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SPATIALLY HETEROGENEOUS IMPACTS ON RANGELAND AFTER SOCIAL SYSTEM CHANGE IN MONGOLIA

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ABSTRACT

After the social system in Mongolia changed from socialism to capitalism in the early 1990s, the cooperative system called **negdel**, which helped to disperse the grazing pressure, collapsed. As a consequence of the collapse, scientists warned that grazing pressure would become concentrated and fixed at particular locations, resulting in land degradation. However, no quantitative studies of such potential local concentration have been performed in Mongolia. In this study, using satellite images and large-scale thematic maps, we analysed the local vegetation change in relation to possible control factors, including open water, roads and settlements. Individual factors had significant impacts on the local vegetation change: particularly prominent were a beltlike decrease in plant density along the main roads and decreases around densely populated areas. In addition, the interaction between these factors negatively affected vegetation, as seen by a decrease around roads and open water near settlements. This interactive effect is likely a consequence of the basic requirements of the nomadic pastoralists, namely quality grassland, water sources and the services provided by settlements. In our study area in Mongolia, the local pattern of vegetation change was determined by the complex process of pastoralists' decision-making. A comprehensive understanding of this process is essential for devising management plans to counteract this vegetation degradation. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: desertification; remote sensing; local variance; normalised difference vegetation index; social system change; Mongolia

INTRODUCTION

Desertification, which causes irreversible loss of productivity in drylands, is one of the most urgent global environmental threats (Duda and 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 per cent of the total drylands in the world. The global direct annual loss was estimated as US$42·3 billion (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 per cent of desertification is due to climatic change and 87 per cent 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 showed 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 and Chewings, 1994; Ringrose *et al.*, 1996; Harris and Asner, 2003; Getzin, 2005; Dembele *et al.*, 2006).

Nomadic pastoralism is traditional and common in Mongolia. At present, 30 per cent of agriculture and stock-raising consists of nomadic pastoralism (Japan International Cooperation Agency [JICA] 2002; Minato,

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2003). Until early-1990s, cooperative societies, called **negdel**, developed and maintained the infrastructures required for nomadism (e.g. Fernandez-Gimenez, 1999, 2002; Sneath, 2003; Bedunah and Schmidt, 2004). By flexibly dispersing the grazing pressure, nomadic pastoralism contributes to sustainable agriculture and stock-raising in drylands, where environmental conditions are vulnerable and fluctuate (Turner and Hiernaux, 2002). Although there are arguments both for and against the **negdel** system, it was generally recognised that this system helped to control the appropriate spatial pattern of grazing pressure (Imaoka, 2003).

After the social system changed from socialism to capitalism in Mongolia, however, through the failure to privatise the **negdel** system, 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 and Batbuyan, 2004; Mearns, 2004; Kazato, 2005). The collapse of the system for maintaining wells, which became 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 overconcentrated (Fernandez-Gimenez, 1999). Moreover, through the lack of labour power and transportation, which were previously supplied by the **negdel** system, the frequency and distance of seasonal movement have 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).

A social science study based on interviews with local people (Fernandez-Gimenez, 1999) and descriptive measures without quantitative survey data (Niamir-Fuller, 1999; World Resources Institute, 2003; World Bank, 2003) suggested this livestock concentration and resulting vegetation degradation. However, little quantitative evidence of these phenomena exists. In particular, the spatial extent and relative importance of each factor were never investigated quantitatively. The development of proper rangeland use and management plans for a sustainable grazing system in Mongolia require quantitative data.

In this study, we aim to verify the heterogeneous change in vegetation using satellite remote sensing and we discuss the cause of vegetation degradation in relation to possible factors.

MATERIALS AND METHODS

Study Area and Numbers of Livestock

Arkhangai Aimag was selected as the study area. Because the operation of the **negdel** system was successful in this **aimag** (the Mongolian name of a prefecture) and the grazing pressure is high here as compared to the other **aimags** (Figure 1), the impact of grazing before and after the social system change should be evident.

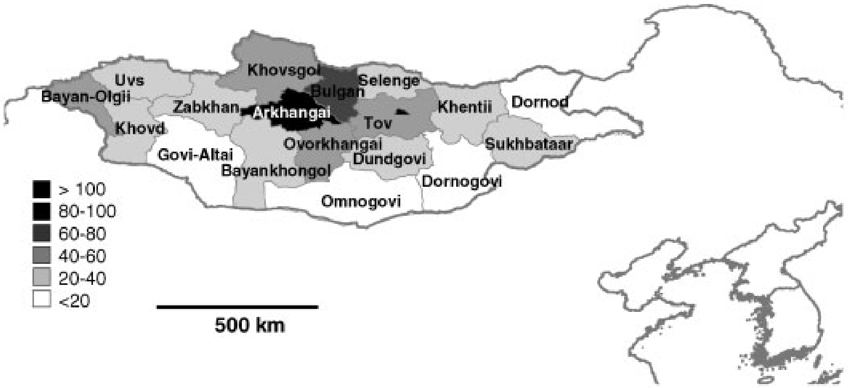

Figure 1. Grazing intensities in 1000 sheep units per square kilometre in each **aimag** in Mongolia in 2000 (National Statistical Office of Mongolia, 2001)

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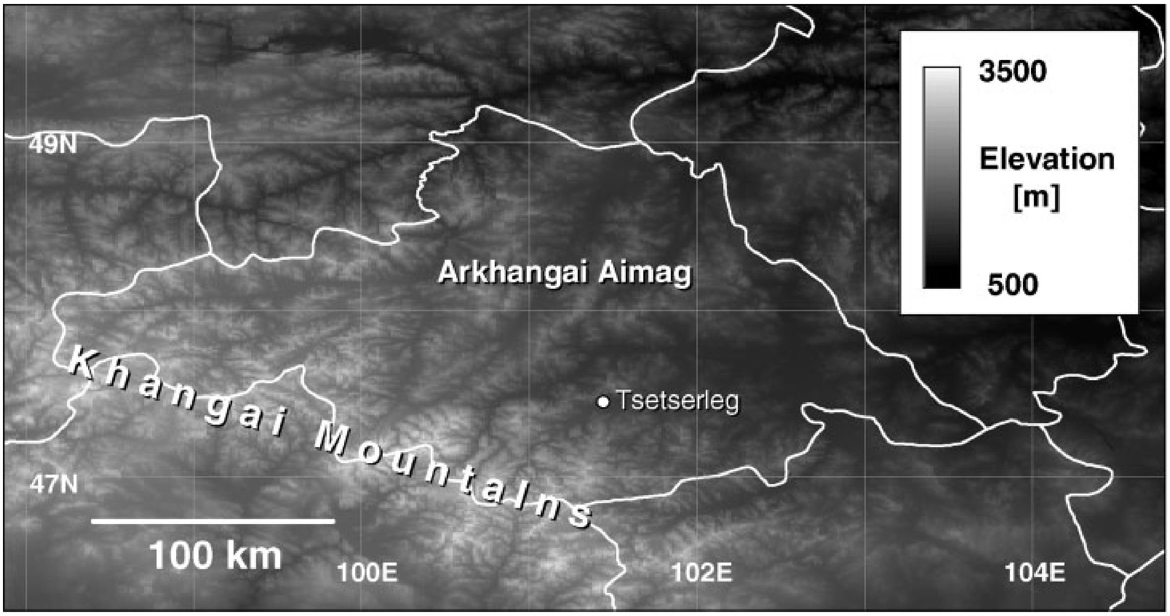

Figure 2. Topography of Arkhangai Aimag made from digital elevation map (Earth Resources Observation & Science [EROS], 2006)

The capital of Arkhangai Aimag is Tsetserleg, located 470 km west of Ulanbator, the capital of Mongolia. In the study area, the mean annual temperature and precipitation are 0·2°C and 313 mm, respectively (National Statistical Office of Mongolia, 2001). Figure 2 shows the topography of Arkhangai Aimag made from digital elevation map (Earth Resources Observation & Science [EROS], 2006), located on the northern slope of the Khangai Mountains. Due to its geographical location, the southwestern part of the study area is undulating and becomes flatter in the northeastern part. Most of Arkhangai Aimag belongs to the forest-steppe ecosystem, where patches of grassland, shrubland and forest are intermingled.

Due to missing data, the weather data from the local station are not sufficient to represent the annual trend of precipitation. Therefore, we used CPC Merged Analysis of Precipitation (CMAP) data (National Oceanic and Atmospheric Administration [NOAA®], 2006) to elicit the trend of annual mean precipitation from longitude 96·26E to 103·75E and from latitude 46·26N to 48·75N; the data are plotted in Figure 3, with the 5-year moving average overlaid. As can be seen in the figure, an increasing trend was observed from the 1980s to the early-1990s, and then annual mean precipitation decreased beginning in mid-1990s.

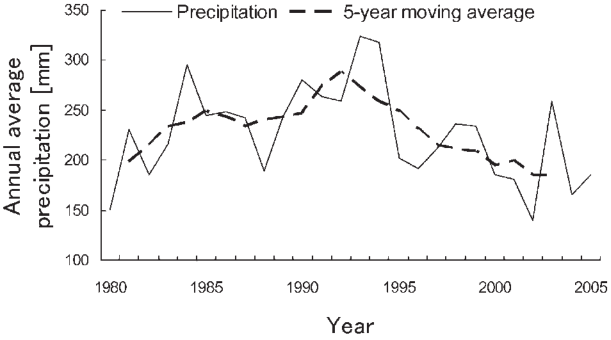

Figure 3. Trend in annual average precipitation around Arkhangai Aimag (NOAA®, 2006)

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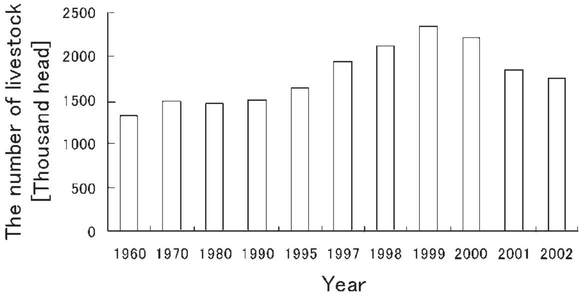

Figure 4. Trend in the number of livestock in Arkhangai Aimag from 1960 to 2002. National Statistical Office of Mongolia, 2001

The number of livestock, converted to sheep units (Hamphrey and Sneath, 1999), is shown in Figure 4. Sheep units are calculated as follows:

$$1\,\text{sheep unit} = 6[\text{horse}] + 7[\text{camel}] + 5[\text{cattle}] + [\text{sheep}] + 0\cdot 9[\text{goat}] \qquad (1)$$

where $[x]$ represents the number of x (National Statistical Office of Mongolia, 2001). The number of livestock was very stable during the socialism era, but it rapidly increased from the beginning of the 1990s to 1999 and then decreased from 2000 (Figure 4). The introduction of a market economy and privatisation of livestock stimulated the increase in the number of livestock, but due to the decrease in precipitation, the number of livestock may have gone beyond the carrying capacity in 1999 and started to decrease thereafter.

Calculation of Local Variance

Local variance (LV) can be used to identify local degradation, such as that around villages, by using satellite imagery with a resolution of about 1 km (Buddle *et al.*, 2004). LV is 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). Biases due to the different sensors and viewing angles are reduced, although a comparison on an absolute basis cannot be carried out (Buddle *et al.*, 2004).

The normalised difference vegetation index (NDVI) value for 1992 and 1995 based on NOAA® AVHRR 1-km 10-d composite data (U.S. Department of the Interior, 2005), and the NDVI values for 1998, 2001 and 2004 based on SPOT VEGETATION 10-d composite data (VEGETATION Program, 2006) were used for the calculation of LVs. These years were selected in order to retain the same time interval for trend analysis. In this study, we consider 1992 as the control period representing the vegetation condition under the management of the **negdel** system, because 1992 is just after the change in social system occurred.

Using 10-d composite data, Buddle *et al.* (2004) calculated integrated NDVI (iNDVI) to represent the vegetation condition for each target year. iNDVI is related to the annual net primary production of vegetation (Tucker *et al.*, 1985; Hurlbert and Haskell, 2003). The calculation of iNDVI requires identification of the phenological characteristics of seasonal NDVI change. Buddle *et al.* (2004) identified these characteristics using the method of Reed *et al.* (1994), but Yu *et al.* (2004) noted that this method is not appropriate for regions with snow cover in winter, such as Mongolia. Therefore, we first identified the phenological characteristics of seasonal NDVI change using the method of Yu *et al.* (2004), which avoids this limitation by using the maximum change in the slope of the curve of NDVI. Yu *et al.* (2004) analysed differences among various biomes, whereas our study focused on a small area within a single biome. Because the scale of the shape of the NDVI curve between pixels we examined was much smaller than that reported by Yu *et al.* (2004), the identified phenological characteristics were very sensitive to small differences in the curve shape, resulting in output that was too erratic. Therefore, we concluded that the method of Yu *et al.* (2004) was not appropriate for our study. Instead, the annual maximum NDVI method (Paruelo and Lauenroth, 1998), which is also related to the annual net primary production of vegetation, was used to represent annual vegetation conditions, by using NDVIs from June to September of each year.

To calculate LVs, the appropriate size of the moving window must be determined. To prevent bias due to different sensors and viewing angles, a smaller window size is desirable, but the window size should be large enough to incorporate the spatial scale of heterogeneous vegetation change being considered. In this study, we considered open water, roads and settlements (towns and villages) as factors that may be driving the heterogeneous vegetation change. The semi-variogram of a permanent river in the study area, which has the maximum spatial scale of these three factors, was calculated to examine the periodicity, revealing that a window size of 115 pixels was most appropriate. For the five calculated LV images, a Mann–Kendall trend test (Helsel and Hirsch, 1992) was applied and the tau coefficient was calculated for each pixel.

Factors Controlling Heterogeneous Vegetation Change

Two different scales of factors were considered as driving the heterogeneous grazing patterns noted in previous studies: (1) landscape scale, including open water (rivers and lakes), settlements (cities and villages) and roads; and (2) field scale, including winter camps and **gers**. In practical terms, it is not possible to locate all camps and **gers**. Therefore, we focused on the former three factors, whose locations can be obtained relatively easily.

The locations of settlements and roads were obtained from the Digital Chart of the World (DCW) 1:1M map (Pennsylvania State University, 2003). Though the traffic volume on roads was also expected to have an effect, corresponding data did not exist. Therefore, assuming the roads found on maps at a larger scale have more importance and thus more traffic, the road map of 1:3M (Ulsyn Geodezi Zurag Zuin Gazar of Mongolia and Glavnoe Upravlenie Geodezii i Kartografii of Russia, 1990) was digitised. Hereafter, we refer to the roads digitised from this map as ‘main roads’.

Various thematic maps illustrate open water in the study area. However, because rivers in drylands are ephemeral and sensitive to local weather, the actual existence of open water cannot be identified from the thematic maps. Therefore, the extent of open water was obtained from ortho-rectified LANDSAT images. We selected LANDSAT images that could be obtained from the Web site of the University of Maryland (2004), with the condition that two images were available of a similar phenological period for the same coverage (Table I).

In the LANDSAT images, pixels were masked if clouds existed on at least one of the pair of images of the same location. To reduce the effect of sensor differences and image degradation, sensor corrections (Stein *et al.*, 1999) were applied. Then the atmospheric effects for the images were reduced using the COST model (Chavez, 1988, 1996), which is one of the improved dark object subtraction methods. Finally, reflectance of the images was calculated to compare each pair.

Many studies have delineated lakes based on remote sensing data (e.g. Bryant, 1999; Brikett, 2000; Bryant and Rainey, 2002), using methods such as histogram manipulation (e.g. Brikett, 2000), image classification (e.g. Frohn *et al.*, 2005) and more sophisticated methods (e.g. Al-Khundhairy *et al.*, 2002). In this study, because our interest was simply the presence or absence of open water, histogram manipulation was selected because of its simplicity. The penetration depth of the visible band is deep (Brikett, 2000), therefore only the near-infrared (NIR) band was used for identification of small rivers with shallow water. Because our target area included various geographical units and ecosystems, manual histogram manipulation was performed in two steps. First, the open water and its flood plain were extracted by interpretation of geographical maps and true-colour satellite images. Second, by examining the spectral histograms of open water and flood plain, the threshold to divide them was determined. For each pair of the images, the image of logical conjunction (where a water pixel appeared when water pixels existed in

Table I. Location and dates of LANDSAT images used for identification of open water

Path/row	Date 1	Date 2
136/027	August 12, 1996	August 21, 2002
133/027	August 21, 1995	July 23, 1999
135/026	September 14, 1987	September 28, 2001
135/027	September 14, 1987	August 22, 1999

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both images) and logical disjunction (where a water pixel appeared when a water pixel existed in at least one image) were calculated. The correlations of these two images with LVs were nearly the same, but the logical disjunction images had a slightly higher correlation. Therefore, the images of logical disjunction were used to determine the spatial distribution of open water.

Multivariate Analysis

To examine the relationships between open water, settlements and roads and the trend of LVs, three-way analysis of variance (ANOVA) was carried out. For open water and roads, we calculated 5-km buffers from these factors, which correspond to the assumed spatial extent of grazing for 1 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 Ulanbator concluded that the spatial extent of the effect of settlement was about 60–80 km (Muller and Bold, 1996); however, the scale of settlement in the present study is 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 LANDSAT images, where the spatial distribution of open water was unknown, were excluded from the analysis. We performed a three-way ANOVA between the three factors, while considering the near/far designation and the trend of LVs.

RESULTS

The spatial distribution of the calculated trend of LVs (tau) is shown in Figure 5. On a per-pixel level, few pixels showed a significant correlation. However, a clear spatial pattern existed, with smaller values of tau (decreasing trend of LVs) near open water, roads and settlements; in particular, there were markedly low tau values around main roads. The impact of roads seems to be dependent on the traffic volume. Tau values also were low around open water, but the scale of the open water seems not to have an effect, as it did with the roads; this can be seen by the low

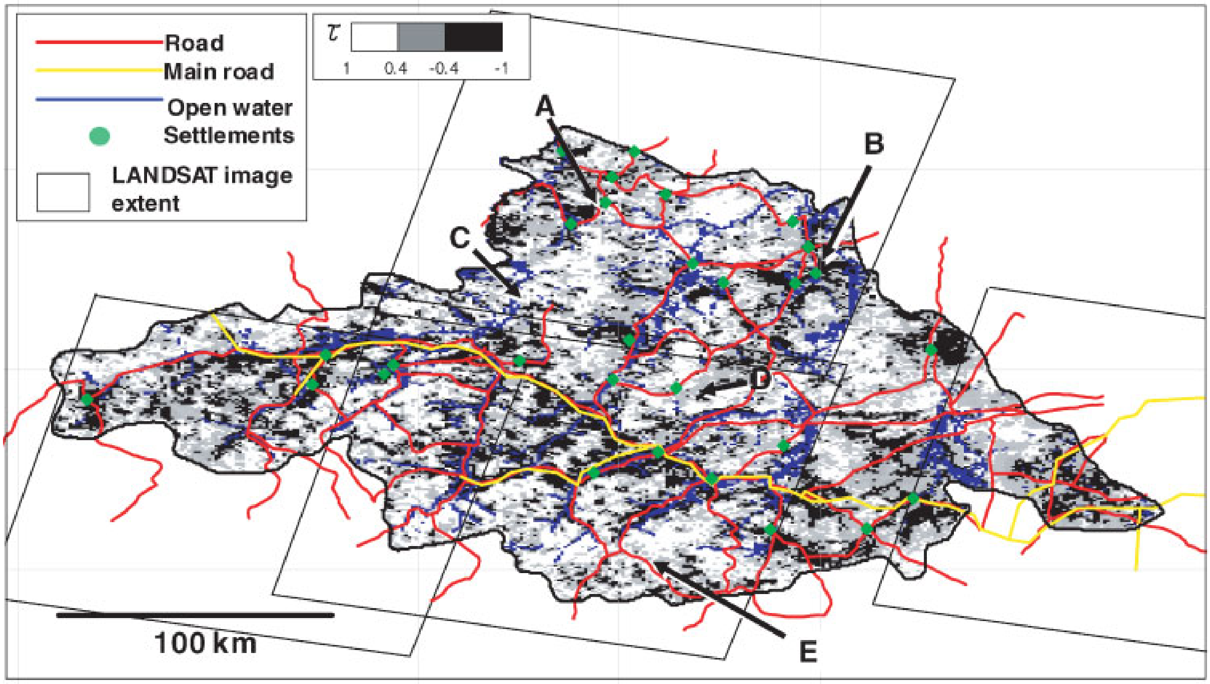

Figure 5. Trend of local variances of maximum NDVI in Arkhangai Aimag from 1992 to 2004

Table II. Results of three-way ANOVA of local variances for 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

Table III. Results of one-way ANOVA of the simple main effect of the interaction

Factor	Condition	*df*	*F*	*p*
Roads	Near settlements	1	964·5	<0·001
Roads	Far from settlements	1	167·85	<0·001
Open water	Near settlements	1	1062·9	<0·001
Open water	Far from settlements	1	198·69	<0·001

tau values around the short and small rivers flowing into larger rivers. The areas where settlements were concentrated (e.g. locations A and B in Figure 5) had very low tau values. In general, tau values were low in the vicinity of these three factors, although there were a few exceptions: (1) location C (Figure 5), which is near a river, had a high tau value; (2) location D, which is near a settlement, had a high tau value; and (3) location E, which is near a road, had a high tau value.

The interactions between road and settlement and between open water and settlement were significant ($p < 0{\cdot}001$; Table II). Together, the main effects of open water, road and settlement were significant ($p < 0{\cdot}001$) but were limited by their interactions (Table II). Each simple main effect showed a significant relationship with the trend of LVs ($p < 0{\cdot}001$; Table III). Therefore, each factor had an impact to some extent; in particular, roads near settlements and open water near settlements (or, settlements near open water) had the strongest relationships with a decreasing trend of LVs (Figure 6).

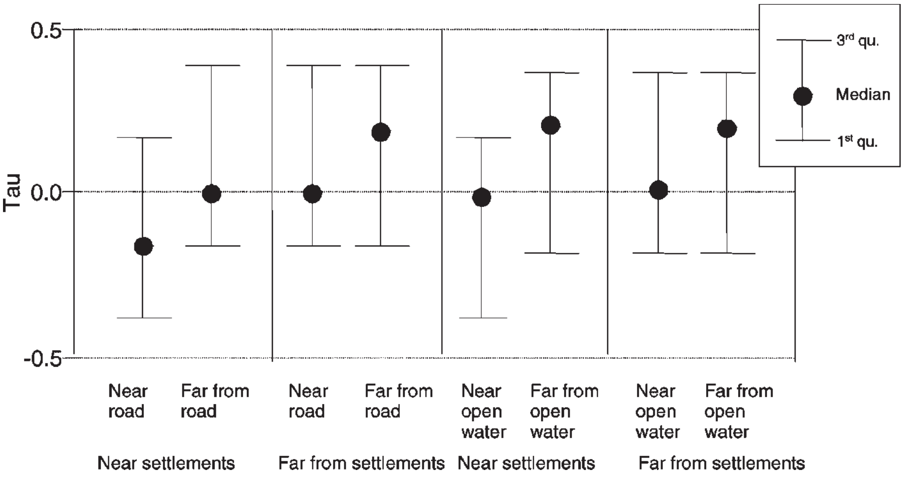

Figure 6. Simple main effects of the interactions between the factors open water, roads and settlements

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DISCUSSION

By analysing LVs, the spatial pattern of vegetation change in relation to social conditions was clearly identified. Our findings showed 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 the requirements of nomadic pastoralists due to the degradation of infrastructures developed during the socialism period. Likewise, our findings suggest that, across the entire rangeland in Arkhangai Aimag, heterogeneous vegetation change is progressing due to the change in access to the requirements of nomadic pastoralists.

The main east–west road crossing Arkhangai Aimag is the factor showing the clearest relationship with vegetation degradation. After the abolition of transportation services from remote areas to towns, which provide medical and educational services and markets, people tended to concentrate around roads (Fernandez-Gimenez, 2002). The accessibility of towns is not linearly related to their distance from particular remote areas; instead it depends on the possible modes of transportation. The use of roads for transportation, as opposed to moving cross-country, reduces travel time; in addition, public modes of transportation, such as buses, travel along roads. This concentrated traffic on roads caused a beltlike pattern of vegetation degradation along roads. In fact, a survey showed that the grazing pressure along the road to Ulanbator increased from 1989 to 1994 (Muller and Bold, 1996). The marked LV decrease around main roads is likely due to more frequent opportunities to take public transportation; Tsetserleg, the capital of Arkhangai Aimag, and Ulanbator, the capital of Mongolia, are located along the main road, which provides access to more sophisticated services found only in large cities.

Areas with concentrated settlements (locations A and B in Figure 5) showed marked vegetation degradation. Similar to the case of roads, the collapse of the transportation services provided by the **negdel** system led to pastoralists becoming concentrated around settlements. This tendency was more evident for poor people without personal modes of transportation than for people who owned their own cars or motorcycles (World Bank, 2003). In Mongolia, pastoralists generally move their **gers** four times per year. Recently, pastoralists, especially those lacking in financial means, have tended to adopt a cycle in which one of the four locations is near a settlement, which is the main cause of the concentration around settlements (Fernandez-Gimenez and Batbuyan, 2004; Kazato, 2005). For both concentrated settlements in our study area, low tau values were seen along the roads—a trend similar to that of the main roads. Although the scale is different, similar processes are likely occurring along small roads and settlements.

Previous studies relating the vegetation degradation around towns to the concentration of livestock (e.g. Ringrose *et al.*, 1996) noted a radial pattern of degradation from towns, which is different from our results, in which the beltlike pattern is marked in the case of main road as well as even smaller roads around towns. This difference may be because the nomadic nature of pastoralists in Mongolia allows them to settle in any place using their **gers**; that is the centre of grazing pressure was not fixed at the centre of towns. As a result of the balance the access to the services of settlements and other resources such as pasture and water, the grazing pressure was dispersed to some extent. As an example for the more balanced grazing pressures within the nomadic communities, those families with cars and motorcycles live away from settlements, where grassland conditions are good (JBIC, 2001). In summary, vegetation degradation has occurred around the settlements and the network of roads that provide access to their services.

Vegetation degradation along open water was also clear (Figure 5). Because livestock require a water source twice a day in summer and once a day in winter, the grazing activity is confined within several kilometres of a water source, and livestock become concentrated around important water sources, such as rivers and wells. The cause of vegetation degradation along open water is the shift of water sources from wells to open water, as the number of wells previously maintained by the **negdel** system has markedly decreased. Figure 7 shows that in Mongolia, between 1992 and 2000 the total number of wells decreased by 26 per cent, from 42 000 to 31 000; in particular, the number of mechanised wells, which have higher maintenance costs, decreased by 67 per cent, from 24 500 to 8000 (Mori, 2003). Because rivers, lakes and wells are the only water sources in the study area, the decrease in the

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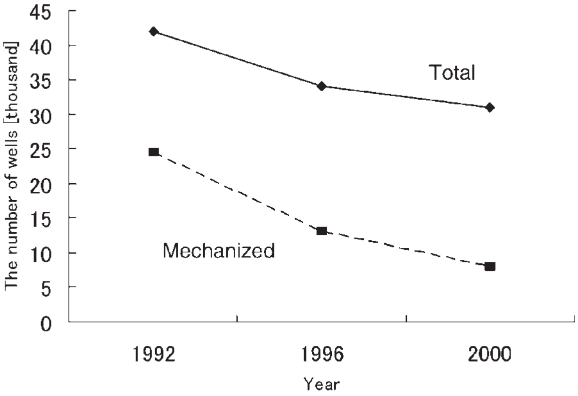

Figure 7. Change in the total number and the number of mechanised wells from 1990 to 2000 (Mori, 2003)

number of wells resulted in an increase in the relative importance of open water for livestock. Mearns (2004) noted vegetation degradation around the remaining wells; therefore, these wells also likely affect the trend of LVs. In this study, however, we could not directly account for the effect of wells due to the difficulty of collecting data on the locations and conditions of wells across the study area.

Both roads and open water were related to the linear decrease of LVs. However, for roads the scale has a significant effect; that is main roads have more impact on vegetation degradation, whereas the effect of open water did not depend on the size of the water source (Figure 5). This may be because the existence of water at the surface is important, irrespective of the width or depth of the source. In terms of constancy, a main stream can be expected to be a more permanent source. We compared two periods for each pair of LANDSAT images used in this study, however, and no example was found of the complete disappearance of rivers, which, at most, became intermittent.

The interaction between settlements and open water was significant (Tables II, III). This means that open water sources near settlements had more impact on vegetation degradation than did sources farther from settlements, and settlements along open water had more impact than settlements without adjacent open water (Figure 6). Such locations, with both a water source and the services of settlements (i.e. medical and educational services and markets), should be preferred by herders. In contrast, the interaction between open water and roads was not significant, perhaps because the roads merely serve as a means to access the services in settlements.

Although, in general, a decreasing trend in LVs could be seen in the vicinity of these three factors, there existed some areas without a low tau value near these factors (see locations C–E in Figure 5). Locations C, D and E are near open water, roads and a settlement, respectively, but an increasing trend of LVs was observed around these three locations. Considering the other factors, however, location C is far from roads and settlements, D is far from settlements and E is far from open water. Therefore, at locations C, D and E, the interactions between open water and settlements, between roads and settlements and between open water and settlements, respectively, might have weakened the effect of the individual factors.

We did not analyse the effect of landform in this study, although it must be related to the three factors analysed as well as to the trend of LVs. However, because main roads, which cross different landform types, showed a significant effect on vegetation degradation, social factors appear to be more important than landform effects.

Because LV is a relative and local indicator of vegetation, the decrease in LVs cannot be interpreted directly as vegetation degradation. The spatial patterns in the trend of LVs, however, and the factors causing these patterns are consistent with existing studies of vegetation degradation (e.g. Fernandez-Gimenez, 1999, 2002; Kazato, 2005). Therefore, we conclude that the spatial patterns of LVs derived in this study are related to the patterns of vegetation degradation. By comparing the spatial patterns in the trend of LVs with the findings of precise field surveys, researchers will be able to develop LV benchmarks as indicators of field conditions, thus improving the accuracy of degradation studies using satellite images.

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CONCLUSION

This study analysed how the changes in the social system in Mongolia that occurred in early-1990s affected local vegetation change in relation to the possible control factors of open water, roads and settlements. The individual factors had significant impacts on the local vegetation change. Moreover, the interactions of some factors affected vegetation, such as the degradation seen around roads and open water near settlements. This interactive effect is likely a consequence of the basic requirements of the nomadic pastoralists, namely quality grassland, water sources and the services provided by settlements. Therefore, in studies of the effects of livestock concentration, multiple factors controlling the grazing regime should be analysed comprehensively. Most previous studies, however, focused on only a single factor. In our study area in Mongolia, the local pattern of vegetation change was determined by the complex process of pastoralists' decision-making. A comprehensive understanding of this process is essential for devising management plans to counteract this vegetation degradation.

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