be included to facilitate understanding of the desertification process (Perez-Trejo, 1994). As was described above, desertification is a process emerging through a complex process at the local scale, while prevailing at a large scale. Complexity and largeness are difficult to understand simultaneously; therefore previous desertification studies have been separated according to scale.

This study, therefore, aims to demonstrate that the desertification process has a cross-scale nature in Mongolia. First, we conducted a spatial analysis based on remote sensing to investigate the current state of Mongolian desertification. More specifically, we verified whether localized desertification which had been noted by social scientists had actually emerged or not. Then, using an animal-vegetation coupling model, we examined how the spatial arrangement of herders' camps, which was modified by the concentration of herders, affected desertification.

2. Desertification in Mongolia Described by Social Scientists

Nomadic pastoralism is traditional and common in Mongolia. At present, 30% of agriculture and stock-raising consists of nomadic pastoralism (Japan International Cooperation Agency [JICA], 2002; Minato, 2003). Until the early 1990s, cooperative societies, called *negdel*, developed and maintained the infrastructures required for nomadism (*e.g*., Fernandez-Gimenez, 1999, 2002; Sneath, 2003; Bedunah & Schmidt, 2004). By flexibly dispersing grazing pressure, nomadic pastoralism contributes to sustainable agriculture and stock-raising in drylands, where environmental conditions are vulnerable and subject to fluctuation (Turner & Hiernaux, 2002). Although there are arguments both for and against the *negdel* system, it has generally been recognized that this system helped to control the appropriate spatial pattern of grazing pressure (Imaoka, 2003). In the change of social system from socialism to capitalism in Mongolia, however, attempts to privatize the negdel system failed and this cooperative system was lost (Japan Bank for International Cooperation [JBIC, 2001]; Fernandez-Gimenez, 2002; Sneath, 2003; Mearns, 2004; Kazato, 2005). Although people still continued to practice nomadic pastoralism, using a kind of tent called a *ger* as their residence, gradually people tended to concentrate and remain in particular areas (JBIC, 2001; Fernandez-Gimenez, 2002; Fernandez-Gimenez & Batbuyan, 2004; Mearns, 2004; Kazato, 2005). The collapse of the system for maintaining wells, which had become entrusted to individual pastoralists, led to a rapid decrease in the numbers of wells. This, in turn, confined people to particular areas with water sources and decreased their mobility, resulting in livestock becoming over-concentrated (Fernandez-Gimenez, 1999). Moreover, through a lack of manpower and transportation, which had previously been supplied by the *negdel* system, the frequency and distance of seasonal movement decreased. Pastoralists are now concentrated in villages and municipal centres with roads, which provide easy access to medical and educational services and markets (Fernandez-Gimenez, 2002; Kazato, 2005).

3. Remotely-sensed Desertification Pattern at a Large Scale

In this section, we tried to investigate the spatial pattern of desertification in Mongolia. In particular, we focused on localized desertification, which has frequently been noted by social scientists, as described also in the last section. A social science study based on interviews with local people (Fernandez-Gimenez, 1999) and descriptive measures without quantitative survey data (Niamir-Fuller, 1998; World Resources Institute, 2003; World Bank, 2003) suggested livestock concentration and resulting vegetation degradation were to blame. However, little quantitative evidence of these phenomena existed. In particular, the spatial extent and relative importance of each factor were never investigated quantitatively.

Arkhangai *aimag*, the 'aimag' is a Mongolian term that means 'province,' was selected as the study area. The area of Arkhangai *aimag* is 55,300 km^2. Because the operation of the *negdel* had once been successful in this *aimag*, and the grazing pressure is currently high here as compared to other *aimags*, the impact of grazing before and after the change in social system was expected to be evident. Here we summarize our methods, but see Okayasu *et al*. (2007) for details. Local variance (LV) can be used to identify local degradation, such as that around villages, using satellite imagery with a resolution of approximately 1 km (Buddle *et al*., 2004). The LVs value using a window size of 115 pixels are calculated for each pixel with a corresponding moving window: LV = [(value of the pixel) – (mean value of the pixels inside the moving window)] ⁄ (variance of the pixels inside the moving window). The LVs were calculated for each year by using maximum NDVI values derived from NOAA1 AVHRR 1-km 10-d composite data (U.S. Department of the Interior, 2005) for 1992 and 1995, and SPOT VEGETATION 10-d composite data (VEGETATION Programme, 2006) for 1998, 2001 and 2004. For the five LV images we thus calculated, we applied a Mann–Kendall trend test and calculated the tau coefficient for each pixel to uncover trends in desertification.

We obtained the locations of settlements and roads from the Digital Chart of the World (DCW) 1:1M map (Pennsylvania State University, 2003) as factors controlling heterogeneous vegetation change. Though the traffic volume on roads was also expected to have an effect, no corresponding data existed. Therefore, assuming the roads found on maps at a larger scale had more importance and thus more traffic, we digitized a 1:3M road map (Ulsyn Geodezi Zurag Zuin Gazar of Mongolia and Glavnoe Upravlenie Geodezii i Kartografii of Russia, 1990). Hereafter, we refer to the roads digitized from this map as 'main roads.' We obtained the extent of open water from ortho-rectified Landsat TM 5 images using a histogram manipulation method (Brikett, 2000).

To examine trends in the LVs and the relationships between open water, settlements and roads , we carried out a three-way analysis of variance (ANOVA). For open water and roads, we calculated 5-km buffers from these factors, which corresponded to the assumed spatial extent of grazing for one day. Based on these buffers, we classified areas as near (*i.e*., within the buffer zone) or far from water or roads (*i.e*., outside the buffer zone). A previous study of grazing concentration around the capital city Ulanbaatar concluded that the spatial extent of the effect of settlements was approximately 60~80 km distance regions (Muller & Bold, 1996); however, the scale

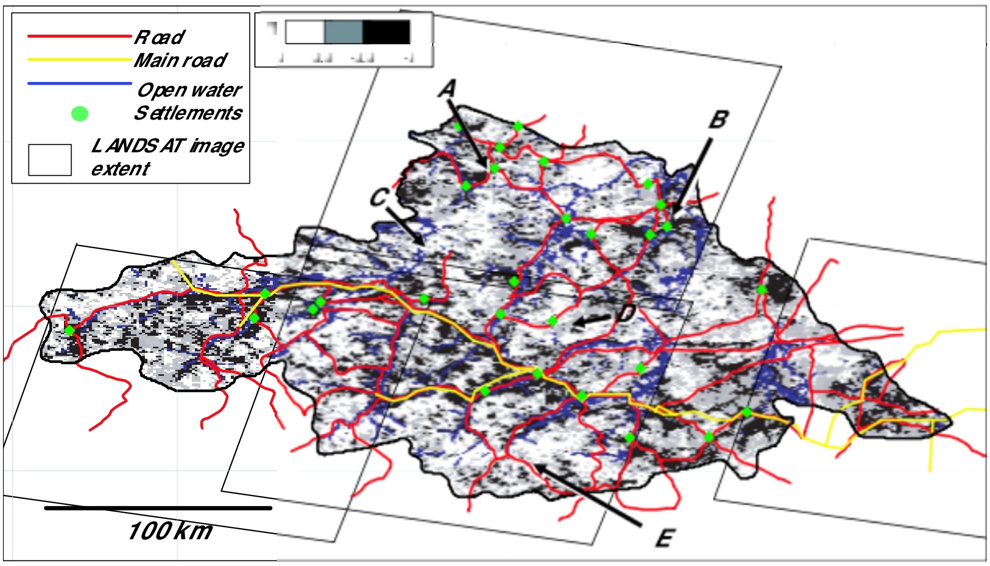

Fig. 1 Trends in local variances of maximum NDVI in Arkhangai *aimag* from 1992 to 2004.

Table 1 Results of a three-way ANOVA of local variances of distance from settlements, roads and open water.

Factor	df	*F*	*P*
Settlements	1	1421.5	<0.001
Roads	1	1054.7	<0.001
Open water	1	791.9	<0.001
Roads × settlements	1	83.0	<0.001
Open water × settlements	1	87.4	<0.001
Open water × roads	1	0.0	0.857
All factors	1	4.9	0.027

of the settlements in the present study was much smaller. Here 25 km was adopted, which resulted in all of the target pixels being approximately divided equally in two. The pixels outside of the Landsat images, where the spatial distribution of open water was unknown, were excluded from the analysis. We performed a three-way ANOVA of the three factors, while considering the near/far designation and the trends in the LVs.

The spatial distribution of the calculated trends in LVs (tau) is shown in Fig. 1. On a per-pixel level, few pixels showed a significant correlation. However, a clear spatial pattern existed, with smaller values of tau (a decreasing trend in LVs) near open water, roads and settlements; in particular, there were markedly low tau values around main roads. The impact of roads seems to depend on the traffic volume. The tau values also were low around open water, but the scale of the open water seems not to have an effect, as it does with the roads; this can be seen by the low tau values around the short and small rivers flowing into larger rivers. A three-way ANOVA of LVs against open water, settlements and roads supports these results (Table 1).

By analyzing LVs, a spatial pattern of vegetation change can be clearly identified in relation to social conditions. Our findings show that the vegetation in the target area was changing heterogeneously, and open water, roads and settlements all had significant effects on the heterogeneous vegetation change. In a previous study in Mongolia, Kazato (2005) noted that the concentration of livestock around open water, roads and settlements resulted from a change in access to nomadic pastoralists' requirements due to the degradation of infrastructures developed during the socialist period. Likewise, our findings confirmed that, across the entire rangeland in Arkhangai *aimag*, heterogeneous vegetation change was progressing due to the change in access to these requirements.

4. Piosphere Dynamics through Close Interaction of Herding Patterns and Vegetation Status

In this section we explore the impact of spatial distribution of animal concentration points (ACPs hereafter) on desertification, in order to bridge different scales. Around ACPs severe localized impact of grazing on vegetation and soil occurs, which was named phosphere (Washington-Allen *et al.*, 2004). Numerous empirical studies of piosphere ecology, including investigations of gradients in vegetation composition and soil nutrients and their causal mechanisms, have revealed complex ecological processes around ACPs (Tolsma *et al.*, 1987; Turner, 1998a, b; Dembele *et al.*, 2006). Empirical studies necessarily analyze prevailing grazing patterns in relation to the prevailing vegetation pattern at a given time, or over very narrow periods of time. However, there is actually a dynamic interaction between the disturbance agent (grazers) and the status of the vegetation and soil. Empirical studies cannot assess the long-term processes related to ACPs because of the limited time span over which observations can be made. Therefore, we developed a model that combines animal and vegetation processes with desertification around ACPs to examine how the spatial and temporal pattern of use by animals around an ACP can increase or reduce the area of desertification.

We used a rangeland model and a grazing model (Okayasu *et al.*, in press). The rangeland model simulated plant growth, plant death and recruitment, and desertification. The grazing model simulated animal movement and grazing. The simulation was carried out in a 5×5 km two-dimensional space composed of 100 × 100 m grid cells, The rangeland model was run in each grid cell. Animals were assumed to move and eat plants in time steps of one day, starting at the center of the space. The model structures are summarized below. Please see Okayasu *et al.* (in press) for more details about the mathematical forms and parameters.

Rangeland model. We adopted a vegetation cover and a dimensionless, abstract herbage productivity parameter, low values of which indicate desertification. These variables were coupled so that low vegetation cover would cause a loss of herbage productivity, which would again result in further reduction of vegetation cover. The following assumptions were adopted in the rangeland model: (1) herbage productivity declines when biomass is below a given threshold; (2) herbage productivity increases when biomass exceeds a given threshold; (3) desertification (loss of herbage productivity) proceeds faster than recovery (gain of herbage productivity); (4) when grazing pressure approaches zero, recovery starts regardless of the status of desertification (*i.e.*, the recovered status is the only stable point when grazing pressure is near zero); and (5) the desertification and recovery processes are slower than plant growth and death. These assumptions are common to most desertification studies.

Grazing model. In each time step, grazing animals start from the center of the space, then move and graze until the total biomass required in one time step is satisfied. We adopted multi-scale optimal movement, which corresponds to the complete taxis movement of Farnsworth and Beecham (1999). This presents an efficient assumption in which the probabilities of movement to all adjoining cells are decided by the biomass of both adjacent and more distant cells. We adopted the biomass density-dependent intake model (Adler & Hall, 2005), which reflects increasingly lower intake efficiency as plant biomass decreases.

Parameters. The parameters were intended only to be on the same order of magnitude as realistic values, because the aim of this study was to determine the fundamental properties of desertification around an ACP. We also assumed that the plant growth parameter was constant, but this is never the case in actual rangeland.

Implementation. We compared the impacts of different animal starting points on the rangeland. In the first setting there were two ACPs located near each other. In the second, there were two camps distant from each other (no overlap in grazing territory). A third setting, for the purposes of comparison, had only one camp.

Figure 2 shows the total herbage productivity for different spatial arrangements of ACPs, which differed even though the total biomass required for one step was the same for all spatial arrangements. The largest total herbage productivity area was found for the setting with one camp because of the diminishing rate of decrease in total herbage productivity with the increase in total required biomass. Compared with the results for two distant camps, those for two camps in close proximity resulted in a markedly larger area of desertification. This resulted from desertification of the area between the two camps (Fig. 3). The desertified area surrounding the two camps had a broad elliptical shape. Taxis movement that encouraged the animals to quickly enter the non-degraded area promoted the occurrence of overlap. Even though the overlap area was initially small, enlargement of the desertified area caused animals to seek plants outside that area, resulting in desertification of the adjacent outer region. As a result, the desertified area grew, especially in the area between the two ACPs, and consequently a larger than expected desertified area formed. These results for the spatial arrangement of ACPs further confirm that total biomass requirement and

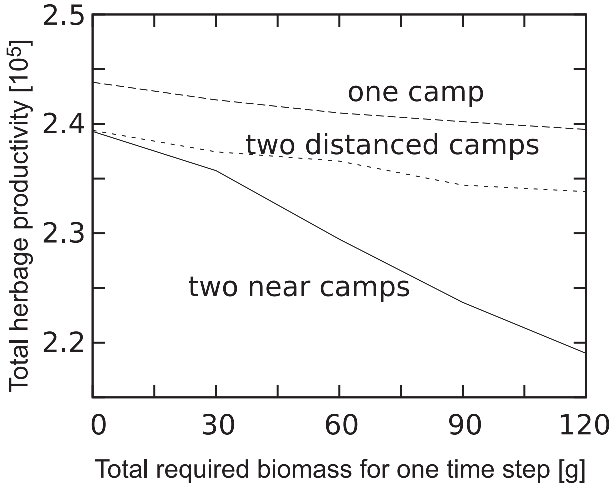

Fig. 2 Total herbage productivity for different spatial arrangements of ACPs with the same total required biomass per time step.

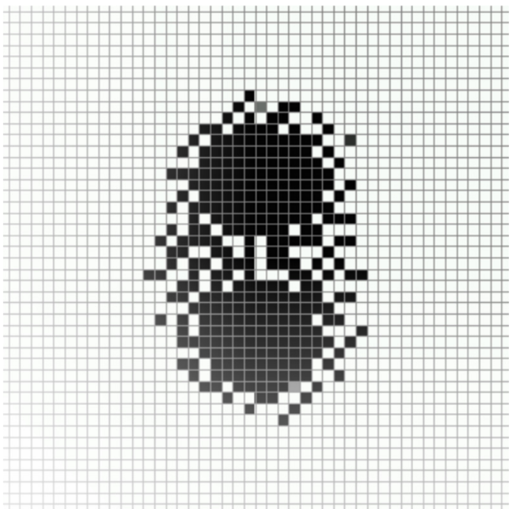

Fig. 3 Spatial distribution of the desertified area (shown as dark cells) for the spatial arrangement of two camps (ACPs) located close to each other.

total livestock number are not the primary indicators of desertification: the spatial arrangement of ACPs and grazing behavior have a much greater effect.

5. Cross-scale Interaction in the Desertification Process

In the first result using satellite remote sensing, we showed that heterogeneous desertification occurs at a large scale in Mongolia. This can be evidence in support of claims by social scientists that the corruption of infrastructure triggered by political regime change has caused the herders to concentrate in specific areas, such as large cities, along main roads and near surface water. When this result alone is considered, the desertification process can be explained as the result of concentration of settlements causing increases in livestock numbers in specific areas, leading to desertification. However, when we also considered the latter result using simulation models, desertification can be interpreted as a more complex process. As shown in Fig. 3, the concentration of poor (small) herders is the worst kind of spatial arrangement with regard to desertification, given the same total numbers of animals. Therefore, considering the results at both scales, the concentration of herders' camps causes desertification through the modification of piosphere-scale dynamics. The series of causal relationships across scales is summarized in Fig. 4. First, the political regime change in the 90s failed to reconstruct the institutions necessary for maintaining the infrastructure to support the dispersal of herders into remote pastures. This prevented poor herders with insufficient money from moving to remote pastures. The concentration of small herders modified the animal-vegetation interaction at the piosphere scale. This interaction enlarged the desertified area beyond the near-camp vicinity. Through these processes, a large-scale belt-like desertification emerged. We successfully demonstrated the cross-scale effect (WRI, 2003) of desertification in Mongolia.

Large-scale studies are required for obtaining an understanding of the spatial extent and magnitude of desertification, which are essential information for rangeland management planning at the national or regional level. On the other hand, developing specific techniques to prevent desertification will require small-scale studies to clarify desertification processes. Cross-scale studies can bridge these studies, *i.e.*, they can answer how small-scale processes affect the extent and magnitude of desertification at the large scale. In other words, improving range management at the small scale can reduce the prevalence of desertification at the large scale. For example, the formation of herders' groups is recognized as a good practice for sustaining rangeland conditions (Upton, 2008), but it has been recognized only in a very general sense, and has not been explicitly linked to the current belt-like desertification in their discussions so far. This study suggests that forming groups so as to prevent the overlapping of daily herding courses or to herd as a unit cooperatively could contribute to the prevention of nationwide desertification better than could be accomplished by reducing livestock numbers or migrating with them. Therefore, the herders' grouping activities should be included in national pasture management planning with explicit spatial information. Moreover, this study recommends the collection of more effective desertification indicators, such as the magnitude of crowding of small herders and so forth, at a large scale.

6. Conclusion

This study has demonstrated the cross-scale nature of desertification by showing the current state of desertification at a large scale using remote sensing and the relationship between the spatial arrangement of herders' camps and the desertification level using simulation models. Utilizing this understanding, national rangeland management planning can specifically include advice on how the daily herders should arrange their land use so as to prevent nationwide desertification. This study suggests that understanding of the explicit linkage between the current activities of herders' groups and the current belt-like desertification can lead to improved rangeland management in Mongolia.

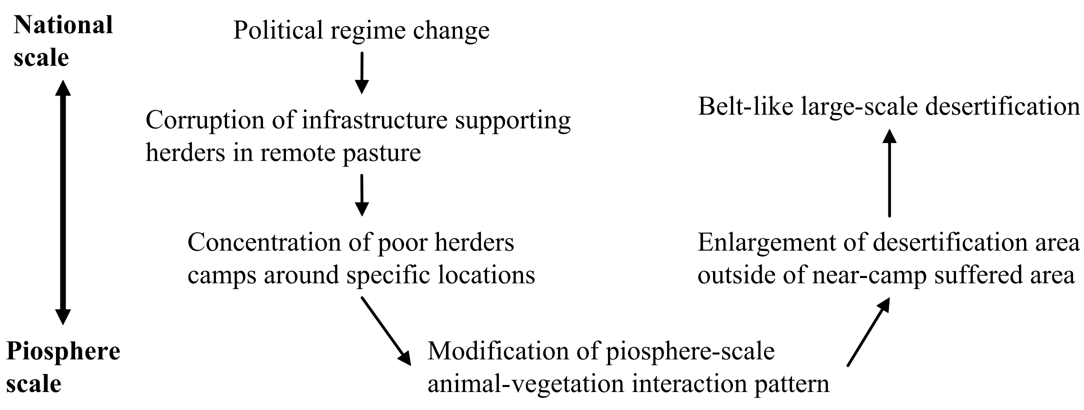

Fig. 4 Causal relationship of desertification across scales in Mongolia.

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