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Spectral detection of grazing degradation in the Xilingol Steppe, Inner Mongolia

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Abstract

In order to detect the grazing degradation of steppe vegetation, spectral reflectance was measured using a portable spectral radiometer in the Xilingol steppe, Inner Mongolia. There is only one main drinking place for animals, which is supplied by a water tank at the center of Branch No.4 site-00. In addition to the measurement of surface reflectance, vegetation surveys were carried out involving floristic composition and plant growth parameters as a function of the distance from site-00 at every 1-km interval until the 5-km point. It becomes clear that the effects of grazing on vegetation and soil mitigated according to the distance from site-00. Negative plant indicators of grazing intensity such as *Stipa grandis* and *Filifolium sibiricum* increased in dominance with distance from site-00, whereas positive indicators of grazing intensity, such as *Cleistogenens squarrosa* and *Agropyron cristatum*, decreased in dominance. Changes in growth parameters along the environmental gradients were reflected on NDVI (Normalized Difference Vegetation Index), in which NDVI was positively correlated with the aboveground biomass ($r = 0.77$, $P < 0.001$), plant height ($r = 0.69$, $P < 0.001$) and coverage ($r = 0.89$, $P < 0.001$), respectively. These results suggested that a spectral vegetation index is effective in the detection of the degradation of grazing grassland in a non-destruction way.

1. Introduction

Grasslands in China account for about 40% of the total territory of China, with more than 355 million ha in area (Ni, 2002). Inner Mongolia holds more than 22% of the total grassland areas of China, and the grassland has been used for grazing by nomadic people for thousands of years, and part of the grassland has been subjected to cultivation since the 1950s. Akiyama and Kawamura (2007) gave gross observation on grassland degradation in China. The Xilingol steppe is a major husbandry region in Inner Mongolia. However, a large area of the steppe is suffering from on-going desertification due to human activities such as overgrazing (Zhou et al., 1995; Li et al., 2000).

Many studies have been conducted concerning the effects of grazing on vegetation in the Xilingol Steppe. There are three types of steppes in Xilingol: meadow steppe, typical steppe and desert steppe. Typical steppe occupies most of the area. Meadow steppe is mainly dominated by *Stipa baicalensis*, *Filifolium sibiricum* and other forbs, whereas typical steppe can be grouped into *Leymus chinensis* steppe and *Stipa grandis* steppe (Li et al., 1988). Detecting the grazing intensity in a steppe for free grazing is the most difficult, and the distance from the nearest village is generally used as an indicator of grazing pressure (Nakamura et al., 2000). The line transect method and long-term point research are useful for investigating the impacts of grazing on vegetation, and some results have been achieved (Li, 1994, 1996; Li et al., 1994; Nakamura et al., 1998, 2000). *Leymus chinensis* and *Stipa grandis* steppes, which are the major original vegetation of typical steppes in Inner Mongolia, shift to an *Artemisia frigida* type steppe under long-term heavy grazing, and to a *Potentilla acaulis* type steppe under sustained overgrazing (Li, 1994, 1996; Li and Wang, 1999). However, steppes under moderate grazing achieved the highest species diversity and ANPP (aboveground net primary production), suggesting that a sustainable utilization of steppe is possible if it is kept under careful management (Chen and Wang, 2000; Li, 1994, 1996; Wang and Wang, 1999a; Wang et al. 1999a, 1999b).

On the other hand, trials for the measurement of bio-information using spectral radiometers had been attempted on many crops and pasture plants, and these results have been summarized by Akiyama (1996). Akiyama and Shibayama (1985) measured six pasture grass populations with three different cutting levels using a field-type radiometer which covers wavelengths of 400-1200nm. As the result of spectral analysis, 650, 850 and 1040 nm reflectance factors are the most suitable for estimating aboveground biomass, leaf area index and the amount of nitrogen in stands. In addition, Itano et al. (2000) measured an Italian ryegrass (*Lolium multiflorum* Lam.) population for obtaining information on pasture management. By observing reflectance intensities at 6 wavelengths ranging from within the visible region to the near-infrared, it was possible to acquire bio-information such as plant coverage, height, aboveground biomass and LAI. Lodging information was also detectable. Spectral reflectance measurement is a promising method for monitoring the condition of the grassland in a non-destructive way and one that is connected with satellite image analysis.

As satellites onboarding super-high resolution and hyper-spectral sensors like IKONOS or EO-1/Hyperion have become ready at hand in recent years (e.g. Thenkabail, 2003), the importance is increasing to collect the site specific information as of the ground truth data. This is the reason that we choose spectroradiometric method corresponding to field data.

Although some concepts and considerations have been given in relation to evaluating and monitoring the qualities of steppes (Li, 1994, 1996; Li and Wang, 1999; Nakamura et al., 2000), there is still the lack of a standard method for judging steppe degradation which is easy to employ for such a huge area. Therefore, the establishment of a management system for the sustainable utilization of grassland is urgently required. We chose an area specified by the Landsat/TM image in the Xilingol Steppe, where the distance from the village can be used as an effective indicator for grazing intensity since the water tank in the village (Branch No.4 of the Baiyinkulun Livestock Farm) is the main drinking place for animals. We therefore analyzed the relationships between the extent of grazing degradation and spectral reflectance factors as a function of the distance from the water tank and combined this with a vegetation survey. The purpose of this study was to test whether the spectral method is effective for detecting grassland degradation in a non-destructive way in the Inner Mongolia steppe.

2. Methods

2.1 Site description

2.1.1 Baiyinkulun Livestock Farm

The Xilingol steppe is situated in the northeastern part of Inner Mongolia, which is about 400 km north of Beijing. The Baiyinkulun Livestock Farm is one of the farms of the Xilingol League and is located in the southern Xilingol Steppe (Fig. 1). The area of the Baiyinkulun Livestock Farm extends approximately 50 km east to west and 30 km north to south.

The steppes are subjected to grazing or mowing spread around the surrounding small villages with water tanks to supply water for living and animal husbandry (Fig. 1). The Baiyinkulun Livestock Farm was an important state livestock farm used for raising military horses during the period of 1950 to 1970. Since the 1970s, it has become a local government-managed livestock farm, and occupies 141,650 ha of grassland in total of which 138,000 ha is used for livestock (grazing and mowing) and 3,650 ha for cropland.

2.1.2 Pipelines

Securing water for animals is the most serious problem which this district faces because the hard base rock prevents the digging of water wells. From 1965 to 1969, pipelines were constructed from the Liyupaozi Lake for transporting fresh water at a distance of 73.2 km. Here, in the Baiyinkulun Livestock Farm, 10 water tanks were built at 5 to 7 km intervals for supplying water for daily living as well as for animals (Fig. 1). Therefore, nomadic people built their houses near the tanks, forming small villages. As thousands of animals went to the tank and back every day to drink water, the land around the drinking place became bare. By carefully watching the summer

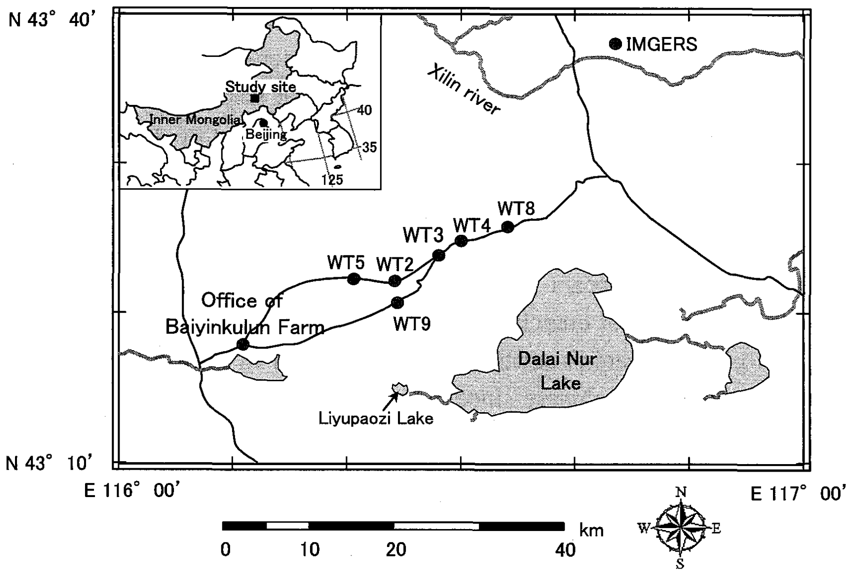

Fig.1. Location of Baiyinkulun Livestock Farm and water tanks along the pipeline, with an inset map showing the location of the study site in northern China.

satellite images of this area, we noticed bright spots appearing at intervals of several kilometers. At the center of each of these, there are circles of bare soil of over 100 m in diameter, which have been formed by the frequent trampling by domestic animals. The gradient of grazing pressure might mitigate in concentric circles inversely proportional to the distance from the village center.

2.1.3 Branch No.4 (Silian village)

The Baiyinkulun Livestock Farm consists of 10 branches. Among them, we are watching with interest Branch No.4 (villagers call it Silian) at water tank No.3 (WT-3). Most of the residents are raising sheep, cattle or goats. The altitude here ranges from 1300 to 1400 m, a gentle slope spreads to the north, and grasslands extend for more than 10 km in each direction. Besides this, several old craters of small volcanic mountains are situated here. Fig.2 is the study site displayed on a Landsat/ETM+ image acquired on August 14,

2001. The cross symbols (×) represent the sampling points for 1999. The total area of Branch No.4 is about 20,000 ha, of which 19,000 ha were available grasslands, consisting of 13,000 ha for grazing and 6,000 ha for mowing according to the statistics of 1997. No croplands nor protective fences for separating grazing from mowing grasslands in this Branch were observed during the experiment period (1998 to 1999). In 1973, Branch No. 4 consisted of only 35 families (172 people). However, this has since in-

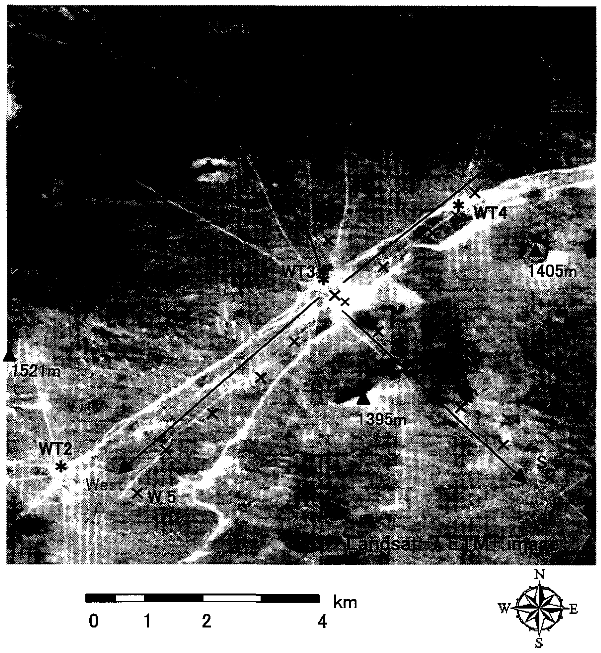

Fig.2. Setting of test sites for vegetation, soil and spectral measurements at Branch No.4 (WT-3) of the Baiyinkulun Livestock Farm in the Xiligol steppe, overlaid on Landsat/ETM+ image acquired on August 14, 2001. The red arrows show two courses from southwest to northeast (W-E course), and north to southeast (N-S course) for the field surveys.
△: Mountain, ∗: WT; Water tank, ×: Points for vegetation survey and spectral measurement; WT2: Water tank No.2 at power substation; WT3: Water tank No.3 at the center of Silian village (Branch No.4); WT4: Water tank No.4 at Silian village (about 2.5 km northeastern from center); Landsat-7 ETM+ satellite data acquired on August 14, 2001. (R:G:B = ETM5:ETM8:ETM2)

creased to 199 families (430 people) in 1999.

2.1.4 Increment of animal number

The yearly changes in animal numbers in Branch No.4 (Silian) are shown in Fig. 3. The horse was the major animal for the farm just after its foundation. However, this has since changed to sheep. The stock numbers increased steeply from years 1985 to 1987, partly due to the reorganization of branches. In addition, the increment in goat numbers is outstanding because of the soaring price of cashmere since 1995. Accordingly, the total livestock has increased to 35,600 HT (sheep equivalent animal unit) in 1999, where 1 horse is 6 HT, 1 cattle is 5 HT and 1 goat is 0.8 HT, according to Zhang and Liu (1992). Thus, the average grazing intensity, which is simply the ratio of the total livestock to grassland area, would be 2.74 HT ha^{-1} for grazing land or 1.89 HT ha^{-1} for the total grassland area, including the mowed land.

2.2 Setting of the test site

Branch No.4 (Silian village) is one of the villages located on the pipeline running east to west. WT-3 (water tank No. 3) at Branch No.4 is situated at 116 °28'10"E, 43°23'56"N. Along the pipeline, a local beaten road passing from southwest to northeast can be found; we call this a W-E course (Fig. 2). To the east from WT-3, WT-4 (water tank No. 4) and several farm houses are located between the 2.5-km (E2.5) and 3-km points (E3). WT-2 (water tank No. 2) and a village called Power substation is located at 6-km west along the pipeline. More than half of the villagers raise animals. On this road, large-sized motor-trucks come and go during the summer season for shipping out produced domestic animals and for carrying in wintering feed. A lot of nomadic people and animals go back and forth along the road. Meanwhile, in the north-south direction (N-S course), small local paths are running but it is difficult to pass full-sized trucks, so there is no farm house nearby.

In the four directions shown in Fig. 2, we used GPS equipment to decide on the test sites, as described below: site-00 was a drinking place near the WT-3. Twenty-one test sites were chosen every 1 km until the 5-km point from site-00 in 4 directions. For instance, at the 5-km point to the east, we called this site E5. Such a configuration in space is illustrated in Fig. 2. Addition to the 21 test sites, site E2.5 was chosen at a distance of 2.5 km from site-00, where there is another tank (WT-2). Besides, S0.1 was chosen at the edge of central circle of bare land, about 100-m south of site-00, to ascertain tolerant species under the highest grazing intensity. Vegetation survey was not able to conduct at site-00, while reflectance was not measured at E2.5 and N5 because of low solar radiation during the surveyed hours.

According to the climate record observed at the IMGERS (Inner Mongolia Grassland Ecosystem Research Station, Chinese Academy of Sciences) meteorological observing station, which is located 28-km north of Branch No.4 (Fig. 1), the annual mean precipitation is 340 mm, and the annual mean air temperature was 0.58oC from 1980 to 1998. The Penman arid index is 2.1 for the area (Li, 1996).

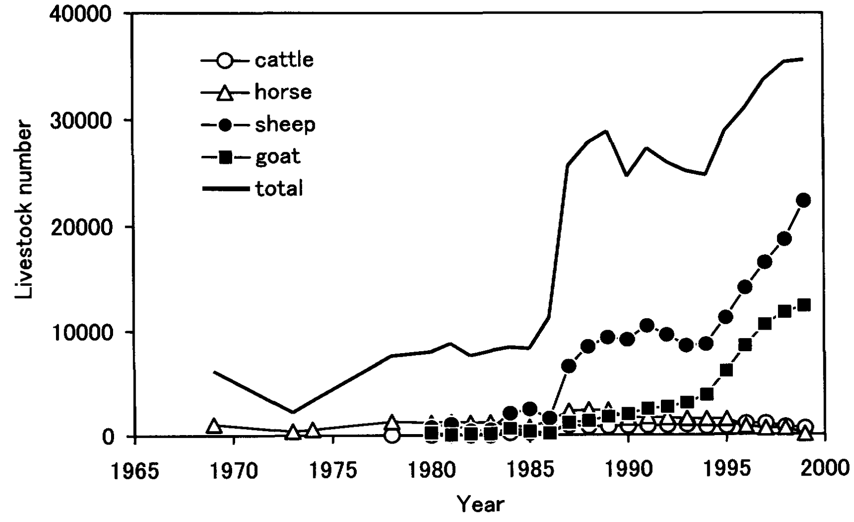

Fig. 3. Changes in animal numbers during the years of 1965 to 1999 at Branch No.4. Total numbers are calculated equivalent to sheep units (HT) where 1 horse is 6 HT, 1 cattle is 5 HT, 1 goat is 0.8 HT, according to Zhang & Liu (1992).

The steppe type in this area is typical steppe and meadow steppe (Li et al., 1988). Typical steppes dominated by *Stipa grandis* and *Leymus sinensis* are mainly present around the areas where the pipeline was established. Most of the typical steppes have been degraded to various degrees after being subjected to grazing for more than 40 years after the establishment of the livestock farm. Meadow steppes are present about 4 or 5 km north or south from the village towards the hills or lake. Accordingly, the soil types of this area are Chernozem for the meadow steppe and Chestnut for the typical steppe (Chen and Huang, 1988; XLSFWS, 1991).

Soil and vegetation surveys as well as spectral reflectance measurements were carried out during the summers of 1998 and 1999 around Branch No.4.

2.3 Vegetation survey

The vegetation survey was conducted according to the method proposed by Braun-Blanquet (1964). Five 1-m^2 quadrates were examined at each site. Firstly, a central quadrat (Qc) was chosen, then another 4 quadrates (Qe, Qw, Qs, Qn) chosen that were stationed 10 m away from Qc in 4 directions (east, west, south and north, respectively) determined using a compass. The canopy height (cm) and total coverage (%) of each quadrat were then recorded, and the mean values of the five quadrates were used to represent the plant height and plant coverage of the site. In addition, within the central quadrat (Qc), the coverage (C, %) and height (H, cm) of each species was estimated. The species frequency (F, %) was measured using the point method of multiple contacts (100 points along two 20-meter lines across the plot, i.e. from Qe to Qw and from Qs to Qn), where F (%) is the number of species touched among the 100 points (Goldall, 1952). We used SDR (the summed dominance ratio) to indicate the dominance of the species in the community (Numata and Yoda, 1957). The species dominance (SDR) was then calculated using the equation: $SDR = (H'+C'+F')/3$, where H' is the relative plant height (cm), C' is the relative coverage (%) and F' is the relative frequency (%); H' (C' or F') = H (C or F) of the species/maximum value of H (C or F) in the quadrat, respectively. Due to the frequency of animal foraging and trampling, there appeared a 100-m circle of bare soil around the site-00. For the vegetation survey, S0.1 was therefore used instead of site-00, 100-m south of site-00, which was able to grow some plants in an extremely sparse coverage and low canopy height. All of the plants were named according to Liu and Liu (1988).

After the vegetation survey and spectral measurements, all aboveground parts were removed at the soil surface level, and the total fresh weight (FW, g) in situ was measured using a portable electric balance (Model-BL2200H, Shimadzu Co. Ltd., Kyoto, Japan). Parts of the samples were brought back to IMGERS to be oven dried at 80°C for the estimation of their dry weight (DW, g) of the biomass. A survey of species composition was carried out in 1998, and other quantitative information on the plant community was measured during the summer seasons of 1998 and 1999.

2.4 Soil hardness measurement

The soil hardness (SH, mm) was measured at nine points for each site using a Yamanaka standard type soil hardness tester (Fujiwara Scientific CO.LTD., Tokyo) after the removal of aboveground plant materials. The surface color and moisture of the soil were also measured, but it was too difficult to relate this to the land characteristics because they were strongly affected by the previous rainfall event.

2.5 Spectral reflectance measurement

In order to detect the grazing degradation of grasslands by a non-destructive method, spectral reflectance measurements were carried out. A field-type spectral radiometer (MD-01 type) was used in this experiment which was manufactured by PREDE CO.LTD., Tokyo. This device is able to measure reflectance at 4 visible (450, 545, 650, 699 nm) and 2 near-infrared wavelengths (750 and 850 nm). The measurer stands facing the sun, stretching the optical fiber over the plant canopy keeping a distance of about 1 m between the tip of the fiber and the canopy. As the instant view angle of this equipment is 10°, if keeping a 1-m distance, the reflectance value inside 35.3 cm in diameter can be measured. Measurements were carried out during clear daytime between 9:00 and 15:00 local time to get strong and constant solar radiation. The spectral reflectance was corrected to a relative value using a standard white board (Spectralon, Labsphere CO.LTD. USA). The spectral measurements were repeated 7 times for each quadrat. After omitting the maximum and minimum values, the remaining 5 data points were averaged. The measurements were repeated for all 5 of the quadrates for each site.

In order to compare the quantitative biological information of grasslands, we used NDVI, a spectral vegetation index. The NDVI (Normalized Difference Vegetation Index) is a popular spectral vegetation index proposed by Rouse et al. (1974). It comes from the principle that chlorophyll in green leaf absorbs red light, while mesophyll cells reflect the near infrared wavelengths. Therefore, it relates to the biomass and vigor of vegetation. The following is the equation for NDVI.

NDVI = (NIR - Red) / (NIR + Red)

Here, NIR is the intensity of near infrared reflectance at 850 nm, and Red means red reflectance at a wavelength of 650 nm in this experiment.

3. Results

3.1 Changes in species composition with distance from water tank

Fig. 4 shows the changes in dominance (SDR, %) of major species with increasing distance from site-00 in the N-S and W-E directions (see Fig. 2). As described above, site-00 is the drinking place for animals near the water tank No.3 (WT-3) of the Silian village (Branch No. 4). Due to frequent animal foraging and trampling, site-00 displayed a bare cover of plants. We illustrated the result of S0.1 in Fig. 4 to indicate vegetation under an extremely high grazing pressure 100 m from site-00 in a region where some plants are able to grow in an extremely low coverage of 20% and a plant height of 3.4 cm (also see Fig. 5a). With increasing distance from site-00 in all 4 directions (N, S, W, E), there was a similar tendency in terms of species dominance changes with distance

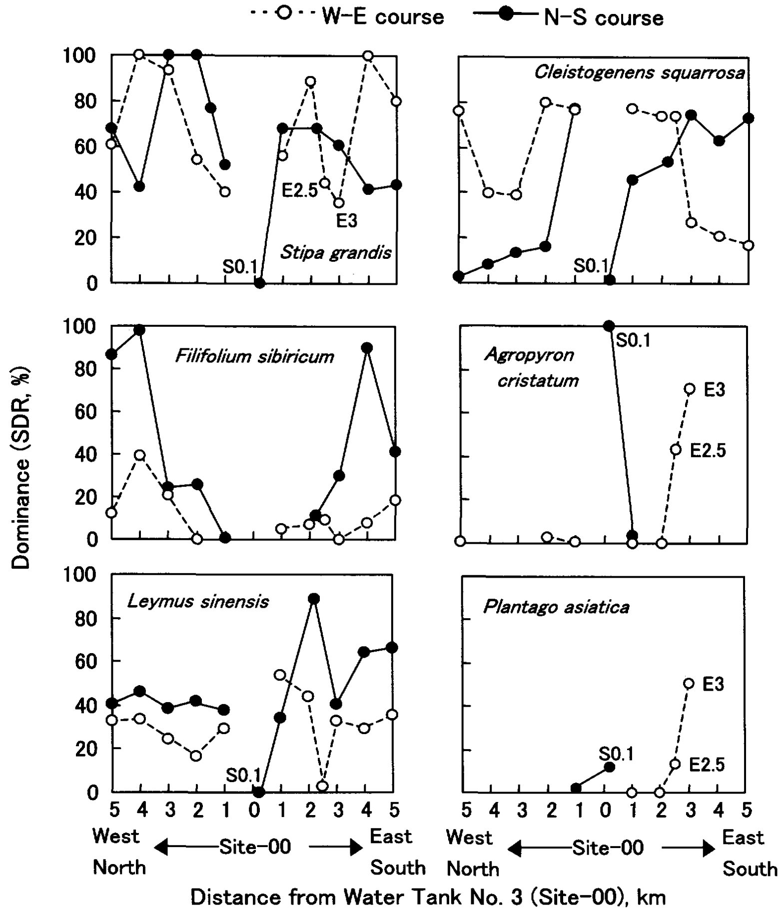

Fig. 4. Changes in dominance (SDR, %) of the major species with distance from the village of Branch No.4 (WT-3: site-00) in the Xilingol steppe (July, 1999). The W-E course is from site-00 to the southwestern and northeastern 5-km points, and the N-S course is from site-00 to the northern and southeastern 5-km points (detailed see Fig. 2). Inserted E2.5 and E3 indicates that these two sites are kind of special due to the fact that they are near WT-4 (water tank No. 4). Site-00 is bare land, therefore the results of S0.1, 100-m south of site-00, is illustrated to represent vegetation under extreme grazing pressures.

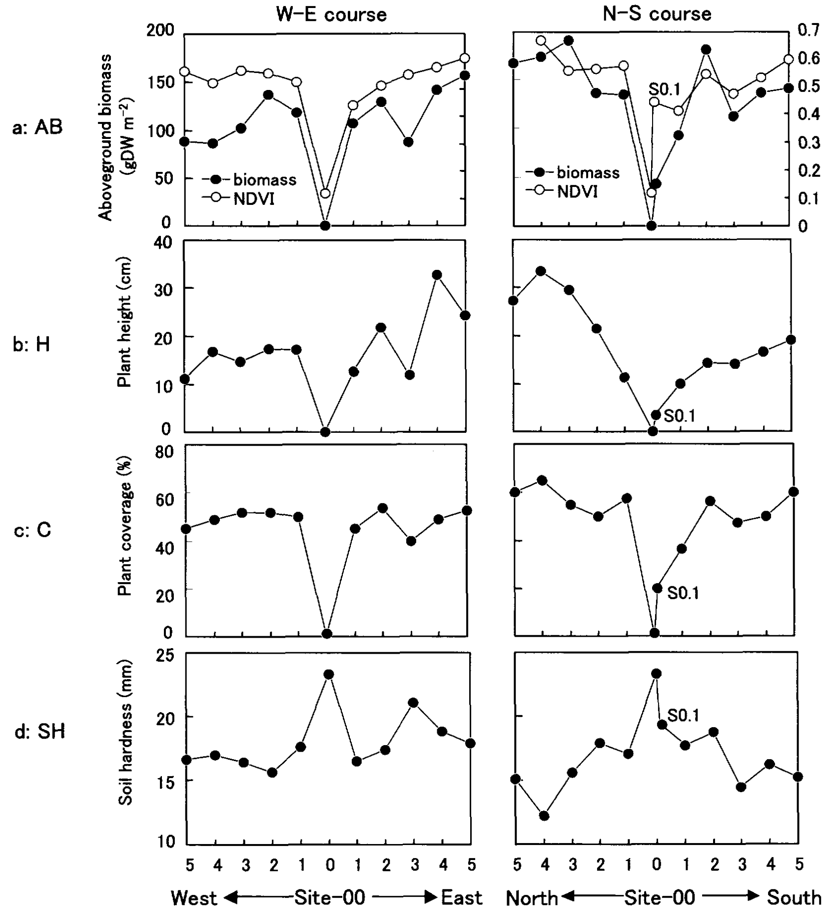

Fig. 5. Changes in plant quantity information and soil hardness according to the distance from the water tank at Branch No.4 of the Baiyinkulun Livestock Farm.
a: aboveground biomass (AB) and NDVI, b: plant height (H), c: plant coverage (C) and d: soil hardness (SH). NDVI is the Normalized Difference Vegetation Index obtained from the following equation: NDVI = (NIR-R)/(NIR+R), where NIR is the near infrared reflectance and R is the red one. NDVI at E2.5 and N5 were not measured because of the low solar radiation during surveyed hours.

from site-00. That is, negative indicators of grazing intensity suggested by Li et al. (1999) (see discussion for details), such as *Stipa grandis* and *Filifolium sibiricum*, increased in dominance (SDR, %) with distance from site-00. Whereas positive indicators of grazing intensity, such as *Cleistogenens squarrosa* and *Agropyron cristatum*, decreased in dominance with distance from site-00. Such a tendency in the W-E direction seemed not as clear as in the N-S direction as a result of disturbances due to the existence of other water tanks (WT-2 and WT-4) and farm houses along the pipeline. The areas inside a 1-km diameter from site-00 were thought to be subject to heavy grazing, where positive indicators for grazing intensity, i.e. *A. cristatum* and *C. squarrosa*, dominated the communities. Whereas negative indicators for grazing intensity, i.e. *S. grandis* and *F. sibiricum*, were absent or with lower SDR values at sites a distance of 1 km from site-00. In the meantime, a widespread weedy species, *Plantago asiatica*, appeared at these sites, also indicating the effects of human daily life. Because of another water tank (WT-4) located near E3, sites E2.5 and E3 exhibited a reduced SDR of *S. grandis* and an increased SDR of *A. cristatum*, as well as the presence of the weedy species *P. asiatica*.

Similarly, the grazing pressure seemed to decline with distances of greater than 2 km from site-00, since the biomass increased from 42.9 g DW m^{-2} (S0.1 at 100 m away from site-00) to more than 180 g DW m^{-2} (see Fig. 5a). For sites at distances of between 2 and 3 km away from site-00, *Stipa grandis* and *Leymus chinensis* were found, and dominated the community with increasing SDR with distance away from site-00. Meanwhile, *Cleistogenes squarrosa* decreased in SDR with increasing distance away from site-00 for distances of more than 2 km, and this also was indicative of a decreased grazing intensity, especially for distances greater than 2 km away from the village.

For distances of 4 or 5 km from the village in the N-S direction, meadow steppe appeared instead of typical steppe. This area was mainly used for mowing or for light grazing by horses. *F. sibiricum* and *S. grandis* (data mixed with *Stipa baicalensis*) dominated the communities and with more richness in species, including many forbs.

3.2 Changes in quantitative biological parameters with distance from water tank

Fig. 5 shows quantitative biological information on the grasslands such as the aboveground biomass (a: AB), the plant height (b: H), the plant coverage (c: C) and the soil hardness (d: SH) as a function of distance from WT-3 (site-00) at Branch No.4 to the 5-km points for the four directions. Because there was a similar trend in biomass changed with a distance from site-00 towards to the four directions between 1998 and 1999, we only illustrated the results of 1999 in Fig. 5 for explanation.

In the N-S direction of Fig. 5a, AB increased linearly with increasing distance from site-00, and remained at over 160 g DW m-2 for distances of between 3 and 5 km (N3, N4 and N5). A similar trend is observed in the W-E direction, however, for the same reason as the changes in the species composition described above, it is not as clear as in the case of the N-S direction because of disturbances by the existence of other water tanks and farm houses along the pipeline. On the same graph (Fig. 5a), the changes in the NDVI values are drawn. The NDVI curves appeared to be almost proportional to AB, C and H.

Slow but constant increments were observed from site-00 to N4 in H of Fig. 5b and reached a maximum value (34 cm) at N4 in the N-S direction. In the W-E direction, the maximum value reached was 33 cm at E4, but the curve had roughness and hollows.

The coverage (C) in Fig. 5c showed almost the same patterns for the N-S and E-W directions. In both directions, steep V shapes formed between site-00 at the 1-km points, securing 50% coverage, then it became almost constant out to the 5-km points. The maximum coverage was 66% at N4. Hollows at E3 were commonly found in all three sets of data. This result might have been affected by farm houses near WT-4.

3.3 Soil hardness (SH)

The changes in SH are shown in Fig. 5d in relation to the distance from site-00. The values are over 20 mm (very tough) around site-00, but soften with distance to 12 mm at N4. This trend was clear in the northerly direction, but was obscure in the W-E direction. The SH curve had another peak at the E3 site.

4. Discussion

4.1 Floristic composition changes after long-term heavy grazing

Li et al. (1999) established a grazing experimental plot (21 ha) with 21 subplots in IMGERS and compared it with different stocking rates in an *Artemisia frigida* steppe about 30-km north of Branch No. 4 in the Xilingol steppe. This study began in 1990 with the aim of investigating short and long-term effects of grazing on vegetation and soils. The results of the first 3-5 years have been reported involving changes in species composition, species diversity, as well as the above and belowground biomass with grazing management (Han et al., 1999; Li and Wang, 1999; Wang and Wang, 1999a, 1999b). Li (1994) suggested six ecological groups in relation to grazing intensity in the steppe, *i.e.* decreaser, disappearer, increaser, invader, species adapting to moderate grazing and fluctuating species. Decreaser and disappearer are negative indicators for grazing pressure such as *Achnatherum sibiricum*, *Stipa grandis* and *Filifolium sibiricum*, while increaser and invader are positive indicators such as *Carex duriuscula*, *Artemisia frigida*, *Cleistogenes squarrosa*, *Agropyron cristatum* and *Potentilla acaulis* (Li, 1994; Nakamura et al., 1998; Han et al., 1999).

In this study, such a change in species composition with distance from the village was clear in the N-S direction, but was disturbed by the existence of farm houses along the W-E direction. For example, due to the WT-4 located at 2.7-km east of the Silian village, these sites (E3 and E2.5) exhibited a reduced dominance of *Stipa grandis* and an increased dominance of *Agropyron cristatum*, as well as the appearance of the weedy species *Plantago asiatica*. A similar tendency was observed at the W4 and W5 sites close to WT-2 (Fig. 4). However, along the N-S direction, there were no farm houses found in the areas at distances of between 1 km and 5 km from the site-00. It was obvious that the changes in species composition along the N-S direction could be explained by long-term grazing effects with decreasing grazing intensity with increasing distance away from site-00. Moreover, it indicated that areas at a distance of 3 km away from the village (i.e. at S3 or N3) may be under a relatively moderate grazing pressure, reaching higher biomass and dominated with *Stipa grandis*, with the highest SDR in the N-S direction (Figs. 4 and 5a).

4.2 Relations between NDVI and biological parameters

Fig. 6 shows the relationships between NDVI and several biological parameters, such as the aboveground biomass (AB), the coverage (C), the plant height (H) and one soil parameter (soil hardness, SH) measured during the 1999 experiment using the same data as in Fig. 5.

This includes all sites on the W-E and N-S courses. A high correlation was observed, particularly between NDVI and C ($r = 0.89$, $P < 0.001$, $n = 21$). The correlations of NDVI vs. AB ($r = 0.77$, $P < 0.001$, $n = 21$), and NDVI vs. H ($r = 0.69$, $P < 0.001$, $n = 21$) were also significant, although the correlation coefficient was not as high as that of NDVI vs. C. The same tendency was reported using satellite data analysis (Kawamura et al., 2003), that the correlation was much higher in the coverage (%) than in plant height because remote sensors sharply sense the percentage plant coverage in the nadir angle, so it is more sensitive to horizontal information than to vertical. Xiao et al. (1997) analyzed Landsat/TM data for detecting steppe vegetation types in Xilingol using 1987 image. In the multispectral classification, 14 vegetation cover types were recognized. Among them, the total area of degraded and desertificated grasslands, summed from the *Stipa krylovii* steppe, *Artemisia frigida* steppe and desertificated grasslands, accounted for 26.4% of the total 29,440 km^2 of land area.

4.3 Relation of spectral reflectance and grazing degradation

Land degradation triggered in arid/semiarid grasslands in the world is mainly caused by overgrazing (UNEP, 1984). However, by raising freely several thousands of flock on several thousands of hectares of grassland, it is difficult to quantify grazing pressure in each area. Without such a grassland management record, how can we judge objectively the extent of the overgrazing? A simple ratio of the total animal

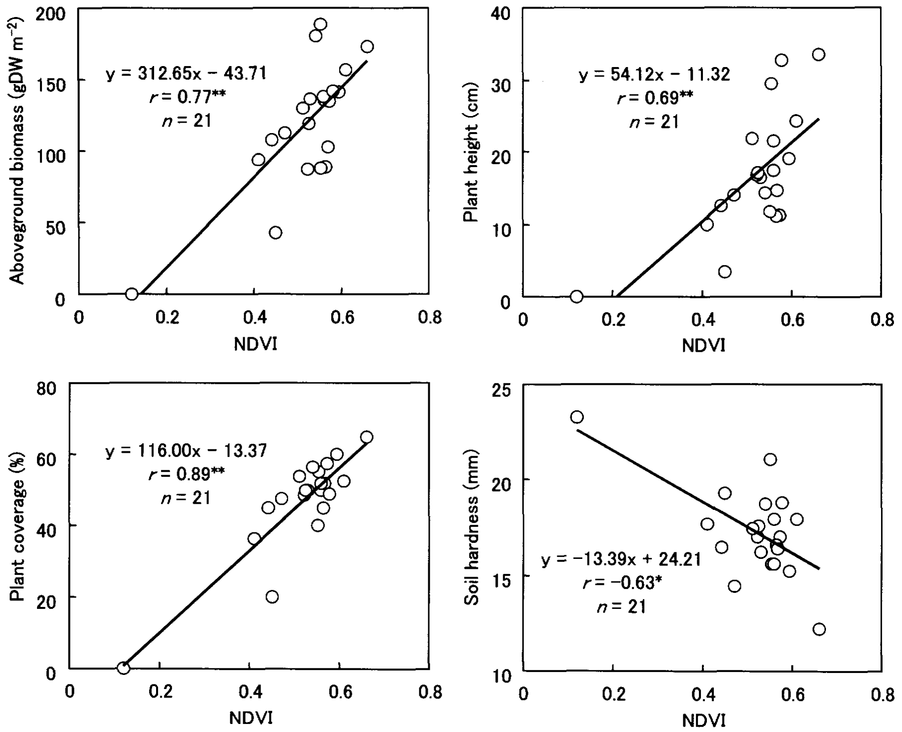

Fig. 6. Relationships between NDVI and several plant quantity parameters observed in 1999 at Branch No.4. Each point coordinate data used 21 test sites in Fig.5.
Upper left; aboveground biomass (AB) vs. NDVI; Upper right: plant height (H) vs. NDVI; Bottom left; plant coverage (C) vs. NDVI; and Bottom right; soil hardness (SH) vs. NDVI
* $P < 0.01$; ** $P < 0.001$.

numbers 35,600 HT by the grassland area yields 2.74 head ha^{-1} in average over 13,000 ha at Branch No.4. Although it is similar to the optimal stocking rate (2.67 head ha^{-1}) obtained by the grazing experiments done by Wang et al. (1999a) at IMGERS, the area around the village is suffering from overgrazing of hundreds of times this level.

In semi-arid districts, a deterioration of grassland is easily brought about by overgrazing, meaning a frequent removal of herbage. In addition, the treading by animal causes a destruction of aboveground organs and root systems as a result of soil compaction (Kubo and Akiyama, 1977).

The possible mechanisms of grazing degradation are summarized in Table 1. Herbage biomass decreases and plants become dwarfed, and plant litters are removed by grazing animals and strong wind. Herbage production reduces by the serious and continuous removal of assimilation organs under ceaseless heavy grazing, sometimes resulting in bare land. This is why it is easy to dry up the soil surface. At the same time, the floristic composition become poor and simple, but some tolerant species prosper forming rugged patches consisting of unpalatable species. Meanwhile, the soil becomes compact by frequent trampling, and defecation brings about an enrichment of the soil chemical components by supplying large amounts of feces and urine exhausted by animals. At the ecosystem level, the soil surface becomes dry, resulting in a decline in herbage productivity and species diversity. Most of these changes in plant and soil conditions are related to an enhancement in the brightness captured by spectral-radiometer or satellite sensors which are reflected in NDVI values in this experiment. These are the characteristics of the direct deterioration of grassland caused by overgrazing.

The extent of land degradation occurred so rapidly around the village, that the biomass and the floristic composition had changed drastically step by step. Landsat/TM data of middle-resolution can not follow such sudden changes. In that meaning, getting the field spectral data together with the biological information are useful for using super-high resolution satellite data in the near future. Under similar point of view, Harris and Asner (in print) detected grazing gradient with airborne imaging spectroscopy in Utah, USA, and showed that detection of persistent grazing gradients with imaging spectroscopy is feasible. But they did not refer about changes in the floristic composition.

The spectral reflectance data could not detect the changes in floristic composition directly in this experiment. Fukuo et al. (2000) measured some unpalatable species communities such as *Iris*, *Potentilla* and *Caragana microphylla* using the same spectroradiometer of this study, and found that there existed weak relationships between vegetation indices and plant coverage ratio of the species. However, it was difficult to generalize for such unpalatable communities. In the meanwhile, inedible species for animals are apt to form distinctive and pure communities near the village, which may be detectable from the difference of texture in the highly resolution satellite images. By this method, Yamamoto (personal communication, 2000) detected weed communities in grasslands using roughness index of satellite image. If we can find a spectral index able to specify plant indicators for grazing degradation, spectral detection of grazing degradation may improve to detect the changes in floristic composition due to overgrazing. Nevertheless, our results indicated that NDVI achieved by spectral reference could well reflect the

Table 1. Effects and mechanisms of land degradation caused by overgrazing and its detection using spectral reflectance

Animal actions	Effects on plant & soil	Changes of plant & soil	Ecosystem level
Foraging	Plant height & biomass	Dwarf and bare*	Decline in productivity
Foraging	Litter accumulation	Dissappear*	Soil drying
Foraging	Composition	Deforage tolerant species	Floristic deterioration
Foraging	Unpalatable community	Rugged surface	Floristic deterioration
Trampling	Lodging and organ dying	Loss of leaf area*	Decline in productivity
Trampling	Soil (physical effect)	Soil harden*	Soil degradation
Defecation	Soil (chemical effect)	Enrichment	Weedy species

*: Increase reflectance or decrease NDVI.

growth parameters such as aboveground biomass, plant coverage and height along grazing intensity gradients. This strongly suggested that spectral detection of grazing degradation with a spectral vegetation index (e.g. NDVI) is effective in the Xilingol steppe in a non-destruction way.

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