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Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices

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Abstract. Early drought detection and impact assessment on the amount of pasture biomass are important in Mongolia, whose economy strongly depends on livestock production. The country's large area and a lack of information on grass availability due to the sparseness of biomass-observing and/or meteorological stations make it difficult to optimize nomadic livestock output in the Mongolian dry climate. The application of a new satellite-based method for drought detection and for assessment of wild biomass in Mongolia was investigated. Measurements of biomass at an experimental station in a semi-dry steppe ecosystem during 1985–1997 were compared with the Advanced Very High Resolution Radiometer (AVHRR)-based vegetation health (VH) indices. The results showed the indices can be used as proxies for biomass production estimation (biomass anomaly, BA) applying the following equation $BA = 43.201 + 0.881\ VHI$ ($R^2 = 0.658$).

1. Introduction

Mongolia is a country of nomadic livestock husbandry. Its economy depends much on livestock products. In the past 10 years, livestock husbandry has expanded following a 38% increase in the number of domestic animals (Food and Agriculture Organization (FAO) 2000). This trend is expected to continue.

Mongolia's livestock production depends much on the productivity of natural grassland. The major obstacles limiting grassland productivity are the dry climate with frequent droughts which suppress the development of grass biomass (National

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Atlas of Mongolia (NAM) 1990, Suttie 1999). When drought occurs, the farmers move their livestock to less drought-affected areas. This is not a trivial task since information about grass condition is not available. Therefore, early drought detection and assessment of its impact on biomass reduction are important tasks for livestock survival in Mongolia.

Meteorological data might be used for biomass estimation. Mongolia has, however, only 35 weather-observing stations for an area of 150 Mha of land (4.3 Mha per station). Considering the dry climate and large spatial variability of summer rainfall in Mongolia, estimation of pasture conditions and biomass availability from meteorological data cannot be accurate for such a large area.

During the past decade, scientists have been investigating the application of the Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) for land classification and monitoring dry/wet conditions in Mongolia (Adyasuren and Bayarjargal 1992, Bayarjagal *et al.* 2000). In parallel, grassland biomass has been measured since 1985. The goal of this research was to test advanced AVHRR-based vegetation health (VH) indices for pasture biomass estimation. These indices were successfully used as proxy for estimation of crop yield and pastures biomass in other parts of the world (Kogan 2001, 2002, Kogan *et al.* 2003) but have not been applied to the Mongolian environment.

2. Data

Both *in situ* and satellite sensor observations were used in this research.

2.1. In situ *observations*

In situ data included data on biomass and meteorological variables. Pasture biomass has been measured since 1985 at the Tumentsogt Research Station (TRS) located in eastern Mongolia (47.4° N and 112.5° E). The measurements were made at a 1 ha (2.4 acres) experimental field (EF) typical for the TRS location. This EF was fenced to preserve natural biomass growth. The procedure included cutting and weighing above-ground live biomass on the area of 1 m^2 in four corners of the EF every 10 days. The average weight from four 1 m^2 plots was recalculated for the entire 1 ha area and expressed in tons per ha ($t\,ha^{-1}$). For the following 10 days' measurements, the four plots were moved to the neighbouring locations of the EF. Meteorological variables included monthly total precipitation and mean temperature (1985–1995) collected from Ondorhaan weather station (OWS), which is the closest (25 km to the east) to the EF.

2.2. *Satellite sensor observations*

Satellite sensor observations included radiances (solar radiation reflected and emitted by the vegetation) measured by the AVHRR instrument flown on the National Oceanic and Atmospheric Administration's (NOAA) afternoon polar-orbiting satellites. The NOAA Global Vegetation Index (GVI) dataset (Kidwell 1997) from 1985–2000 was used in this study. The GVI is produced by sampling the AVHRR-based 1 km spatial resolution daily radiances in the visible (VIS, 0.58–0.68 μm), near-infrared (NIR, 0.72–1.1 μm) and thermal infrared (IR, 10.3–11.3 and 11.5–12.5 μm) spectral bands. The data were truncated to 8 bit precision and spatially sampled and mapped to a 16 km^2 latitude/longitude grid. To minimize cloud effects, these maps were composited over a 7-day period by saving radiances for the day that had the largest NIR–VIS values. Further data processing included post-launch calibration of VIS and NIR, calculation of the NDVI (NDVI = [NIR − VIS]/[NIR + VIS]) and conversion of the 10.3–11.3 μm IR radiance to brightness temperature (BT), which was corrected for the nonlinear behaviour of the sensor (Kidwell 1997).

3. Method: vegetation health indices

VH indexes were developed from NDVI and BT using the following processing algorithm: (a) removal of temporal high frequency noise (clouds, Sun and sensor angular effects, etc.) from annual time series; (b) calculation of climatology from many years of data; and (c) estimation of medium-to-low frequency fluctuations of NDVI and BT (departure from climatology) associated with weather variations. The final product included three indices NDVI-based Vegetation Condition Index (VCI), BT-based Temperature Condition Index (TCI) and Vegetation Health (VH) Index

$$\mathrm{VCI} = 100(\mathrm{NDVI} - \mathrm{NDVI}_{\mathrm{min}})/(\mathrm{NDVI}_{\mathrm{max}} - \mathrm{NDVI}_{\mathrm{min}}) \tag{1}$$

$$\mathrm{TCI} = 100(\mathrm{BT}_{\mathrm{max}} - \mathrm{BT})/(\mathrm{BT}_{\mathrm{max}} - \mathrm{BT}_{\mathrm{min}}) \tag{2}$$

$$\mathrm{VH} = a\,\mathrm{VCI} + (1 - a)\mathrm{TCI} \tag{3}$$

where NDVI, $\mathrm{NDVI}_{\mathrm{max}}$ and $\mathrm{NDVI}_{\mathrm{min}}$ (BT, $\mathrm{BT}_{\mathrm{max}}$ and $\mathrm{BT}_{\mathrm{min}}$) are the smoothed weekly NDVI (BT) and its 1985–2000 absolute maximum and minimum (climatology), respectively; a is a coefficient quantifying a share of VCI and TCI contribution in the VH. The share of VCI and TCI in Mongolia is not known; however, based on a previous study (Kogan 2001) this share is assumed to be equal ($a = 0.5$).

Principally, VCI and TCI assess a particular year's NDVI and BT dynamics relative to the range of their variation during extreme (stressed to favourable) conditions. The thresholds for the extreme conditions were derived by calculating maximum and minimum NDVI and BT values from 15-year satellite sensor data for each Mongolian land pixel and each week. VCI, TCI and VH characterize moisture, thermal and vegetation health conditions, respectively.

4. Landscape, biomass and vegetation health indices in Mongolia

The location of TRS and OWS have a typical steppe ecosystem with the dominant *Stipa grandis* species (Adyasuren and Bayarjargal 1992). Total annual precipitation amounts to 250 mm with large variation (160–380 mm) from year-to-year (table 1). Although up to 85% of rains occur in June–August, they are insufficient to provide intensive vegetation growth. Therefore, live biomass does not exceed 170 $\mathrm{g\,m^{-2}}$ during the peak season (Togtohyn *et al.* 1995). Following rainfall seasonal cycle, biomass increases from 0.3 to 1.4 $\mathrm{t\,ha^{-1}}$ between May and August, declining thereafter (table 1). The amount of biomass fluctuates from year-to-year coherently with rainfall variation.

Similar to other world regions (Kogan 2001), the AVHRR-derived indices match generally with climate and ecosystem zones in Mongolia (NAM 1990). Maximum NDVI and BT (figure 1) identifies all major vegetation types from desert in the south (blue/grey colour) with extremely hot temperatures (black/grey) to forest–steppe (green)/forest (cyan) for NDVI and cooler temperatures (pink/brown) in the north.

Table 1. Climatology (1985–1995) at Ondorhaan meteorological station and end-of-month biomass (1982–1997) at Tumentsogt, Mongolia.

	Precipitation (mm)			Temperature (°C)			Biomass* (t ha^{-1})		
Month	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
January	1.9	5.2	0.3	−22.7	−18.2	−27.6			
February	2.3	6.2	0	−18.8	−13.6	−23.2			
March	3.0	7.4	0.5	−9.1	−3.9	−14.3			
April	6.3	22.0	0.2	2.0	5.1	0.2			
May	12.5	26.5	0.4	11.0	12.9	8.3	0.3		
June	36.8	55.0	11.0	16.3	18.5	14.5	0.7	0.9	0.4
July	86.5	173	33.6	18.5	21.8	17.0	1.2	2.0	0.7
August	56.4	80.0	41.2	16.8	19.6	15.1	1.4	1.8	0.8
September	23.7	48.0	4.8	9.7	11.8	7.8	1.0	1.4	0.5
October	8.6	22.3	2.9	1.4	4.3	−1.3			
November	3.5	13.5	0	−11.3	−7.5	−16.3			
December	2.8	4.6	0.3	−19.7	−16.6	−23.1			
Annual	243	377	168	−0.5	21.8	−27.6	1.4	2.0	0.8

*For annual biomass maximum values during the growing season are shown.

5. Results

Similar to VH indexes, which assess deviation of vegetation condition from climatology, biomass of each 10-day period was expressed as a percentage of the 1982–1997 mean (normal). Thus, values under 100 characterize below normal and over 100 above normal biomass amount.

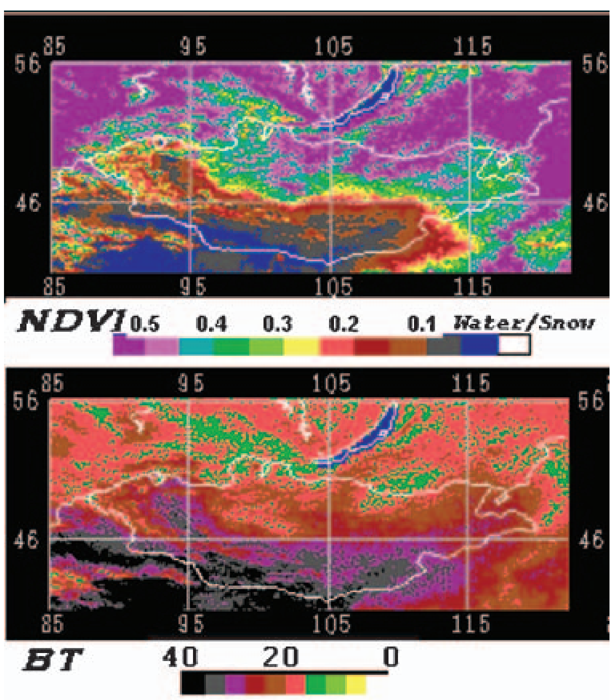

Figure 1. Climatology (1985–2000 maximum) of AVHRR-based NDVI and BT (°C) at the end of July (the peak of the growing season), Mongolia. (Vertical and horizontal lines and the corresponding numbers on the images are longitude (°E) and latitude (°N).)

5.1. *Classification of conditions*

Similar to other arid areas, above/below mean biomass in Mongolia was associated with wetter/drier conditions. Following this principle, all investigated years were classified as wet and dry, aiming to find VH thresholds corresponding to these conditions. Two cases in figure 2 indicate below (60–90% in 1986) and above (110–130% in 1996) mean biomass was associated with VH below 40 and above 60, respectively. Besides, satellite sensor data matched with *in situ* data, both in values and seasonal dynamics.

From all investigated years, VH and biomass anomaly (BA) mismatched in 1990 because May–August period was extremely wet (rainfall 150–200% of mean) and cool (1–2°C below mean), which resulted in excessive soil wetness and correspondingly smaller vegetation growth. This problem is not addressed here since there were not enough cases for analysis. Some discrepancies in 1995 were likely to be attributed to erroneous biomass measurements since both weather (dry and hot) and satellite sensor data coherently indicated intensive drought around the EF area.

5.2. *Statistical analysis*

Regression of BA versus VH is shown in figure 3. Because both variables were expressed relative to normals, all observations ($n = 60$) during the growing seasons of the eight-year period were included in statistical analysis. A biomass anomaly below 90% (reduction of biomass more than 10% below mean) occurred when VH dropped below 50 (the level indicating the beginning of vegetation stress; Kogan *et al.* 2003). A biomass anomaly below 70% (more than 30% reduction) is associated with a very intensive vegetation stress (VH below 30). An above normal biomass (BA larger than 100%) corresponds to favourable conditions with VH above 50. This relationship explains 66% of variance with 10% error of estimate. The VCI, which characterizes moisture conditions, has slightly larger correlation with biomass anomaly than TCI. There is some concern that vegetation indices might be influenced by grazing. This might occur if in some areas animal concentration increased considerably. However, vast expanse of pasture lands, nomadic traditions and family-oriented livestock husbandry in Mongolia prevent such herd concentration, unless drastic climate change were to trigger such an event (Togtohyn *et al.* 1995).

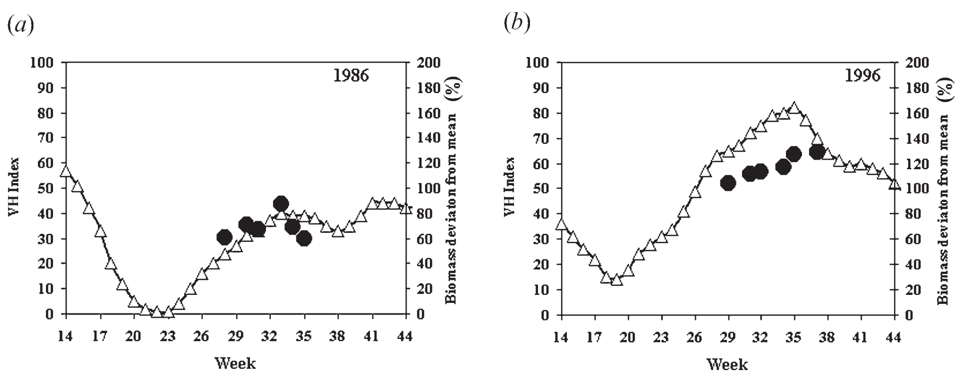

Figure 2. Dynamics of biomass anomaly (filled circles) and VH (line with triangles) in (*a*) 1986 (dry), (*b*) 1996 (wet).

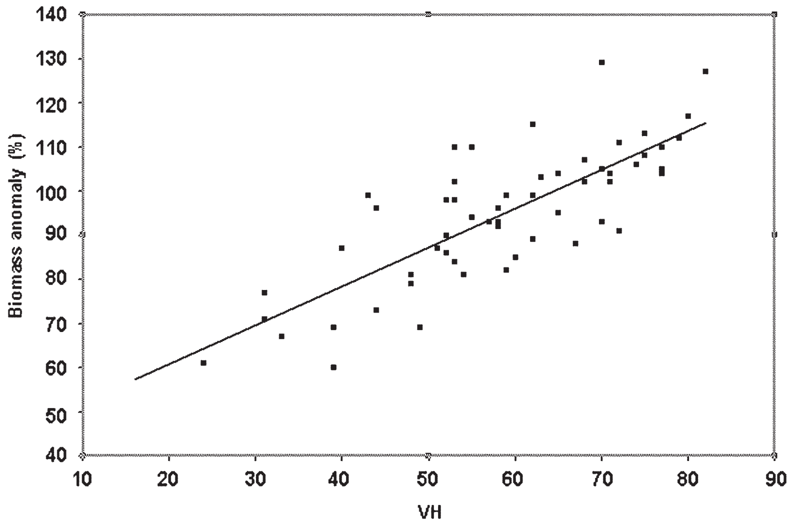

Figure 3. Correlation between biomass anomaly (BA) and VH index (BA = 43.201 + 0.881 (VH); $R^2 = 0.658$; $n = 60$; SE = 9.85%).

5.3. *Vegetation health in post-experimental period*

Since biomass and weather data for Mongolia were not available after 1997 the VH was used for weather-related analysis of vegetation health. As seen in figure 4, 1998 and 1999 were mostly favourable/fair years for vegetation development, although some areas experienced vegetation stress in mid season. Conversely, the vegetation of 2000 in Mongolia experienced large area vegetation stress (red colour). This event was a part of a larger area's unfavourable vegetation conditions due to strong drought, which stretched from eastern China throughout the far west of Mongolia (Kogan 2002). Eastern Mongolia was the most severely affected.

6. Conclusions

This study indicated the utility of the new AVHRR-based VH as a sole source of information about weather impacts on pasture vegetation. Considering Mongolia's vast lands, harsh climate, limited weather network, spatial distribution of herds and lack of communication, these results can be used for providing advice to farmers on the quantity of biomass when they search for better grazing places. Therefore, these results are useful for monitoring pasture productivity. In addition to numerical estimation of vegetation density/fraction and crop production (Kogan 2001, 2002, Kogan *et al.* 2003), these indices can be used for real-time assessment of pasture conditions and biomass production. These assessments are extremely beneficial in the areas where weather data are not available and/or non-representative due to the sparseness of the weather-observing network.

Although ground-based biomass measurements are location-specific and satellite sensor radiances characterize an area, the authors' recent study (Kogan *et al.* 2003) indicated that their year-to-year variations (especially in extreme years) are correlated.

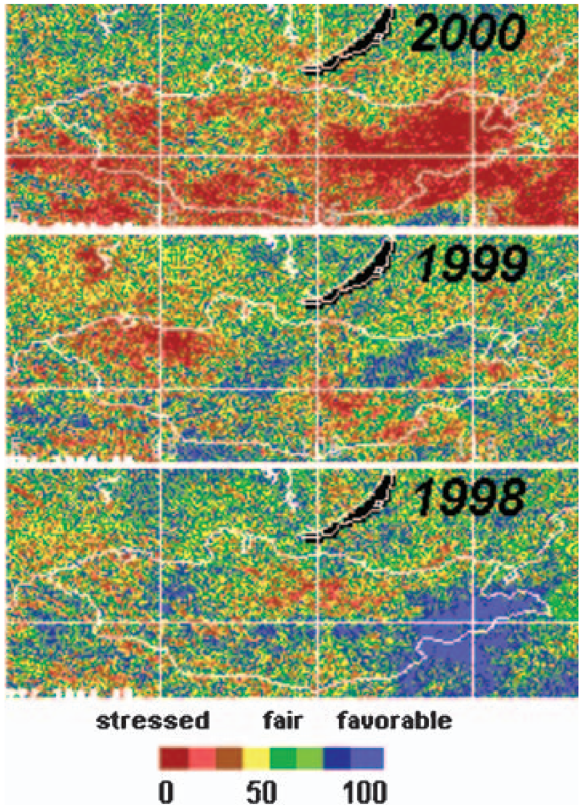

Figure 4. Vegetation health index in mid July (week 28), 1998–2000, Mongolia.

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