Relationship between Soil Moisture and Vegetation Activity in the Mongolian Steppe

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Abstract

Drought has become widespread throughout the Northern Hemisphere since the mid-1950s, affecting the Mongolian steppe and pastureland used for livestock. Given this background, we investigated the relationship between modeled root-zone soil moisture (W_m) and vegetation activity based on Normalized Difference Vegetation Index (NDVI) data for the Mongolian steppe during the period 1982−2005. In general, interannual change in NDVI coincided with that in W_m. NDVI showed a stronger correlation with W_m ($r = 0.91$) than with precipitation (P) ($r = 0.65$). A strong positive correlation was found between seasonal changes in NDVI and above-ground biomass ($r = 0.94$).

A comparison between years with high and low $NDVI_{max}$ revealed that the significant difference in P led to a significant time-lagged (about a half month) difference in W_m and finally to that in NDVI with time lags of about one month. In addition, $NDVI_{max}$ value of a given year was correlated with the W_m value for the current year ($r^2 = 0.53$), and was more strongly correlated with the combination of the current year W_m and the preceding year $NDVI_{max}$ of ($r^2 = 0.55$). This result suggests that on the interannual basis, the vegetation activity is primarily controlled by the current year soil moisture and slightly affected by underground structures stored in the root system.

1. Introduction

A strong drying trend has been observed over land areas in the Northern Hemisphere since the mid-1950s, especially over northern Eurasia, including Mongolia (Dai et al. 2004). The arid continental climate in Mongolia has created an extensive area of pastureland that is the main source of forage for livestock farming, which is a major industry in the country's economy. In the Mongolian steppe, the increasing frequency of drought has led to problems in the farming of livestock and pasturing (e.g., Natsagdorj 2003). This situation motivated us to assess the temporal trend in vegetation conditions in the Mongolian steppe.

Soil moisture deficit is commonly the most important stress factor for vegetation activity, especially in arid and semi-arid regions. Soil moisture deficits limit the growth of pasture in Mongolia (Miyazaki et al. 2004; Zhang et al. 2005; Nakano et al. 2008; Shinoda et al. 2010). Previous studies have examined the relationships between seasonal and interannual climate parameters and vegetation activity, especially between precipitation and the remotely sensed Normalized Difference Vegetation Index (NDVI), which generally increases with increasing precipitation (e.g., Shinoda 1995; Suzuki et al. 2003; Iwasaki 2006). However, a limited number of studies have examined the relationship between soil moisture and NDVI for various vegetation types (Farrar et al. 1994; Yang et al. 1997; Adegoke and Carlenton 2002; Mendez-Barroso et al. 2009). Soil moisture is widely recognized as a key parameter that links precipitation and vegetation. In the present study, we investigated the effect of modeled root-zone soil moisture on vegetation activity in the Mongolian steppe, based on remotely sensed NDVI data for seasonal and interannual periods during 1982−2005.

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2. Data and method

2.1 NDVI data

We investigated seasonal and interannual variations in monthly NDVI data and assessed their relationships with root-zone soil moisture. We used a 21-year (1982−2002) monthly 1° × 1° grid of NDVI data from the bimonthly 8-km-resolution Global Inventory Modeling and Mapping Studies dataset (GIMMS) produced by Tucker et al. (2005). The GIMMS NDVI data sets were generated from the National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR), which includes corrections for NDVI variations arising from calibration, view geometry, volcanic aerosols, and other factors unrelated to vegetation change (Pinzon 2002; Tucker et al. 2005). For the period 2003−2005, we derived monthly 1° × 1° grids of NDVI data from the semimonthly 8-km-resolution data that was re-sampled into monthly 1° × 1° data; subsequently, the monthly data were composited by choosing the higher NDVI between two 15-day datasets for each month. These NDVI data are used in climate models and biogeochemical models to calculate the photosynthesis, exchange of CO_2 between the atmosphere and the land surface, land-surface evapotranspiration, and the absorption and release of energy by the land surface.

2.2 Observed data

We analyzed data collected at nine stations distributed widely across the Mongolian steppe, including within the major vegetation zones of forest steppe, steppe, and desert steppe (Fig. 1). Above-ground biomass (AGB) data for the period 1986−2005 were obtained from the Institute of Meteorology and Hydrology of Mongolia (IMH). At the nine stations, AGB observations of a fenced pasture, representing the naturally occurring species above ground, were conducted on the 4th, 14th, and 24th of each month during the growing season (May−September). During these observations, the canopy height of the pasture exceeded 1 cm. The pasture AGB, which is considered an available source for livestock in this area, was not influenced by grazing.

2.3 Modeled data

To represent the extratropical characteristics of winter soil freezing and spring snowmelt in Mongolia, we used daily model-estimated soil moisture (W_m) data (Nandintsetseg and Shinoda 2010).

This model is a version of the one-layer water balance model developed by Yamaguchi and Shinoda (2002) for low-latitude arid regions. This kind of water balance model has been widely used for operational monitoring of soil moisture in many regions of the world (e.g., Huang et al. 1996; Dai et al. 2004). This model calculates absolute plant-available W_m based on precipitation (P) and air temperature (T) data with a limited number of measured soil parameters (e.g., soil wilting point and field capacity). Potential evapotranspiration (PET) was calculated with the method proposed by Thornthwaite (1948). Model performance was validated using soil moisture (10-day observations) ($r = 0.91$, $p < 0.05$)

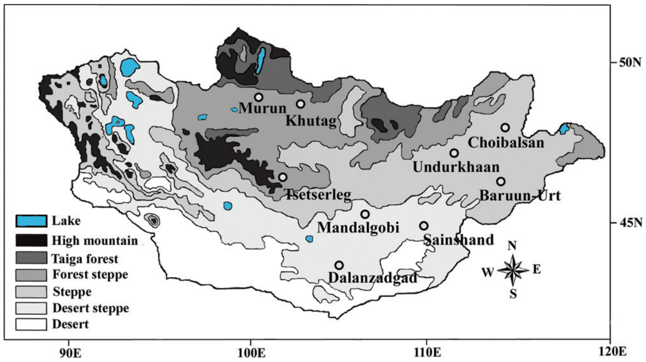

Fig. 1. Locations of nine stations at which soil moisture was measured and vegetation zones in Mongolia.

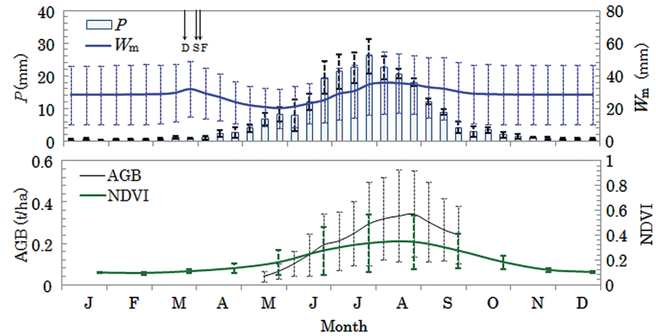

Fig. 2. Seasonal changes in 10-day (a) precipitation (P), soil moisture (W_m), the timings of snow disappearance (vertical arrows) for the three zones (F: forest steppe, S: steppe, and D: desert steppe), and (b) 10-day above-ground biomass (AGB) and monthly NDVI averaged over nine stations with their standard deviations (vertical dashed bars) in the Mongolian steppe during 1982−2005.

during April to October for the period 1986−2005, as measured at the nine stations (Nandintsetseg and Shinoda 2010). The data was expressed as plant-available soil moisture (mm) in the upper 50 cm soil layer and were calculated as the actual total soil moisture minus the moisture content at the wilting point. This soil layer represents the major rooting zone of the grasses that dominate most of the Mongolian steppe. It is important to note that our aim was to explore the general relationships between vegetation activity and soil moisture at a regional scale (over the Mongolian steppe); therefore, the parameters considered in this study were averaged (P, W_m, AGB, and NDVI) over the nine stations.

2.4 Statistical analysis

To study interannual variations in the yearly-maximum NDVI ($NDVI_{max}$), we considered up to five variables as parameters to explain the residuals of the temporal relationship between the current-year $NDVI_{max}$ and summer W_m (June−August). A Stepwise multiple-regression model was run by using 24-year data sets (1982−2005) of $NDVI_{max}$ and W_m (Table 1). The five variables, which were used in this analysis, are W_m of the current year, W_m and $NDVI_{max}$ of the first and second preceding years. At first, the current year W_m and then following the preceding year $NDVI_{max}$ during 1982−2005 were considered, and then followed by the association effect of W_m for the first and second preceding years. Finally, we applied all five variables, including $NDVI_{max}$ of the two preceding years.

3. Results

3.1 Seasonal changes in NDVI and W_m

Figure 2 shows seasonal changes in monthly NDVI and 10-day AGB during the growing season, and P and W_m in the 0 −50 cm soil layer averaged over the nine stations with their standard deviations during the period 1982−2005. In the previous study, we found a latitudinal gradient in W_m, with soil being drier in the southeast. This gradient is approximately consistent with the distribution of vegetation cover in the Mongolian steppe (Nandintsetseg and Shinoda 2010). W_m and NDVI revealed a large spatial variance compared to that of P during the study period. In early spring, W_m showed a slight increase (about 5 mm) due to the spring snowmelt when daily $T > 0$°C. The timings of snow disappearance over the three zones were found within a 10-day period, likely having a minor influence on the timings of snowmelt-derived increase in W_m. The changes in W_m may have in turn affected on the vegetation activity in the Mongolian steppe. It has been reported that the beginning of plant emergence and senescence of *Stipa* spp. generally occur in early May and late September, respectively, in the Mongolian steppe (Shinoda et al. 2007). In spring, during the emergence stage, NDVI increased with increasing W_m due to the snowmelt and mostly as a result of the onset of the rainy season in late May. NDVI continued to increase, reaching a peak in August, which is the plant maturity stage (and which coincides with the maximum (36 mm) in W_m). Subsequently, NDVI decreased during the senescence stage in autumn (September), matching by the decrease in W_m. After mid-October, soil moisture was assumed constant (as soil water was frozen) when the daily mean temperature was < 0ºC. The dormancy season of NDVI occurs in winter (October−April).

The present results reveal a strong correlation between seasonal changes in NDVI and those in AGB ($r = 0.94$, $p < 0.05$) during the growing season. Thus, NDVI was selected as a vegetation activity parameter in analyzing the relationship between soil moisture and vegetation activity. We also found a stronger correlation between NDVI and W_m ($r = 0.91$, $p < 0.05$) than between NDVI and P ($r = 0.65$, $p < 0.05$). An additional analysis showed that W_m and NDVI for each of the three zones exhibited significant correlation as mentioned above (at a regional scale).

3.2 Interannual variations in NDVI and W_m

Figure 3 shows the $NDVI_{max}$ and summer W_m anomalies averaged over the nine stations for the period 1982−2005. $NDVI_{max}$ showed a stronger correlation with summer (June−August) W_m ($r = 0.76$, $p < 0.05$) than with summer P ($r = 0.69$, $p < 0.05$). In general, a slight decreasing trend in $NDVI_{max}$ was found, in conjunction with the decreasing trend in W_m and it was significantly ($p < 0.05$) decreased particularly after 1995, reflecting a significant decreasing trend in W_m and an increasing trend in PET. The combined effects of these two latter trends may account for the rapid decreasing trend in $NDVI_{max}$ during recent decades.

To examine the mechanism of the $NDVI_{max}$ anomaly that occurs on an interdecadal scale and that is formed and maintained during the course of the year, we analyzed years with high and low $NDVI_{max}$ values over the Mongolian steppe (Fig. 3). Figure 4 shows 10-day W_m, P, and monthly NDVI for years characterized by high and low $NDVI_{max}$ values. Based on Fig. 3, two composites for years with high and low $NDVI_{max}$ over the past two decades were selected for an interdecadal comparison of extreme years. As shown in Fig. 4, seasonal changes in NDVI consistently followed those in W_m during years with both high and low $NDVI_{max}$ values. We found no significant difference between high and low $NDVI_{max}$ years in terms of NDVI during the early growth period (May−June). However, a clear difference in NDVI was observed in July, reflecting a difference in W_m; differences between the two composites are observed in August and September. These differences resulted from the leading significant differences in P and W_m from July to August. This result shows that the significant difference in P led to a time-lagged (about a half month) significant difference in W_m, finally to that in NDVI with time lags of approximately one month. The substantial difference in W_m, which occurred in September, was maintained during winter. This indicates that W_m

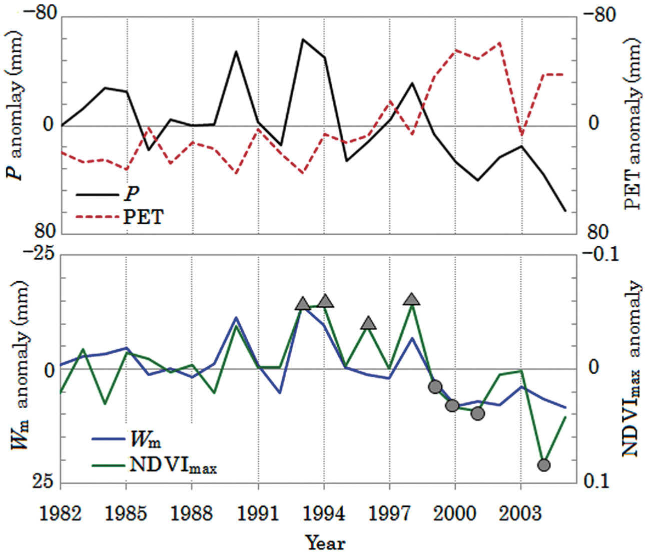

Fig. 3. Interannual (1982−2005) anomalies (a) of precipitation (P), potential evapotranspiration (PET), and (b) soil moisture (W_m) for the period June−August, and maximum NDVI ($NDVI_{max}$) averaged over nine stations in the Mongolian steppe (values are in reverse order). Triangles and circles indicate years with high and low values of $NDVI_{max}$, respectively.

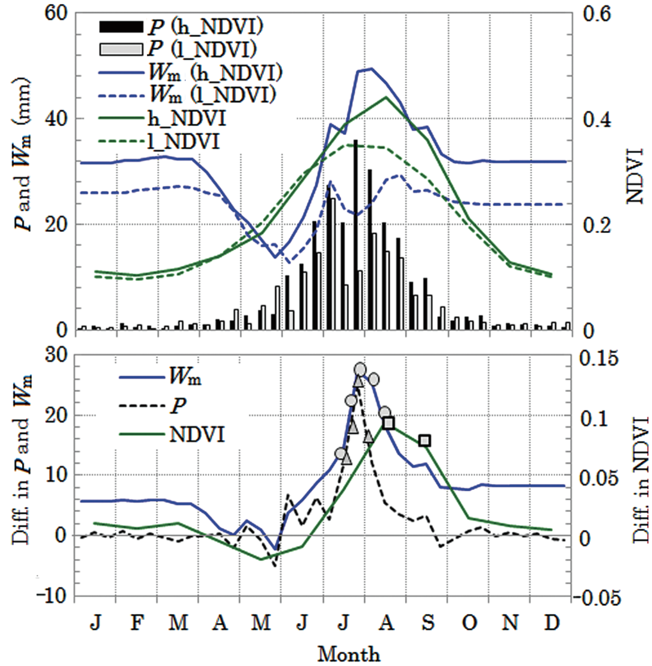

Fig. 4. Seasonal changes in 10-day (a) precipitation (P), modeled soil moisture (W_m), and monthly NDVI, comparision of the composites for 1993, 1994, 1996, and 1998 (h-NDVI is high-$NDVI_{max}$ years) with those for 1999, 2000, 2001, and 2004 (l_NDVI is low-$NDVI_{max}$ years) (Fig. 3), (b) as well as their differences. Triangles, circles, and squares indicate differences between high- and low-$NDVI_{max}$ years in terms of P, W_m, and NDVI, respectively, significant at the 5% level.

acted as a memory of the P anomaly via soil freezing and as an initial moisture condition for vegetation activity in the subsequent year.

Furthermore, to gain a better understanding of interannual variations in $NDVI_{max}$, we proposed five parameters; W_m of the current, the first and second preceding years, and $NDVI_{max}$ of the first and second preceding years as predictive variables during 1982−2005 (Table 1). The coefficient (r^2) of determination for $NDVI_{max}$ with W_m of the current year was 0.53. The addition of $NDVI_{max}$ for the first preceding year resulted in a slight increase in the proportion of explained variance, from 0.53 to 0.55 with the same level of statistical significance ($p < 0.001$), whereas an addition of the other variables resulted in a reduction of the significance level.

Table 1. Models that account for interannual variation in current-year maximum NDVI for the Mongolian steppe. The rows correspond to stepwise multiple regressions with different sets of variables during 1982−2005. Wm indicates soil moisture during June−August; N is yearly-maximum NDVI. The models include variables with a significant effect, in which (t), (t − 1), and (t − 2) indicate the current, first, and second preceding years, respectively.

N	Possible variables	Model	r^2	p
1	$W_{m(t)}$	$N(t) = .27 + .004\, W_{m(t)}$	0.53	< 0.001
2	$W_{m(t)}$, $N_{(t-1)}$	$N(t) = .3 + .004\, W_{m(t)} + .06\, N_{(t-1)}$	0.55	< 0.001
3	$W_{m(t)}$, $W_{m(t-1)}$, $W_{m(t-2)}$	$N(t) = .26 + .004\, W_{m(t)} + .0003\, W_{m(t-1)} + .0009\, W_{m(t-2)}$	0.57	< 0.005
4	$W_{m(t)}$, $W_{m(t-1)}$, $N_{(t-1)}$, $W_{m(t-2)}$, $N_{(t-2)}$	$N(t) = .23 + .004\, W_{m(t)} + .0004\, W_{m(t-1)} + .14\, N_{(t-1)} + .0002\, W_{m(t-2)} + .19\, N_{(t-1)}$	0.60	< 0.008

4. Discussion and conclusions

We investigated the relationship between modeled root-zone soil moisture and vegetation activity based on remotely sensed NDVI data, focusing on the Mongolian steppe during 1982−2005. On both seasonal and interannual time-scales, NDVI was more strongly correlated with soil moisture than with precipitation, suggesting that soil moisture plays an important and immediate role in controlling vegetation activity. This result is consistent with the findings of Yang et al. (1997), Adegoke and Carlenton (2002), and Mendez-Barroso et al. (2009).

A comparison between years with high and low $NDVI_{max}$ revealed that a significant difference in P led to a half-monthly time-lagged significant difference in W_m, finally a difference in vegetation activity, with time lags of about one month. Soil moisture anomalies were maintained throughout the following freezing winter. This implies that soil moisture acted as a memory via soil freezing and as an initial soil moisture condition for the vegetation activity in the subsequent year. This coincides with the results of Shinoda (2005).

Interannual fluctuations in $NDVI_{max}$ were strongly dependent on W_m of the current year and even more strongly dependent on a combination of the current year W_m and $NDVI_{max}$ of the preceding year. This result suggests that vegetation anomalies were likely stored as underground structures in the root system. To the best of our knowledge, this is the first study in Mongolia to point to the combination of soil moisture and root memories as predictor of vegetation. Several previous studies have reported that the current and preceding year's precipitation have a strong influence on NDVI of the current year in Africa (Martiny et al. 2009) and North America (Wang et al. 2003). Iwasaki (2006) examined the potential of predicting NDVI using the leading winter and spring precipitation and air temperature in Mongolia, revealing that NDVI is influenced by June precipitation with the additional influence of December precipitation. This relationship can be explained by the status of soil moisture content in the root zone as described in our study.

$NDVI_{max}$ for a given year showed a weak dependence on the preceding year's $NDVI_{max}$. Shinoda et al. (2010) reported that in the Mongolian steppe, manipulated soil moisture deficit resulted in a marked reduction in above-ground phytomass but did not substantially affect below-ground phytomass (which was several times greater than above-ground phytomass). The effect of snow mass memory as seen in Central Eurasia (Shinoda 2001), was not dominant in Mongolia, because the yearly-maximum snow depth is only 3.4 cm in this region (Morinaga et al. 2003). Therefore, it is likely that the large root system provided a basis for rapid recovery of above-ground phytomass, leading to a weak carry-over of vegetation anomalies, as revealed by $NDVI_{max}$ in the present analysis. In future applications, the concepts of soil moisture and root memory presented in the present study would provide a useful basis for an early warning system of reduced pasture production during drought.

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