INT. J. REMOTE SENSING, 20 JANUARY, 2004,
VOL. 25, NO. 2, 327–346

Interannual variations of the grassland boundaries bordering the eastern edges of the Gobi Desert in central Asia

F. YU*, K. P. PRICE

Kansas Applied Remote Sensing (KARS) Program and Department of Geography, University of Kansas, Lawrence, KS 66045, USA

J. ELLIS

Natural Resource Ecology Laboratory, Colorado State University, Ft Collins, Colorado 80523, USA; e-mail: jime@nrel.colostate.edu

J. J. FEDDEMA

Department of Geography, University of Kansas, Lawrence, Kansas 66044, USA; e-mail: feddema@ku.edu

and P. SHI

Institute of Natural Resources, Beijing Normal University, Beijing 100 851, China; e-mail: spj@bnu.edu.cn

(*Received 15 October 2001; in final form 7 January 2003*)

Abstract. The Mongolian Steppe that borders the northern and eastern edges of the Gobi Desert in central Asia is one of the world's largest grasslands, extending across the nation of Mongolia and the Inner Mongolian Autonomous Region (IMAR) of China. Recent findings show that this region has one of the strongest warming signals on Earth since the late 1970s. The objective of this study was to evaluate the relationships between climate and interannual variation of the grassland boundaries in Mongolia and IMAR between 1982 and 1990. The remote sensing data used in this study were the 15–day maximum Normalized Difference Vegetation Index (NDVI) composites derived from the Global Area Coverage of the Advanced Very High Resolution Radiometer (AVHRR). Monthly precipitation, mean monthly temperature, and monthly actual evapotranspiration (AE) were derived from meteorological station records acquired during the study period across the eastern Mongolian Steppe. The occurrence of onset of green–up, as determined with time-series NDVI data, was used to identify vegetated and non-vegetated areas. Great interannual variation of the Gobi boundary position was observed over the study period. This boundary variation was largely controlled by the climate before the growing season (the 'preseason' climate). Along the eastern edge of the Gobi desert in central IMAR, preseason AE was the major climatic factor affecting the annual shift of the Gobi boundary, while further north in Mongolia, preseason temperature was the driving climatic factor. Our findings suggest that the response of vegetation communities to climate changes varied as a function of land-use intensity within the ecosystem.

---

*Author for correspondence; e-mail: fyu@ku.edu/price@ku.edu

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN: 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/0143116031000084297

1. Introduction

The climate of north-east Asia (China, Russia and Mongolia) has undergone significant changes over the last 20 years. Recent findings show that this region has one of the strongest warming signals on Earth ($+\sim 1.5^{\circ}$ C 1979–1997, Chase *et al.* 2000). Concerns over accelerating climate change have triggered an increase in the number of studies focusing on large-scale changes in terrestrial land cover (e.g. Tucker *et al.* 1986, Ellis and Galvin 1994, Ojima *et al.* 1994, Lambin and Ehrlich 1997, Justice *et al.* 1998). It is believed that at the global scale, rapid environmental changes are mainly associated with climatic variations and anthropogenic activities. Environmental change is apparent in the arid and semiarid regions of central Asia where sparse vegetation provides little protection to the relatively thin soils, resulting in severe soil losses, land degradation, and in some instances even desertification (Thornes 1985, Thripathy *et al.* 1996, Xue 1996). Environmental degradation is also associated with decline in primary productivity, which alters biogeochemical exchanges between the earth and the atmosphere (Nicholson *et al.* 1998, Prince *et al.* 1998). The monitoring of ecosystems that are sensitive to climate change, such as arid and semiarid regions, can improve our understanding of the relationships between climate and ecosystem dynamics. This improved understanding will allow us to predict areas most prone to rapid environmental change, which is critical for future land use planning purposes.

Previous studies of land cover change conducted in Africa's Sahel region showed that precipitation was the dominant climatic factor affecting ecosystem dynamics and the major constraint on human land use practices. Natural vegetation in the drylands of the Sahel is well adapted to high variability in precipitation (Rutherford 1980, Prince *et al.* 1998). Analysis of remote sensing images over this area indicates that there is a strong linear relation between precipitation and above-ground live biomass (Tucker *et al.* 1986, Malo and Nicholson 1990). Year-to-year variation in net primary productivity (NPP) of the Sahel was explained by the interannual variability in precipitation (Tucker *et al.* 1986, 1991, 1994, Nicholson *et al.* 1998). These studies showed the boundaries of the Sahara (defined at the $200\,\mathrm{mm\,y^{-1}}$ of precipitation) varied greatly between 1980 and 1997 and precipitation was the major factor contributing to this variation.

The studies in Africa described above focused on the impact of precipitation on vegetation in warm regions where temperature is not a limiting factor. As latitude or elevation increases, temperature becomes a more important factor affecting biomass productivity. In the mid- and high-latitude regions, a relationship between biomass and temperature has been documented using remotely sensed data (Schultz and Halpert 1993, 1995). Indeed, both precipitation and temperature play an important role in controlling photosynthetic activities. With recent evidence of climatic warming in central Asia (Chase *et al.* 2000), an improved understanding of vegetation response to changing water budgets, which include consideration of both temperature- and precipitation-related impacts, is critical to understanding future land use potential.

The objectives of this study are two-fold: (1) to assess the ability of remotely sensed data to monitor interannual variation of the desert/non-desert boundary in east central Asia, and (2) to evaluate the response of arid/semiarid vegetation to climatic variation and land-use intensity at two adjacent climate and edaph similar grasslands on the Mongolian Steppe.

2. Study area

The study area is in the eastern part of the Gobi desert residing within Mongolia Plateau in east central Asia. The Mongolian Steppe is one of the world's largest grassland and shrubland environments, extending across the nation of Mongolia and the Inner Mongolia Autonomous Region (IMAR) of China (figure 1). This region extends from the Greater Xingan Mountains (Da Xingan Ling) in the east to the Gobi Desert in the west (108–125° E), and from the Ordas plateau in the south to the Hulun Lake in the north (40–50° N). The total area is approximately 200 000 km^2. Annual rainfall ranges from less than 100 mm at the western edge of the Gobi desert to over 400 mm near the foothills of the Da Xingan Ling. In spring, it is usually dry and windy, with high evaporation and relatively low humidity.

2.1. *The Gobi Desert*

As one of the world's largest deserts, the Gobi Desert (figure 1) stretches across a large portion of Mongolia and northern China. In Mongolia, Gobi means 'waterless place'. It is also called Sha-mo ('sandy area') in Chinese. This arc-shaped desert occupies a vast land of about 1600 km east to west and 480–960 km north to south, with an estimated area of 1 300 000 km^2. The Altai and Hangayn Nuruu (Khangai) mountains lie roughly on the north side, the Da Xingan Ling (Greater Xingan Mountains) on the east, the Altun Shan and Nan Shan mountains (the A-erh-chin Mountains, Pei Mountains, and Yin Mountains) on the south, and the Tian-Shan Mountains on the west.

Figure 1. The Gobi desert in central Asia. The study area is defined by the black box.

The surface morphology of this region is typically that of a rolling gravel plateau between higher mountains. The plateau ranges from 910 to 1520 m above ground sea-level. Climate in this region is characterized by short hot summers, long cold winters, and less than 250 mm annual precipitation coming as summer rainfall events. The core desert area is extremely dry, especially in the southern part, which receives less than 50 mm of precipitation annually. Wind and sand storms are common in the winter and early spring. The prevailing north-west winds have removed nearly all this region's topsoil and deposited it in central north China as loess.

Not all the Gobi area, however, is hostile to the rearing of livestock. In areas where water is available from wells and occasional shallow lakes, there is a sparse growth of grass, scrub, and thorny plants sufficient to feed the flocks of the nomadic herders who live throughout the region. In fact, the vast grassy steppes of this study area are among the largest and most productive grasslands in the world, supporting the world's largest population of sheep and goats, and the fourth largest population of cattle (Zhang 1992).

2.2. *Land cover types and land use history in the study area*

Distribution and structure of the vegetation communities in this study area are strongly regulated by a continental climate gradient. Temperature extremes increase and precipitation decreases as distance increases from northern and eastern edges of the Plateau into the centre of the desert. As a result, the climate pattern follows a strong east-to-west gradient in IMAR and north-to-south gradient in Mongolia. From the Da Xingan Ling to the central desert, for example, mean annual precipitation decreases gradually from about 350 mm near the foothills of the Da Xingan Ling to less than 50 mm in the centre of the desert. The coefficient of variability of annual precipitation ranges from 0.25 to 0.40, indicating the non-equilibrium ecosystem characteristics in this region (Ellis 1992).

Three types of grassland (meadow steppe, typical steppe, and desert steppes) and desert were classified along this radiant gradient (figure 2). Of these grass steppes, meadow steppe is the most and the desert steppe the least productive in terms of annual primary productivity. In the grasslands of IMAR, biomass ranges between 4000 and 10 000 $\mathrm{kg\,ha^{-1}}$ for the meadow steppe, 2000–3000 $\mathrm{kg\,ha^{-1}}$ for the typical steppe, 300–700 $\mathrm{kg\,ha^{-1}}$ for desert steppe, and less than 300 $\mathrm{kg\,ha^{-1}}$ for the desert areas (Zhang 1992, figure 3). The dominant grass types for the meadow steppe include *Filifolium sibiricum*, *Festuca ovina*, *Stipa baicalensis*, and at lower elevations, *Aneurolepidium chinense*. The dominant grass types of the typical steppes include *Stipa grandis*, *Aneurolepidium chinense* and *Agropyron michnoi*. The desert steppe is dominated by short grasses including *Stipa krylovii*, *Stipa bungeana* and *Thymus serpyllum* (Ellis 1992). The forest is composed primarily of deciduous trees including *Betula platyphylla*, *Populus davidiana* and *Quercus* spp. The dominant coniferous tree is *Larix gmelinii*.

Land use throughout the study area is dominated by livestock grazing. Mongolian pastoralists have used this area for several thousand years as a sustainable mode of land use. In the last half-century, however, unsustainable land use practices have led to drastic degradation in some areas of IMAR (Sneath 1998). Since 1949, Chinese governmental policies in IMAR have stimulated a rapid increase in human population density and livestock grazing intensity in this region

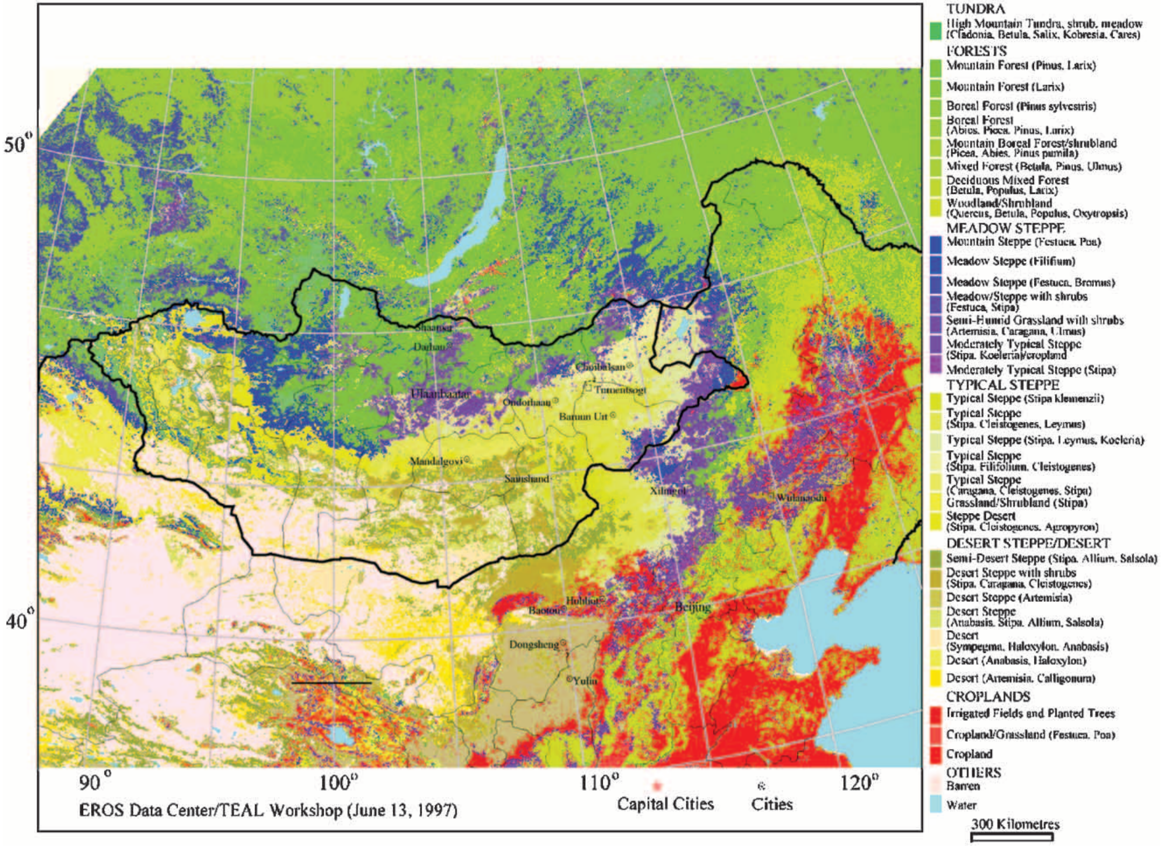

Figure 2. Land cover types in central Asia, provided by Dr Togtohyn Chuluum and Dr Dennis Ojima, Natural Resource Ecology Laboratory, Colorado State University. Data processing was constructed at the EROS Data Center. This land cover map was the unsupervised classification result derived from 1 km AVHRR data, spanning a 12–month period (April 1992–March 1993).

Figure 3. Vegetation types in central Inner Mongolia, China. (*a*) Meadow steppe, (*b*) typical steppe, and (*c*) desert steppe.

(Ellis 1992). As a result, IMAR has suffered serious land use abuse. Furthermore, with the Chinese agricultural reforms of the 1980s, which were designed to increase production, an increased utilization of these lands would be expected. In the mean time, no dramatic changes in land use management have occurred in Mongolia over the past millennium. The Mongolian Steppe, due to its similar grassland environments and a contrast of land use practices between IMAR and Mongolia, makes this area ideal for exploring the interactions of land use and climate changes since the 1980s when climate and land use changes accelerated.

3. Data and methodology

3.1. *NOAA AVHRR NDVI data*

The Normalized Difference Vegetation Index (NDVI) is a commonly used vegetation index derived from remotely sensed measurements of electromagnetic energy in the red and near-infrared spectral regions. It is defined as (NIR−RED)/(NIR+RED), where NIR and RED are the spectral reflectance in near-infrared and red wavelength, respectively. The red spectral response is inversely related to absorption by plant chlorophyll while the near-infrared spectral response increases as leaf canopy layers increase. NDVI is therefore sensitive to vegetation density and photosynthetic capacity (Asrar *et al.* 1984, Tucker and Seller 1986, Prince 1991). Research has established that NDVI in arid and semiarid regions is highly correlated with such biophysical parameters as Leaf Area Index (LAI), biomass, and vegetation cover (e.g. Tucker *et al.* 1986, Running 1990, Justice *et al.* 1998).

A 9–year (1982–1990) NOAA (National Oceanic and Atmospheric Administration) Advanced Very High Resolution Radiometer (AVHRR) NDVI 15–day maximum composite dataset with a spatial resolution of 4.2 km × 4.2 km was used in this study. This dataset was processed and archived by the Global Inventory Mapping and Monitoring Study (GIMMS) group at NASA/Goddard Space Flight Center (GIMMS). The continental GIMMS NDVI dataset was derived from Global Area Coverage (GAC) data, which was collected from 1982 to 1992 by three different on-board sensors: (1) NOAA-7 from January 1982 to February 1985, (2) NOAA-9 from February 1985 to October 1988, and (3) NOAA-11 from October 1988 to December 1992. These images were processed using methods described by Holben (1986). Detailed information on the processing of the GIMMS data can be found in Los *et al.* (1994). Composite NDVI images can greatly reduce cloud and other atmospheric effects while at the same time retaining the dynamic vegetation information (Holben 1986).

The NDVI datasets were geometrically transformed to the Lambert Azimuthal Equal Area projection using control points and the nearest-neighbour spectral resampling approach. The smoothing algorithm developed by Van Dijk *et al.* (1987) was applied to the time–series NDVI profiles to further minimize the effects of anomalous values caused by atmospheric haze and cloud contamination. More recent studies evaluating the quality of AVHRR NDVI data have shown that even after applying the smoothing technique, non-vegetation noise remains in the maximum NDVI composites (Schultz and Halpert 1995, Myneni *et al.* 1998). Factors contributing to non-vegetation noise include water vapour, cloud contamination, aerosols, solar illumination, viewing angle, instrument degradation, sensor change-over and orbital drift (Schultz and Halpert 1995). For this reason, the NDVI data were then recalibrated for orbital and detector drift using a hyper-arid area of the Gobi Desert as an invariant target as described by Myneni *et al.* (1998).

3.2. *Estimating the boundary between desert and grasslands*

Studies conducted in the African Sahel have shown a strong direct linear correlation between annual rainfall and integrated NDVI over the growing season (e.g. Malo and Nicholson 1990, Tucker *et al.* 1991, Nicholson *et al.* 1998). In the Sahel, the areas receiving less than 200 mm y^{-1} of precipitation are normally considered desert lands. Therefore, the NDVI integrated over the growing season was used to estimate precipitation and track the shifting 200 mm y^{-1} boundary (Tucker *et al.* 1991, 1994, Nicholson *et al.* 1998). In our study area, although integrated NDVI values explained 54% of the variation in annual precipitation, the NDVI response was found to taper off at annual rainfall level of 300 mm (figure 4(*a*)). The higher correlation between the annual actual evapotranspiration (AE) and accumulated growing season NDVI ($R^2=0.70$, figure 4(*b*)) indicates that in the mid-latitude dryland, temperature, associated with the precipitation, plays an important role in determining the vegetation photosynthetic activity. For this reason, precipitation alone in this region is insufficient for explaining boundary shift between desert and non-desert areas. An alternative approach therefore, has to be used to define the desert/non-desert boundary in the study area.

From previous studies, it has been shown that seasonal changes in NDVI can be related to vegetation phenological stages (e.g. onset of green-up, maximum greenness, end of greenness, etc.) (Lloyd 1990, Reed *et al.* 1994, DeFries *et al.* 1995). The onset of greenness refers to the time when plants emerge from a dormant state (moisture or temperature induced) and begin to actively photosynthesize. In this study the occurrence of an onset of greenness event is used to differentiate between desert and non-desert conditions. This onset phenological event is identified as 'sudden increase in NDVI', as described by Lloyd (1990) and Reed *et al.* (1994). Vegetation is very sparse in the Gobi Desert and therefore onset of green-up in the desert was undetectable with AVHRR NDVI data. Delineating between areas where an onset of green-up event occurs and where the event is undetectable make it possible to identify the Gobi Desert boundary. It is important to point out that it was not assumed that the lack of a green-up event in the area means that the area had converted to a desert, but that it has undergone desert-like conditions in that particular time period.

The approach used in this study examined the seasonal variation in the NDVI for each pixel to identify the period when an NDVI value increases rapidly. A set of constraints were applied to determine the occurrence of onset of green-up, including that (a) NDVI increases for three successive periods, that is, there should be at least one and a half months of progressive increasing of NDVI; (b) NDVI increases greatest during the particular periods; (c) the NDVI value is greater than 0.05; and (d) this event must occur in a reasonable time period, that is from April to August, the normal period during which plants in this region green-up. These constraints were set to delimit the effect of non-vegetation information, such as soil, cloud and snow melt event.

Compared to the NDVI threshold-determined desert boundary approach described by Tucker *et al.* (1994), this measurement compensates for many factors that affect the image quality. By establishing parameters for the NDVI profiles instead of using only the NDVI values, we may not need to correct the NDVI dataset for

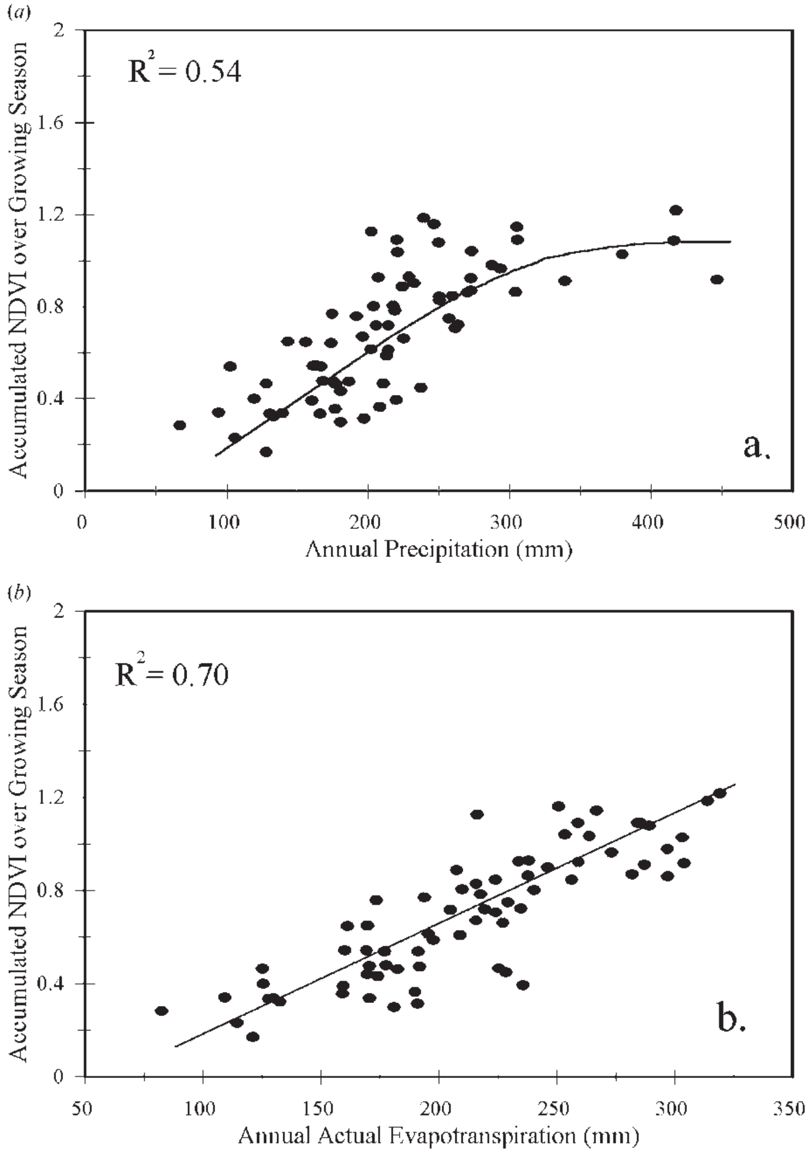

Figure 4. Relationship between (*a*) mean annual precipitation and mean accumulated NDVI over the growing season (May–September), and (*b*) mean annual AE and mean accumulated NDVI over the growing season (May–September), from 1982 to 1990 for 27 meteorological stations in the grasslands of Inner Mongolia.

soil background and atmospheric effects, and the bias towards high view angles for the NDVI composites (Allen *et al.* 1994, Tucker *et al.* 1994, Tieszen *et al.* 1997).

3.3. *Climate data analysis procedure*

We collected monthly precipitation and monthly mean temperature from 16 available meteorological stations (12 in Inner Mongolia, and four in Mongolia, in

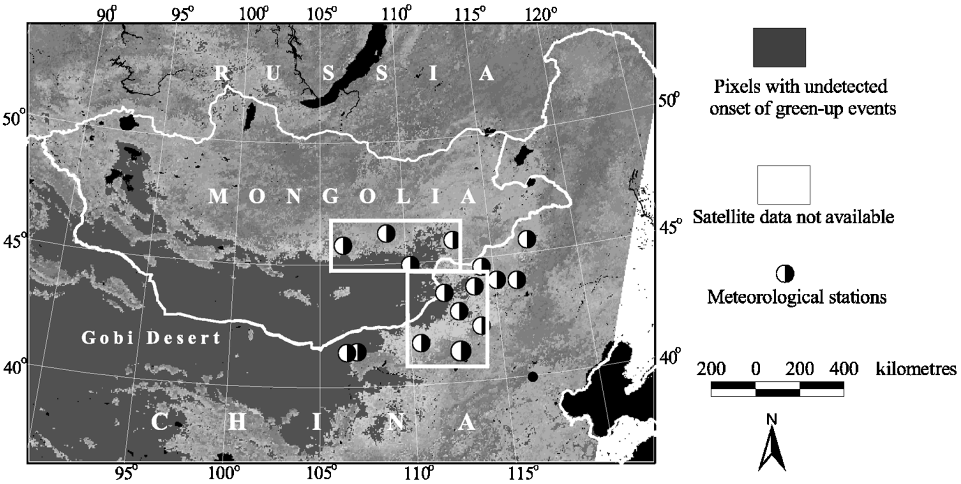

Figure 5. Spatial distribution of the estimated Gobi desert extent (in black) in 1983. The annual temperature and precipitation data in 1983 were the closest to the long-term mean values (1961–1990) over the study period (1982–1990). Areas with detectable green-up events are represented in shades of grey.

figure 5) along the east and south fringe of the Gobi Desert to explore the relationship between Gobi boundary shift and annual climatic variability. The monthly climate data were obtained from 1981 to 1990. A modification of the Thornthwaite water budget model was used to estimate monthly actual evapotranspiration (AE) (Thornthwaite 1948, Savage *et al.* 1996).

Previous studies using both observation (e.g. Goward and Prince 1995, Potter *et al.* 1999) and simulation models (e.g. Zeng *et al.* 1999) show that there is a complicated lag effect between vegetation and precipitation. The lag time varies from several days to 1 year or even longer (Goward and Prince 1995). Yu *et al.* (2000) found that the timing of onset of green-up for vegetation of the Inner Mongolia steppe is significantly associated with the temperature and precipitation occurring in the previous fall, winter and the current spring. Meanwhile, soil moisture accumulation normally takes place during the time of plant dormancy, and thus precipitation falling during the fall and winter will have significant effects on vegetation in the following growing season. In this study area, although only about 20–30% of the annual precipitation falls in the winter and spring, accumulated snow is an important water source for livestock and wildlife, as well as spring plants emergence in the spring (Shi *et al.* 1989). Potter *et al.* (1999) found that in the arid and semiarid areas of the middle latitude in the Northern Hemisphere, the temperatures from the previous 1–year period could have a significant influence on the net primary production (NPP) of the next growing season. Therefore, in this study, the climate data (precipitation, temperature and AE) were accumulated from October of the previous year through the beginning of the growing season (June) of the year being studied (e.g. climatic impacts on vegetation in the 1990 growing season were based on accumulated climatic data from October 1989 to June 1990). Hereafter, this accumulated climatic measurements (previous October to current June) used in this study will be referred to as ‘preseason’ climate data.

3.4. *Statistical analyses*

Linear regression models were used in this study to determine which climatic factor(s) have significant influences on the Gobi boundary extent in IMAR and Mongolia, respectively (figure 5). The primary dependent variable was the areal extent of desert area inside the defined study regions in IMAR and Mongolia (boxes in figure 5). Preseason climate data from the meteorological stations inside the defined regions were used as the independent variables to model these two Gobi desert areas. Since our dataset has both temporal and geographical linkages among cases, autocorrelation was controlled during the regression analyses through calculating the Durbin–Watson statistic. The small case number ($n=9$) for this study necessarily limited the analysis to binary regression only. Model comparisons were then focused on R^2 values and model significance.

4. Results

4.1. *General spatial pattern of the vegetation/non-vegetation boundary*

Figure 5 shows the spatial distribution of the estimated extent of the Gobi Desert in 1985. The year of 1985 was selected for validation purposes because the weather in that year was similar with the average climate conditions over the study period. In figure 5, black areas represent locations where the onset of green-up was undetectable, while areas with detectable green-up events are represented in shades of grey. Dark grey indicates an earlier green-up at the beginning of growing season and light grey for later green-up. The relation between the green-up timing and climate variation for different land cover types in central Asia can be found in Yu *et al.* (2003).

Figure 6 shows the mean time-series NDVI from 1982 to 1990 for the three

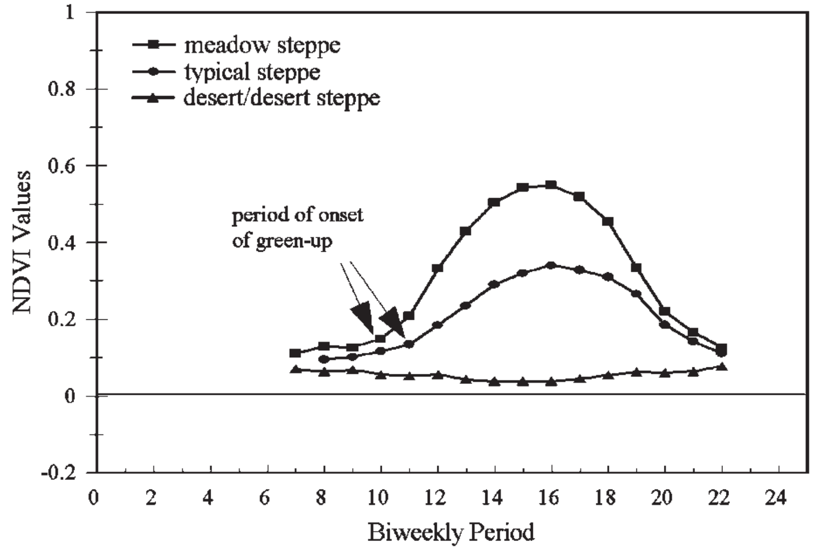

Figure 6. Mean time-series NDVI between 1982 and 1990 for three types of grassland in Inner Mongolia, China. Mean onset of green-up events occurred in late May for the meadow steppe, and in early June in the typical steppe. No onset events can be detected from NDVI curves for the desert and desert steppes.

types of grasslands in Inner Mongolia. The rapid increases in the NDVI of the typical and meadow steppes during the spring signals the occurrence of the onset of green-up. In the dry area of desert/desert steppe, the NDVI values were the lowest and had the least variation in the amplitude. As a result, onset of green-up cannot be detected for this open and sparsely vegetated land surface. Similar phenological patterns were reported in grasslands across the climate gradient in Sahel (Justice *et al.* 1989) and the dryland of southern California (Moody and Johnson 2001).

A comparison of the desert distribution as shown in figure 5 with figure 2 shows a good correlation between these maps, suggesting that the use of date of onset of green-up is a good delineator of desert and steppe boundaries. The desert and part of the desert steppe show no detectable onset of green-up event throughout the 9–year study period. The boundary between detectable and undetectable onset of green-up illustrates the highly variable characteristics of the desert steppe as the transition zone or ecotone between the desert and grasslands.

4.2. *Interannual variation of the desert boundary*

Figure 7 shows the extent of the desert boundary as predicted using the onset of green-up for years 1982–1990. The interface of the Gobi desert and grassland shifted dramatically along the eastern and northern edge of the desert, while little

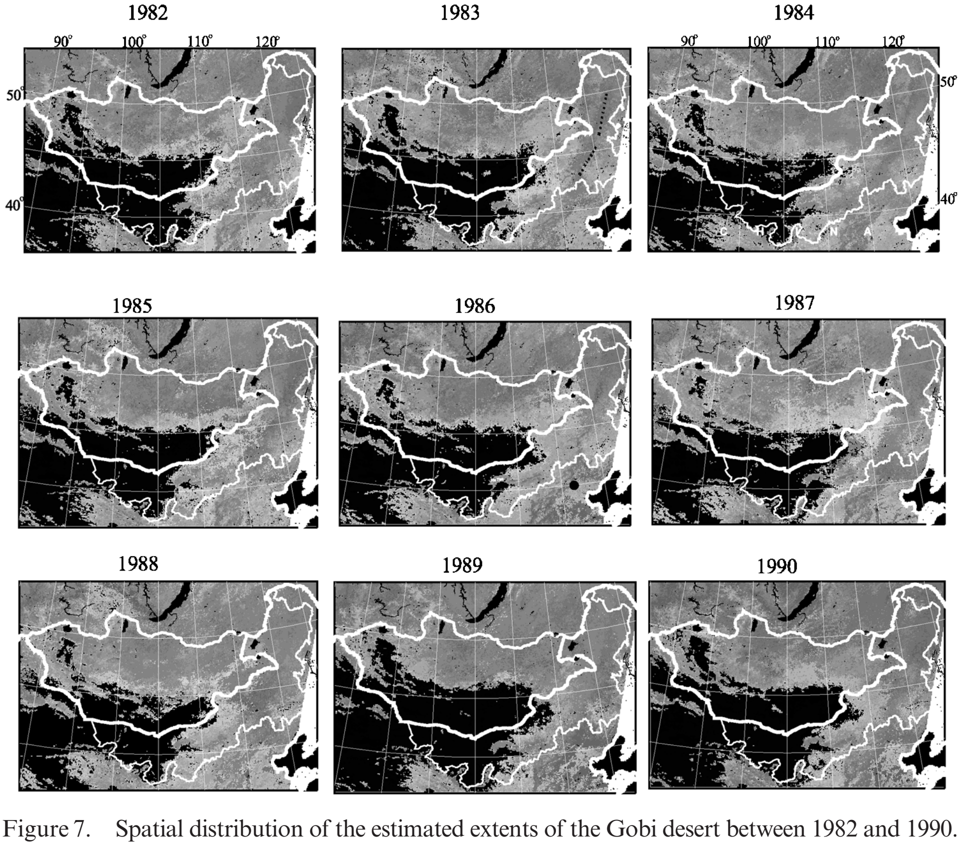

Figure 7. Spatial distribution of the estimated extents of the Gobi desert between 1982 and 1990.

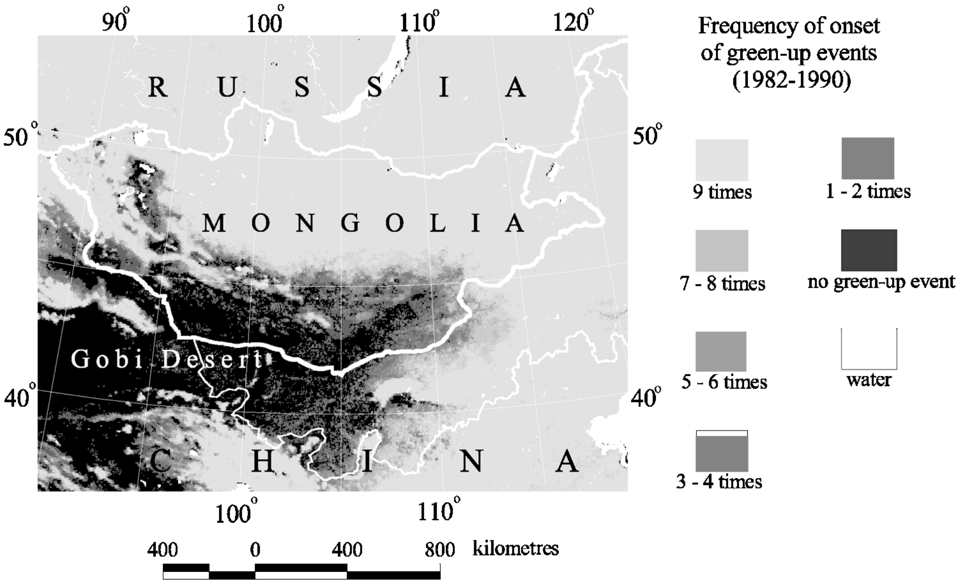

Figure 8. Frequency of detectable onset of green-up events in central Asia between 1982 and 1990. The frequency of onset event is less than 100% for the desert and desert steppe (less than nine occurrences in the 9 study years). NDVI trajectories for the plants in wetter regions (typical steppe, meadow steppe, and forest regions) exhibit green-up patterns every spring.

movement of the desert boundary was observed at the mountain-defined south edges of the desert. The desert area in central Asia as defined by the undetectable onset events displayed in figure 6, varies greatly from year to year, ranging from 1 160 000 km^2 to 1 570 000 km^2 during 1982–1990 (figure 7). From 1982 to 1988, the desert area seemed to experience a shrinking trend. A sudden expansion of the desert area, however, was observed in 1989 to reach its maximum area during the study period. In 1990, the boundaries retreated but did not return to the original position observed in 1982. This may be due to (1) the effects of 1982–1983 El Niño events (one of the strongest during last century, Myneni *et al.* 1998); and (2) peaked warming winter and spring temperature in the years of 1989 and 1990 (Keeling *et al.* 1996).

The frequency of onset of green-up map (figure 8) again shows the highly variable nature of most arid and semiarid boundaries. As shown in figure 8, the onset of green-up is never detected in the core desert areas. Across the desert steppe from the Gobi to the typical steppe, the occurrence of detectable onset gradually increases from 2 to 9 during the 9–year study period. A possible explanation for the lower onset frequency in this region is that vegetation in the arid and semiarid is well adapted to the highly variable annual rainfall of the non-equilibrium ecosystems, keeping dormant in dry years and greening up in years when rainfall is sufficient (Rutherford 1980). As a result, the desert steppe (the transitional zone between desert and typical steppe) displayed a typical steppe-like phenological pattern in the wet year and a desert-like pattern in a dry year.

4.3. *Relationship between the Gobi area and climate data*

4.3.1. *Relationship between the Gobi area and climate data in central IMAR, China*

The linear regression analysis showed a significant correlation between the areal extent of the Gobi desert in central IMAR and the preseason AE from 1983 to 1990 ($p < 0.05$, $R^2 = 0.50$). The result from the Durbin–Watson test shows there is no significant temporal autocorrelation among the time-series datasets of the Gobi area and preseason AE. No significant correlation, however, between the Gobi area and the preseason temperature or preseason precipitation is observed during this period.

Vegetation growth in arid and semiarid areas is usually controlled by soil moisture and soil temperature (Sala *et al.* 1988, Yang *et al.* 1998). High preseason AE value reflects abundant biologically available moisture before the beginning of the growing season. The result of the regression analysis suggests that a wet, warm, early spring is the primary factor that allows early seed germination and emergence of dormant plant life-forms. Conversely, high temperature with low precipitation in winter and early spring often result in soil moisture depletion, suppressing seed germination and initial grass growth in the spring and truncating primary productivity. Similarly, French and Sauer (1974) found that the growth of some early developing species in the US short-grass prairie was closely correlated with soil moisture and solar radiation.

Figure 9 shows the annual preseason climate anomaly for the Gobi desert area in central IMAR from 1982 to 1990. Considerable interannual variability in the areal extent of the Gobi area and the climate variables can be observed during this

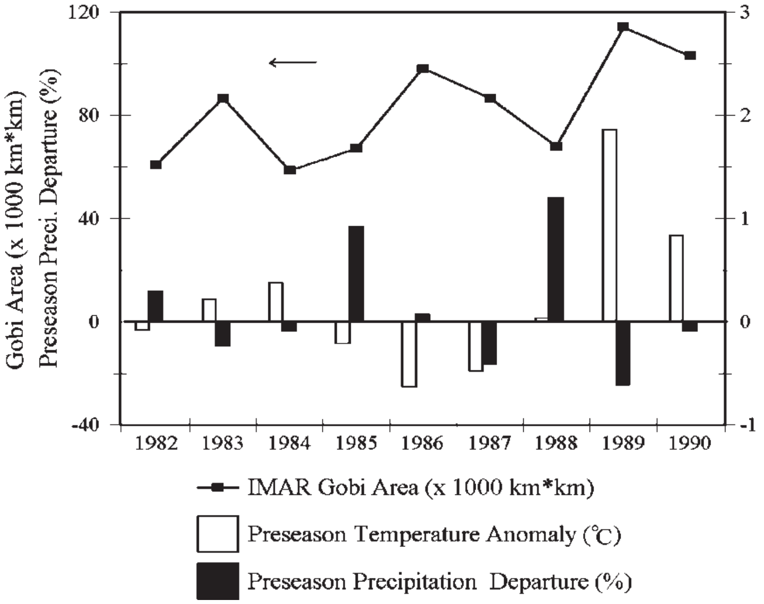

Figure 9. Annual preseason climate anomaly (precipitation departure (%) and temperature anomaly (°C)) and the Gobi area in central IMAR from 1982 to 1990. This climate anomaly was derived based on the long-term climate data from 1961 to 1990. Precipitation departure was calculated as the percentage deviation from the long-term mean, and the temperature anomaly was the deviation from the long-term mean (in °C).

study period. Generally speaking, the Gobi desert expanded along the east boundary after a warm, dry winter and spring and contracted after a wet preseason when temperatures were near normal. During the study period, the Gobi desert in central IMAR seems to be expanding, a trend that appears to be associated with the warming in the late 1980s (figure 9).

4.3.2. *Relations between Gobi area and climate data in Mongolia*

Unlike the situation in IMAR, linear regression results show a significant impact of the preseason temperature on the areal extent of Gobi desert in Mongolia (figure 5). Variations in mean annual preseason temperature explained over 80% of the variance in the Gobi areal extent ($p < 0.05$, $R^2 = 0.87$). Durbin–Watson test shows no temporal autocorrelation problem among the Gobi area and temperature variables. No significant correlation between Gobi extent and preseason precipitation and preseason AE can be found in this area.

Figure 10 displays the Gobi extent and the preseason climate in Mongolia. Again, the highly variable Gobi areal extent reflects the dynamic nature of the grassland ecosystems in this region. Preseason precipitation was relatively stable during the study period. Preseason temperature fluctuated following a similar pattern that matches the Gobi extent (figure 10). In years when annual temperature increased, the desert boundary moved northward and in years when temperature dropped, the Gobi retreated southward. The regression results suggest that temperature in Mongolia is the dominant climatic factor controlling the annual shift of the desert boundary during this study period during which there is little variation in preseason precipitation. This finding matches in part with the results from some warming scenarios described by Mabutt (1989) and Greco *et al.* (1994). They noted that increases in temperature of 0.5–2.0° C might raise evapotranspiration by 0.2–2.0 mm per day in the desert, unless accompanied by increased rainfall. For the

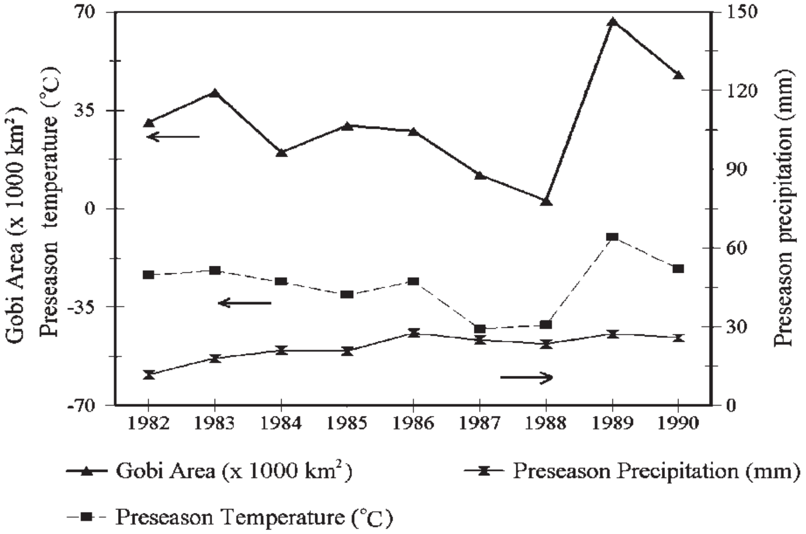

Figure 10. Extent of the Gobi and the preseason climate (accumulated from the previous October to the next June) in Mongolia.

grassland in Mongolia, the increased preseason temperature depleted the spring soil moisture and consequently affected the vegetation spring growth.

5. Discussion

Previous research indicates that precipitation is the primary climatic factor influencing grassland performance and productivity. The regression results in this study, however, suggest that this is not always the case. The results for the Mongolia desert suggest that temperature, in association with precipitation, is the major factor affecting the desert areal extent.

Figure 11 shows the relationship between the central IMAR Gobi extent and the preseason AE derived as the mean value from the five meteorological stations inside the defined region. The relationship between the climatic factor and the Gobi extent was abnormal in 1984. The average climate conditions over the five stations show the preseason of 1984 was dry and AE was lower than the 9–year mean. Yet the Gobi areal extent was the smallest in the 9–year study period. An examination of the monthly climate data shows that four out of the five stations recorded a dry preseason condition, while one station in the desert steppe recorded a relatively wet spring. This increase in precipitation apparently triggered spring growth in the region and offset the expanded desert area created by dry conditions in the other sites. The significant relationship between the Gobi extent and the preseason precipitation (if 1984 is excluded) ($p<0.05$, $R^2=0.66$) seems to agree with the finding of Hulme and Kelly (1993) in Sahara. They found that over 80% of the year-to-year variation in the Sahara desert can be explained by the rainfall data in the Sahel. The higher correlation between preseason AE and Gobi areal extent ($p<0.05$, $R^2=0.70$), however, may imply that preseason AE is a better predictor than preseason precipitation.

It is important to point out that preseason AE and preseason precipitation are

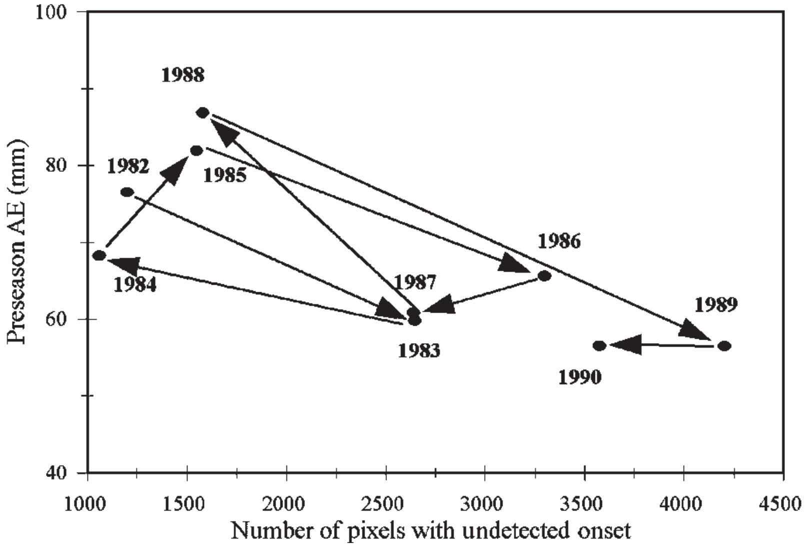

Figure 11. Relationship between the central IMAR Gobi extent and the preseason AE derived as the mean value from the five meteorological stations inside the defined region.

highly correlated with each other ($R^2 = 0.94$). Preseason AE being a better predictor could suggest that although preseason precipitation is an important influencing factor on Gobi extent, it is not the only one. Unlike that in the Mongolian desert area, both preseason precipitation and temperature in IMAR varied greatly during the study period. Preseason AE has the characteristics reflecting the dynamics of both the precipitation and temperature and thus provides us with a better index for modelling the variations of Gobi desert in IMAR.

Compared to the Mongolian grasslands, the greater shift of the desert boundary in IMAR seems to support the conclusion of Sneath (1998) that the degradation in IMAR is more severe than in Mongolia due to the different land use patterns in these two regions. In IMAR, the unsustainable land use practices (overgrazing) or a combined result of overgrazing and climate stress can trigger shifts in vegetation to a transition position and thus make the area more susceptive to environmental changes (Ellis *et al.* 2002). Preseason temperature explained over 87% of the annual change in the Gobi desert in Mongolia, while in eastern central IMAR, 50% of the variation in the Gobi Desert was explained by the annual changes in preseason AE. The difference in the correlation between these climate variables and the Gobi areal extents may be attributed to the differences in land use practices including livestock utilization of the grasslands in these regions.

6. Conclusions

Our results showed that time-series AVHRR NDVI data can be used to monitor temporal desert boundary dynamics even in areas where precipitation is not the only factor controlling year-to-year variation in desert type conditions. Varying combinations of preseason climate conditions clearly influenced the contraction and expansion of the Gobi Desert. Along the eastern edge of the Gobi Desert located in central IMAR, preseason AE was the major climatic factor affecting the annual shift of the desert boundary, while preseason temperature was the dominant factor controlling the desert extent in Mongolia.

Although the 9–year study period is of limited use to evaluate the interactive effects of climate change and land use on a dryland ecosystem, this study can help to provide insights into the effects of changing climate conditions and land use patterns on land productivity and future land use potential. Comparisons of the relationships between climate conditions and the desert boundaries in eastern IMAR and Mongolia suggested that responses of vegetation communities to climate changes vary as a function of land-use intensity within the ecosystem. Further study with long-term remote sensing, climate and livestock data are needed for integrated ecosystem assessment to monitor, detect and analyse the degradation or desertification processes on the Mongolia Steppe.

Acknowledgments

The authors acknowledge the financial support provided by the National Science Foundation through Models and Methods for Integrated Assessment Program ATM-0001478. The authors thank Dr Compton Tucker (Biospheric Sciences Branch Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center) for providing the GAC AVHRR dataset. The authors also wish to thank Mr Chenyang Xiao for the discussion with the statistical analysis, and Dr Stephen

Egbert, Mr Mike Houts, Dr Mark Jakubauskas, and Dr Mingliang Liu for their help with manuscript review.

References

ALLEN, T. R., BARA, T. J., and WALSH, S. J., 1994, Observed biases in the conterminous U.S. AVHRR satellite data set: a North Carolina case study. *GeoCarto International*, **9**, 52–62.

ASRAR, G., FUCHS, M., KANEMASU, E. T., and HATFIELD, J. L., 1984, Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Journal of Agronomy*, **76**, 300–306.

ASHLEY, M. D., and REA, J., 1975, Seasonal vegetation differences from ERTS imagery. *Photogrammetric Engineering and Remote Sensing*, **41**, 713–719.

CHASE, T. N., PIELKE, R. A., KNAFF, J., KITTEL, T., and EASTMAN, J., 2000, A comparison of regional trends in 1979–1997 depth-averaged tropospheric temperatures. *International Journal of Climatology*, **20**, 503–518.

DEFRIES, R., HANSEN, M., and TOWNSHEND, J., 1995, Global discrimination of land cover types from metrics derived from AVHRR Pathfinder data. *Remote Sensing of Environment*, **54**, 209–222.

DI, L., RUNDQUIST, D. C., and HAN, L., 1994, Monitoring relationships between NDVI and precipitation during vegetative growth cycles. *International Journal of Remote Sensing*, **15**, 2121–2136.

ELLIS, J., 1992, Key issues in grassland studies. In *Grasslands and Grassland Sciences in Northern China*, edited by J. Ellis (Washington, DC: National Academy Press), pp. 183–198.

ELLIS, J., and GALVIN, K., 1994, Climate patterns and land-use practices in the dry zones of Africa. *BioScience*, **44**, 340–349.

ELLIS, J., PRICE, K. P., YU, F., CHRISTENSEN, L., and YU, M., 2002, Dimensions of desertification in the drylands of northern China. In *Global Desertification: Do humans cause deserts? (Chapter 10)*, edited by J. F. Reynolds and D. M. Stafford Smith (Germany: Dahlem University Press), pp. 167–180.

FRENCH, N., and SAUER, R., 1974, *Phenological Studies and Modeling in Grasslands*. In *Phenology and Seasonality Modeling*, edited by H. Lieth (New York: Springer-Verlag), pp. 227–236.

GOWARD, S. N., and PRINCE, S. D., 1995, Transient effects of climate on vegetation dynamics: satellite observations. *Journal of Biogeography*, **22**, 549–563.

GRECO, S., MOSS, R., VINER, D., and JENNE, R., 1994, *Climate Scenarios and Socio-economic Projections for IPCC WG II Assessment* (Washington, DC: IPCC, IPCC-WMO and UNEP).

HOLBEN, B. N., 1986, Characteristics of maximum–value composite images from temporal AVHRR data. *International Journal of Remote Sensing*, **7**, 1417–1434.

HULME, M., and KELLY, M., 1993, Exploring the links between desertification and climate change. *Environment*, **35**, 4–11, 39–45.

JUSTICE, C. O., MARKHAM, B. L., TOWNSHEND, J. R. G., and KENNARD, R. L., 1989, Spatial degradation of satellite data. *International Journal of Remote Sensing*, **10**, 1539–1561.

JUSTICE, C., HALL, D., SALOMONSON, V., PRIVETTE, J., RIGGS, G., STRAHLER, A., LUCHT, W., MYNENI, R., KNJAZIHHIN, Y., RUNNING, S., NEMANI, R., VERMOTE, E., TOWNSHEND, J., DEFRIES, R., ROY, D., WAN, Z., HUETE, A., LEEUWEN, W., VAN WOLFE, R., GIGIO, L., MULLER, J-P., LEWIS, P., and BARNSLEY, M., 1998, The Moderate Resolution Imaging Spectroradiometer (MODIS), land remote sensing for global change research. *IEEE Transactions on Geoscience and Remote Sensing*, **36**, 1228–1249.

KEELING, C., CHIN, J., and WHORF, T., 1996, Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. *Nature*, **382**, 146–149.

LAMBIN, E. F., and EHRLICH, D., 1997, Land-cover changes in sub-Sahara Africa (1982–1991): application of a change index based on remotely sensed surface temperature and vegetation indices at a continental scale. *Remote Sensing of Environment*, **61**, 181–200.

Lloyd, D., 1990, A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery. *International Journal of Remote Sensing*, **52**, 534–544.

Los, S. O., Justice, C. O., and Tucker, C. J., 1994, A global 1° by 1° NDVI dataset for climate studies derived from the GIMMS continental NDVI data. *International Journal of Remote Sensing*, **15**, 3499–3518.

Mabutt, J. A., 1989, Impacts of carbon dioxide warming on climate and man in the semi-arid tropics. *Climatic Change*, **15**, 191–221.

Malo, A. R., and Nicholson, S. E., 1990, A study of rainfall and vegetation dynamics in the African Sahel using normalized difference vegetation index. *Journal of Arid Environments*, **19**, 1–24.

Moody, A., and Johnson, D., 2001, Land-surface phenologies from AVHRR using the discrete Fourier transform. *Remote Sensing of Environment*, **75**, 305–323.

Myneni, R. B., Tucker, C. J., Asrar, G., and Keeling, C. D., 1998, Interannual variations in satellite-sensed vegetation index data from 1981 to 1991. *Journal of Geophysical Research*, **103**, 6145–6160.

Nicholson, S. E., Tucker, C. J., and Ba, M. B., 1998, Desertification, drought, and surface vegetation, an example from the west African Sahel. *Bulletin of the American Meteorological Society*, **79**, 815–829.

Ojima, D. S., Galvin, K. A., and Turner, B. L., 1994, The global impact of land-use change. *Bioscience*, **44**, 300–304.

Potter, C. S., Klooster, S., and Brooks, V., 1999, Interannual variability in terrestrial net primary production, exploration of trends and controls on regional to global scales. *Ecosystems*, **2**, 36–48.

Prince, S. D., 1991, A model of regional primary production for use with coarse resolution satellite data. *International Journal of Remote Sensing*, **12**, 1313–1330.

Prince, S. D., de colstoun, E. B., and Kravitz, L. L., 1998, Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. *Global Change Biology*, **4**, 359–374.

Reed, B. C., Brown, J. F., Vanderzee, D., Loveland, T. R., Merchant, J. W., and Ohlen, D. O., 1994, Measuring phenological variability from satellite imagery. *Journal of Vegetation Science*, **5**, 703–714.

Running, S. W., 1990, Estimating terrestrial primary productivity by combining remote sensing and ecosystem simulation. In *Remote Sensing and Biosphere Functioning*, edited by R. J. Hobbs and H. A. Mooney (New York: Springer-Verlag), pp. 65–86.

Rutherford, M. C., 1980, Annual plant production–precipitation relations in arid and semi-arid regions. *South African Journal of Science*, **76**, 53–56.

Sala, O. E., Parson, W. J., Joyce, L. A., and Lauenroth, W. K., 1988, Primary production of the central grassland region of the United Sates, spatial pattern and major controls. *Ecology*, **69**, 40–45.

Savage, M., Brown, P. M., and Feddema, J., 1996, The role of climate in a pine forest regeneration pulse in the southwestern United States. *Ecoscience*, **3**, 310–318.

Schultz, P. A., and Halpert, M. S., 1993, Global correction of temperature, NDVI and precipitation. *Advances in Space Research*, **13**, 277–280.

Schultz, P. A., and Halpert, M. S., 1995, Global analysis of the relationships among a vegetation index, precipitation and land surface temperature. *International Journal of Remote Sensing*, **16**, 2755–2777.

Sneath, D., 1998, State policy and pasture degradation in inner Asia. *Science*, **281**, 1147–1148.

Shi, Y., Shi, Y., Bai, Z., Sun, J., Li, W., Xiao, H., and Bao, Y., 1989, *Physical Geography in Inner Mongolia, China* (Hohhot, China: Inner Mongolia People' Press), pp. 78–104.

Thornthwaite, C. W., 1948, An approach toward a rational classification of climate. *Geographical Review*, **38**, 55–94.

Tieszen, L. L., Reed, B. C., Bliss, N. B., Wylie, B. K., and Dejong, D. D., 1997, NDVI, C_3 and C_4 production, and distributions in Great Plains grassland land cover classes. *Ecological Application*, **7**, 59–78.

Thornes, J. B., 1985, The ecology of erosion. *Geography Journal*, **40**, 222–235.

Thripathy, G. K., Ghosh, T. K., and Shah, S. D., 1996, Monitoring of desertification process in Karnataka state of India using multi-temporal remote sensing and ancillary information using GIS. *International Journal of Remote Sensing*, **17**, 2243–3357.

TUCKER, C. J., and SELLERS, P. J., 1986, Satellite remote sensing of primary production. *International Journal of Remote Sensing*, **7**, 1395–1416.

TUCKER, C. J., JUSTICE, C. O., and PRINCE, S. D., 1986, Monitoring the grasslands of the Sahel 1984–1985. *International Journal Remote Sensing*, **7**, 1571–1581.

TUCKER, C. J., DREGNE, H. E., and NEWCOMB, W. W., 1991, Expansion and contraction of the Sahara desert from 1980 to 1990. *Science*, **253**, 299–301.

TUCKER, C. J., NEWCOMB, W. W., and DREGNE, H. E., 1994, AVHRR data sets for determination of desert spatial extent. *International Journal of Remote Sensing*, **17**, 3517–3565.

VAN DIJK, A. V., CALLIS, S. L., SAKAMOTO, C. M., and DECKER, W. L., 1987, Smoothing vegetation index profiles, an alternative method for reducing radiometric disturbance in NOAA/AVHRR data. *Photogrammetric Engineering and Remote Sensing*, **33**, 1059–1067.

XUE, Y., 1996, The impact of desertification in the Mongolian and the Inner Mongolian grassland on the regional climate. *Journal of Climate*, **9**, 2173–2189.

YANG, L., WYLIE, B., TIESZEN, L., and REED, B., 1998, An analysis of relationships among climate forcing and time-integrated NDVI of grasslands over the U.S. Northern and Central Great Plains. *Remote Sensing of Environment*, **65**, 25–37.

YU, F., PRICE, K. P., LEE, R., and ELLIS, J., 2000, Analysis of the relationships between climatic variation and seasonal grassland development in central Asia. *Proceeding of the Annual ASPRS Meetings, Washington DC, 22–26 May* (on CD-Rom), 11pp.

YU, F., PRICE, K. P., ELLIS, J., and SHI, P., 2003, Response of seasonal vegetation development to climatic variation in eastern central Asia. *Remote Sensing of Environment*, accepted.

ZENG, N., NEELIN, J. D., LAU, K-M., and TUCKER, C. J., 1999, Enhancement of interdecadel climate variability in the Sahel by vegetation interaction. *Science*, **286**, 1537–1540.

ZHANG, X., 1992, Northern China. In *Grasslands and Grassland Sciences in Northern China*, edited by J. Ellis (Washington, DC: National Research Council), pp. 39–54.