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ORIGINAL PAPER

Assessment of drought frequency, duration, and severity and its impact on pasture production in Mongolia

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Abstract Drought frequency, duration, and severity and its impact on pasture productivity in the four main vegetation zones of Mongolia were analyzed using meteorological, soil moisture, and vegetation data during the growing season (April–August) of 1965–2010. Meteorological and pasture drought characteristics were explored using the Standardized Precipitation Index (SPI), the soil moisture anomalies percentile index (W_p), and Palmer Drought Severity Index (PDSI) on 1-month timescale. Generally, 35–37 (15–16 %) by SPI for meteorological drought while 27–29 (12–13 %) by W_p, and 16–21 (7–9 %) by PDSI for pasture drought with different durations were identified over the four vegetation zones during the study period. Most of these droughts (80 % by SPI and 50–60 % by both W_p and PDSI) observed during the entire events occurred on a 1-month duration with moderate intensity. Drought frequencies were not significantly ($p > 0.05$) different within the four zones. The frequency of the short-term meteorological droughts was observed relatively greater than pasture droughts; however, pasture droughts were more persistent and severe than meteorological droughts. The three indices show that the frequency and severity of droughts have slightly increased over the 46 years with significant ($p < 0.05$) dry conditions during the last decade of 2001–2010 in the four zones (except in the high mountain). The results showed the W_p was more highly significantly correlated with the precipitation anomalies ($r = 0.68$) and pasture production ($r = 0.55$) than PDSI ($r = 0.51$, $p < 0.05$ and $r = 0.38$, $p < 0.10$, respectively). A statistical model, based on pasture production and the W_p, suggested that the consecutive drought months contribution during the growing season was 30 % ($p < 0.05$) and that pasture production was more sensitive to the occurrence of droughts during June–August ($R^2 = 0.32$, $p < 0.05$) as seen in 2000–2002 and 2007. We concluded that a greater severity and frequency of growing-season droughts, during the last decade of 2001–2010, have driven a reduction in pasture production in Mongolia.

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1 Introduction

The Mongolian steppe is facing negative climate change impacts, which induced significant vulnerabilities in the region as a result of extreme weather events such as droughts, harsh winters (*dzuds*), dust storms, and desertification (IPCC 2007; Mandakh et al. 2007; Nandintsetseg et al. 2007; Kurosaki et al. 2011; Gombolhuudev 2011; Sternberg et al. 2011). Precipitation variability and drought events are the key factor driving pasture production, livestock dynamics, and human subsistence in this region, and it has caused a significant amount of damage to the economy and society. The pasture production of the Mongolian steppe is the basis for the nutrition of approximately 40.2 million head of livestock, which is the livelihood basis of the country's rural population (National Statistical Office of Mongolia 2002). *Dzuds* occur when the winter conditions, particularity heavy snow cover and/or very low temperature, prevent livestock from accessing pasture or from receiving adequate hay and fodder. It was reported that livestock mortality is higher in the years of combined drought and *dzud* than years of *dzud* alone. This occurs because in drought years, animals do not get enough strength to overcome the subsequent *dzuds* (e.g., Begzsuren et al. 2004). This combination of droughts and *dzuds* has been responsible for the loss of millions of animals upon which nomadic herders depend for their well-being as seen in 2001 (National Statistical Office of Mongolia 2002). Therefore, understanding drought characteristics and predicting are of particular concern in this country. However, in order to have a better planning and managing pasture, it is necessary to develop a scientifically based drought monitoring tool as an early warning system. Such tools can be used to make quantitative measures of drought characteristics that can be used to minimize drought impacts on pasture production.

Drought has been studied based on its frequency, duration and severity, and spatial extent in terms of a region or application-specific index. A number of drought indices such as Standardized Precipitation Index, SPI (McKee et al. 1993), Effective drought index, EDI (Byun and Wilhite 1999), Palmer Drought Severity Index, PDSI (Palmer 1965), and Surface Water Supply Index, SWSI (Shafer and Dezman 1982) have been developed and widely used in various parts of the world (Wilhite et al. 2000). Of these, SPI has received much attention since its introduction by McKee et al. (1993). Known as a simple and objective measurement of meteorological drought, it has been applied effectively to dry regions (Hayes et al. 1999; Wu et al. 2001; Morid et al. 2006; Sternberg et al. 2011). Meteorological drought is usually the first step in drought propagation through the entire hydrological cycle and therefore is tremendously important in drought monitoring. In fact, lack of precipitation is usually the predominant factor triggering a drought event. Therefore, it is one reason why SPI is a widely used as meteorological drought index. On the other hand, PDSI is among the most widely used indices of agricultural drought. However, it has several limitations; it performs poorly in indicating short-term changes in soil moisture (e.g., Alley 1984; Guttman 1991), and it does not take into account snowfall (Karl 1986). This index, therefore, may not be suitable for monitoring of agricultural drought in the cold climate that is widespread in the middle to high latitudes, including Mongolia. So far, less attention has been given to detect agricultural (hereafter pasture) drought and its monitoring index regardless of its negative impact on the Mongolian steppe. Determining an appropriate and user-friendly index that reflects the direct impact of drought on the pastureland is crucial in the country. Soil moisture is a good candidate for pasture drought index, because it reflects the recent precipitation and antecedent available water storage indicating agricultural potential (Keyantash and Dracup 2002). Moreover, soil moisture status in the root zone is a governing factor of vegetation growth via the availability of water for transpiration; thus, it could be used as a direct parameter of pasture drought. Furthermore, it has been found that soil moisture deficits limit the growth of pasture in Mongolia (Munkhtsetseg et al. 2007; Shinoda et al. 2010; Nandintsetseg and Shinoda 2011, 2012; Bat-Oyun et al. 2011). Hence, it is essential to use a soil moisture index (e.g., soil moisture percentile anomalies) for assessing pasture drought in this country.

The objective of the study was to analyze characteristics of meteorological and pasture droughts in the four main vegetation zones in Mongolia, using SPI, soil moisture anomalies percentile (W_{p}), and PDSI during 1965–2010, and their impacts on the pasture production using long-term aboveground biomass data during 1974–2010. The SPI, W_{p}, and PDSI used here were derived from calculations of SPI (McKee et al. 1993), soil water balance (Yamaguchi and Shinoda 2002), and PDSI (Palmer 1965) models. The soil water balance model in this study has been modified and evaluated by Nandintsetseg and Shinoda (2011, 2012) against observed soil moisture from 26 stations over Mongolia.

2 Data and methods

2.1 Dataset description

We used meteorological, vegetation, and soil moisture data collected from twelve stations distributed widely across the cold and arid climate of Mongolia, consisting of the four major vegetation zones: the high mountain, the forest steppe, the steppe, and the desert steppe (Fig. 1). In general, the annual precipitation ranges from over 400 mm in the northern mountains to below 100 mm in the south and is concentrated in the summer months (June–August). Annual mean temperature is lower than −4 °C in the high mountain, lower than 2 °C in the steppe, and desert steppe zones, while approximately 6 °C in the desert regions. Nandintsetseg and Shinoda (2011) reported a latitudinal gradient in the observed soil moisture across Mongolia, with soil being drier in the southeast. This gradient is approximately consistent with the distribution of vegetation cover in Mongolia (Yunatov 1976).

Daily precipitation (P), air temperature (T), and soil hydraulic parameters such as wilting point and field capacity data from the twelve stations during the period of 1965–2010 taken from the Institute of Meteorology, Hydrology and Environment of Mongolia (IMHE) were used to simulate daily soil moisture content, monthly SPI, and PDSI values. At each station, the measurements of soil moisture were conducted on the 8th, 18th, and 28th of each month during the warm season (April–October) using the gravimetric method. Soil moisture was not measured during winter (November–March) because the soil was frozen. Soil moisture data were collected from the upper 50-cm of the soil layer in fenced un-grazed pastures. This soil layer represents the major rooting zone of the grasses that dominate most of Mongolia. In general, the dominant soil texture in the top 50-cm layer was sandy soil (Nandintsetseg and Shinoda 2011). These soil moisture observations were used to validate the water balance model presented in this study.

The growing season (from April to August) in Mongolia is very short (the beginning of plant emergence and senescence occurred in late April–early May and late September,

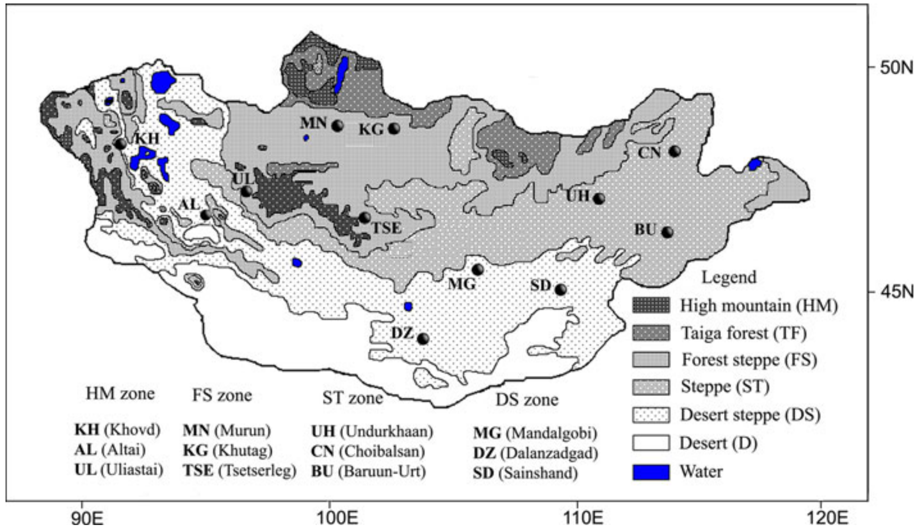


Fig. 1 Location of the selected twelve stations and vegetation zones in Mongolia. Abbreviations of the station name were shown

respectively), which is very dependent on climate, mainly precipitation through soil moisture (Shinoda et al. 2007; Nandintsetseg and Shinoda 2011). We used the yearly maximum above-ground biomass (AGB_8) taken at the end of August for the period 1974–2010, which was obtained from the IMHE. At the twelve stations, AGB_8 measurements were conducted by clipping all plants within four 1 m × 1 m quadrate above 1 cm height in a fenced pasture, which represents the naturally growing grass in this region. This pasture AGB_8, is considered as available forage for livestock, was not influenced by grazing.

2.2 Analysis of drought characteristics

In this study, we used time series of monthly Standardized Precipitation Index (SPI), soil moisture anomalies percentile index (W_p), and Palmer Drought Severity Index (PDSI) as drought indices. The SPI indicates meteorological drought, whereas W_p and PDSI indices represent pasture drought during the growing season. Because of Mongolia's short vegetation growth and intensive grazing season (Jigjidsuren 1984; Shinoda et al. 2010), these drought indices were used to monitor droughts during the critical growing season. In this study, we identified drought severity as moderate, severe, and extreme (mild droughts are not considered). We classified drought duration into short-term (1 and 2–3 months), mid-term (4–5 months which are spanned for single growing season), and long-term (6–10 months and $\geq$10 months, which are spanned for two and more growing seasons) timescales using the three indices on a 1-month timescale.

2.2.1 Standardized Precipitation Index (SPI)

McKee et al. (1993) developed the SPI based on precipitation. The SPI is calculated by fitting historical precipitation data to a Gamma probability distribution function for a specific time period and location, and transforming the Gamma distribution into a normal distribution with a mean of zero and standard deviation of one. The SPI was designed to quantify the precipitation deficit, based on the probability of precipitation for multiple time scales, reflecting the impact of drought on the availability of the different water resources (Hayes et al. 1999). Currently used in sixty countries (Wu et al. 2001), SPI has been applied to East Asia in China (Wu et al. 2001) and Korea (Mi et al. 2003), but it is relatively new to Mongolia (Sternberg et al. 2009). The SPI has been calibrated in previous studies to map onto the beginning and duration of a drought event. The negative values of SPI are compared with the boundaries of different classes of drought. There are many classifications used by different authors. Originally McKee et al. (1993) distinguished four categories of drought with the threshold value of SPI for the moderate drought category equal to $\mathrm{SPI} = -1.0$ (Table 1). Agnew (2000) reported that in this classification, all negative values of SPI are taken to indicate the occurrence of drought—this means that for 50 % of the time drought is occurring. As a result, he suggested a new classification scheme for drought classes by adopting slightly different thresholds (Table 1). In this study, this modified classification of Agnew (2000) shown in Table 1 was used for drought classification. A 1-month timescale SPI was calculated using SPI model (US National Drought Mitigation Center 2006) on to identify meteorological drought dynamics in Mongolia.

2.2.2 *Soil moisture anomalies percentile* (W_p)

Soil moisture percentiles have been used by CPC (2005) to monitor pasture drought. In our study, the percentiles of the estimated soil moisture anomalies (W_p) of the top 50-cm soil layer were used as an index of pasture drought, which was based on the CPC's classification scheme (2005). The soil moisture values used in this analysis were derived from the water balance model described in the studies of Nandintsetseg and Shinoda (2011, 2012). This model is a version of the one-layer water balance model developed by Yamaguchi and Shinoda (2002) for low-latitude arid regions. The water balance model has been tested and widely used for operational monitoring and climate change studies of soil moisture in many regions of the world (e.g., Huang et al. 1996; Shinoda and Yamaguchi 2003; Dai et al. 2004). This model was modified to represent the extratropical characteristics of winter soil freezing and spring snowmelt in Mongolia (Nandintsetseg and Shinoda 2011, 2012). The result of these studies showed good correspondence between the modeled and observed soil moisture values of 26 stations over Mongolia during the period of 1986–2005.

The model was run using daily T and P, and soil hydraulic properties data to simulate root zone soil moisture at twelve stations during 1965–2010. The model performance was validated using the observed soil moisture values ($r = 0.78$, $p < 0.05$) during April to October for the period of 1986–2005, during which continuous observation data were available. The simulated soil moisture is expressed as plant-available soil moisture (mm) in the upper 50-cm soil layer and was calculated as the actual total soil moisture minus

Table 1 Classification of the drought indices values and drought category

Drought category	SPI (Agnew 2000)	W_p, % (CPC 2005)	PDSI (Palmer 1965)
Moderate drought (D1)	−0.84 to −1.27	11–20	−2.0 to −2.99
Severe drought (D2)	−1.28 to −1.64	6–10	−3.0 to −3.99
Extreme drought (D3)	≤−1.65	≤3.0	≤−4.0

wilting point. The W_p values were calculated using the time series of the simulated soil moisture for each month during 1965–2010 of each station with the empirical cumulative probability distribution (Weibull plotting position). Following Andreadis and Lettenmaier (2006) and Sheffield and Wood (2007), Sheffield et al. (2009), we assumed pasture drought occurred when W_p fall below threshold values (Table 1) in given time at the station.

2.2.3 Palmer Drought Severity Index (PDSI)

We also used PDSI as a measure of pasture drought. This water balance-based index was developed by Palmer (1965) to measure the cumulative departure (relative to local mean conditions) in atmospheric moisture supply and demand. The supply-and-demand concept of the water balance equation, upon which the PDSI is based, uses monthly P and T, and available soil moisture. PDSI values and drought category were shown in Table 1.

2.3 Statistical analysis

To determine the impacts of droughts on pasture production, we analyzed the yearly maximum pasture AGB_8 and monthly W_p during the growing season from 1974 to 2010 using the stepwise multiple regression analysis. To identify a collinearity effect among monthly W_p values, multicollinearity tests were performed using variance increase factor (VIF) among the monthly values. Then, the multiple linear regressions were applied to estimate the contribution of W_p to AGB_8.

3 Results and discussion

3.1 Drought frequency, duration, and severity over the last 46 years (1965–2010)

Meteorological and pasture droughts frequency, duration, and severity in Mongolia were explored using SPI, W_p, and PDSI indices during the pasture growing season over the last 46-years (1965–2010). Figure 2 shows the monthly values of P anomaly, SPI, W_p, and PDSI averaged over the twelve stations during the study period. It was found that the SPI values were in phase with and closely following the curve of P anomalies ($r = 0.92$, $p < 0.05$). Although W_p and PDSI values were generally in phase with P anomalies, W_p was more highly correlated ($r = 0.68$, $p < 0.05$) with the P anomalies than the PDSI ($r = 0.51$, $p < 0.05$) on a 1-month timescale. PDSI exhibits lower variability in its values compared to W_p. That is, PDSI followed the general trend of P anomalies; however, it did not capture the P extremes. This may reflect the main disadvantage of PDSI highlighted in the studies of Alley (1984), Guttman (1991), and Karl (1986).

The time series of average values of each index shown in Fig. 2 indicates fluctuation cyclic characterized by wet years (i.e., 1967, 1973–1974, 1976–1977, 1987, 1990, and 1993–1995) and dry years (i.e., 1974, 1978–1979, 1981–1982, 1984, 1999–2002, and 2006–2009), and while the other years were near to normal conditions. In general, all indices show slight increasing trends in droughts during 1965–2010 in conjunction with a decreasing trend in P and increasing trend in T (not shown), and with a significant ($p < 0.05$) increase in frequency and severity of droughts in the 2000s. The intense and prolonged droughts in the 2000s can be ascribed to lower precipitation and warmer temperatures (thus enhanced evapotranspiration).

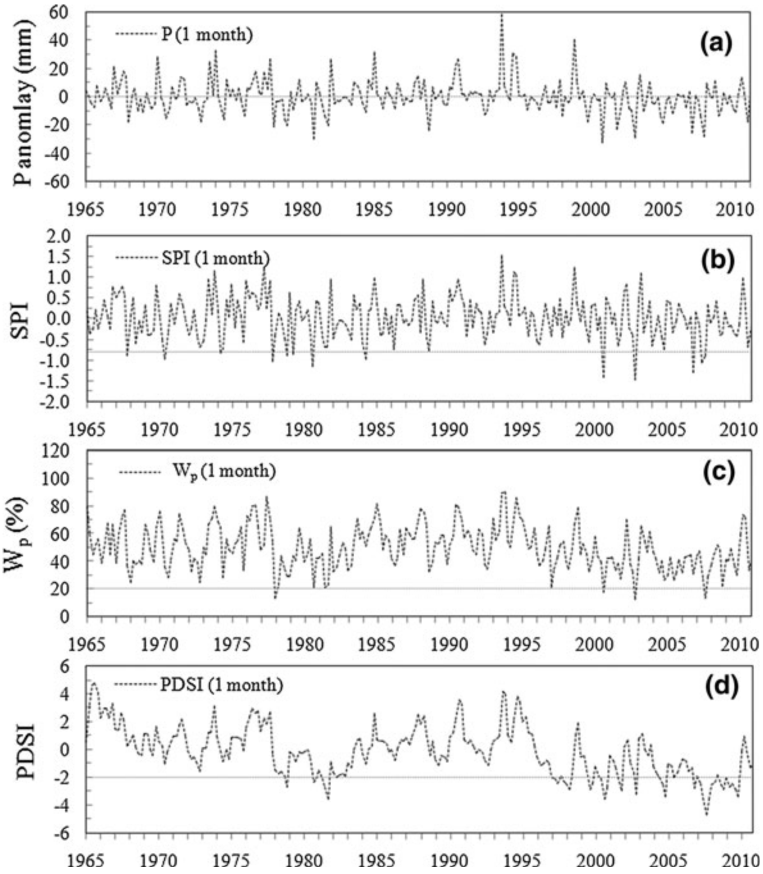


Fig. 2 The monthly values of *P* anomaly (**a**) SPI (**b**) W_p (**c**) and PDSI (**d**) averaged over the twelve stations during the growing season (April–August) of 1965–2010. The *dashed horizontal lines* show the threshold value of the moderate droughts for each index

Since averaged values of the three drought indices over the four regions were used in Fig. 2, the frequency and severity of drought events were not observed. Figure 3 shows the time series of averaged values of SPI, W_p, and PDSI over three stations for each vegetation zone during 1965–2010. All the zones exhibit similar temporal variability, including slight increasing trends in drought frequency and severity during the study period. Significant ($p < 0.05$) increasing trends in droughts during the last decade (2000s) were found in all zones (except the high mountain). However, the drought duration and severity values differ among the indices. Figure 4a shows the frequencies of meteorological and pastoral droughts for different durations at each vegetation zone. During the entire study period, meteorological drought accounts for 35–37 (15–16 %) events, while pasture accounts for 27–29 (12–13 %) events by W_p and 16–21 (7–9 %) events by PDSI. These droughts observed within different durations were identified over the four vegetation zones. Drought frequencies were not significantly ($p > 0.05$) different within the four zones, where the high number of meteorological droughts (50 events) occurred in the steppe zone. Most of these drought events occurred on a one-month timescale (i.e., 26–30 events correspond to 75–80 % of the total drought events by SPI, 16–18 events, 60–62 % of the total drought events by W_p, and 8–11 events, 50–52 % of the total drought events by PDSI), whereas only 1–2 meteorological and pasture droughts events were observed during 4–5 months duration (spanned for one growing season) within the four zones. For the long-term duration (6–8 months, spanned for two growing season), there was no meteorological drought detected in all zones; however, there were 1 (W_p) and 2 (PDSI) pasture droughts observed in the forest steppe and high mountain zones during 2000–2001 and 2006–2007. This result indicated that short-term meteorological droughts more frequently occurred than that of pasture droughts, whereas pasture droughts were more persistent than meteorological droughts in all zones. These findings can be explained in terms of soil moisture memory effect in Mongolia. In the study of Shinoda and Nandintsetseg (2011), the autocorrelation analysis of decay time scale (i.e., lag at which autocorrelation function equals to 1/e) showed that soil moisture memory scales during the autumn and winter (8.2–5.5 months), and during the spring and summer (1.5–3.4 months) in Mongolia. The cold-season climate with low evapotranspiration and strong soil freezing acts to keep the autumn soil moisture to 8.2 months on the Mongolian steppe.

Figure 4b shows the drought months of each class of severity based on the classification scheme listed in Table 1 for each vegetation zone. The analysis clearly shows that moderate (D1) drought months were the most frequently found with all indices (i.e., 26–37 by SPI, 25–29 by W_p, and 27–35 by PDSI) over all four zones. Focusing on both severe (D2) and extreme (D3) droughts months, pasture droughts occurred slightly higher (but not significant at the 0.05 level) than those of meteorological droughts. As shown in Fig. 3, the recent increase in drought severity was unprecedented since the mid-1960s. Focusing on SPI values, the greatest severity of droughts was found during June–August of 2000, 2002, 2006, and 2007. It was found in terms of highest severity months of SPI that June 2007, July 2000, and August 2002 were the driest and hottest (not shown) summer months since 1965 in all stations. These indicate that during the study period, most of the severe summer droughts occurred during the 2000s. Moreover, Fig. 5 shows the comparison of the drought events per decade (i.e., drought frequency in terms of SPI, W_p, and PDSI) for the four vegetation zones. In general, the indices show that the decade from 2001 to 2010 shows the highest number of droughts in the all zones (except in the high mountain). A comparison of

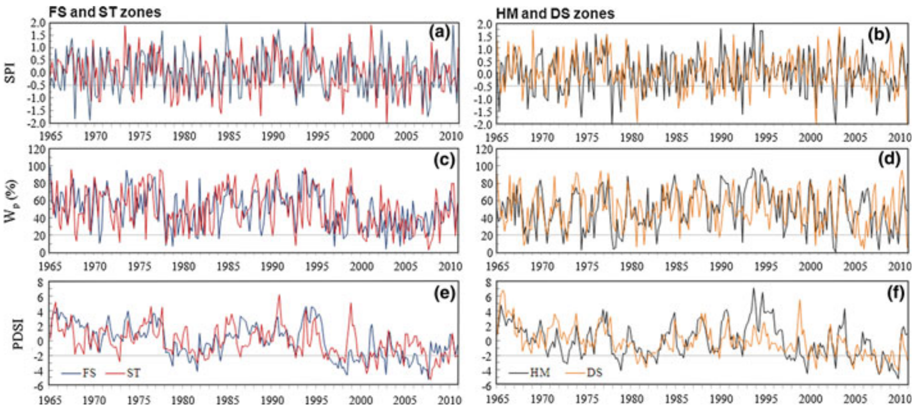


Fig. 3 The growing-season's monthly values of SPI (**a**, **b**), W_p (**c**, **d**), and PDSI (**e**, **f**) averaged over three stations for each vegetation zones during 1965–2010: the forest steppe (FS), steppe (ST), high mountain (HM), and desert steppe (DS). The *dashed horizontal lines* show the threshold of moderate droughts for each index

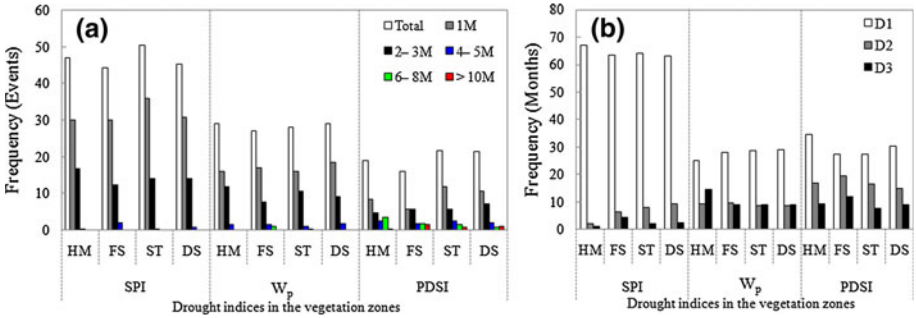
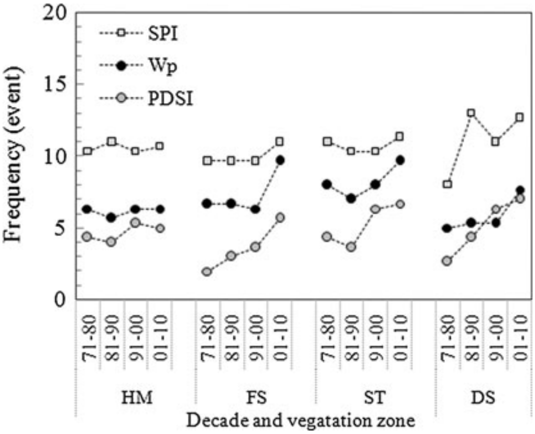


Fig. 4 (**a**) The frequency (events) of meteorological (SPI) and pasture (W_p and PDSI) droughts for each timescales (1 M indicates 1-month timescale, 2–3 M is 2–3 months, 4–5 M is 4–5 months, 6–8 M is 6–8 months, and >10 M is more than 10 months) averaged over three stations for each of three vegetation zones: the forest steppe (FS), steppe (ST), high mountain (HM), and desert steppe (DS). (**b**) The drought months of each class of drought severity (D1 is moderate, D2 is severe, and D3 is extreme) based on the classification scheme shown in Table 1 averaged over three stations for each vegetation zones during 1965–2010

Fig. 5 Comparison of drought events (i.e., drought frequency in terms of SPI, W_p, and PDSI) per decade (four decades from 1971 to 2010) averaged over three stations for each vegetation zones



drought frequencies for the reference period (1971–1990) and the last decade (2001–2010) reveals that meteorological and pasture drought events increased by average factors of 1.1 (SPI), 1.2–1.3 (W_p), and 1.4–1.8 (PDSI) for the all zones (except in the high mountain). This result is consistent with the previous studies of meteorological droughts in Mongolia (e.g., Batjargal 2001; Bayarjargal et al. 2006; Batima et al. 2008; Natsagdorj 2009; Sternberg et al. 2011).

3.2 Drought effects on pasture production

In this section, we analyzed the impacts of drought on pasture production using the yearly maximum pasture aboveground biomass (AGB_8) at the end of August during 1974–2010. Figure 6 shows the long-term average values of AGB_8 and their variability during the study period across the twelve grassland stations representing the four vegetation zones. Spatial average of the long-term AGB_8 was 36.5 g/m^2 over all zones. It was found that favorable conditions (e.g., high precipitation and soil moisture) for high AGB_8 values can be found in the forest steppe (66 g/m^2) and the steppe (48 g/m^2) zones. In contrast, the high mountain (13 g/m^2) and the desert steppe (16 g/m^2) zones have low values of AGB$_8$, which are characterized by low precipitation and high evapotranspiration. As shown in Fig. 6, the four vegetation zones can be differentiated as a stable AGB$_8$ (coefficient of variation, CV = 0.54) in the steppe zone, a moderately stable AGB$_8$ (CV = 0.62) in the forest steppe, and vulnerable AGB$_8$ in the high mountain (CV = 0.73) and the desert steppe (CV = 0.71) zones.

Figure 7 shows the time series of averaged AGB$_8$ (Fig. 7a) and its anomalies (Fig. 7b) averaged over twelve stations in Mongolia. The result showed that the averaged AGB$_8$ over the four zones significantly ($p < 0.05$) decreased by 10.8 g/m^2 (26 % of the mean AGB$_8$) during 1974–2010, with the most pronounced in the forest steppe (by 24.5 g/m^2, 38 % of the mean AGB$_8$). The highest AGB$_8$ was found in the 1970s and 1980s, while the lowest was in the 1990s and 2000s (Fig. 6b). The frequency of years with low AGB$_8$ values has increased over the last 15 years (since 1995), probably due to an increased frequency of droughts (Fig. 2) in this period. The decrease in pasture productivity during 2001–2010 can be attributed to a greater frequency and severity of droughts (Fig. 5).

The response of AGB$_8$ to the growing-season droughts was explored through stepwise multiple regression analysis. For all zone, W_p was significantly correlated ($r = 0.55$, $p < 0.05$) with AGB$_8$ anomalies compared to PDSI ($r = 0.38, p < 0.10$) and SPI ($r = 0.21$ and $p < 0.10$) during the study period. As a result, W_p was selected for assessing the impact of drought on pasture production. It was found that there was a high collinearity between W_{p4} (April) and W_{p5} (May), and also between W_{p6} (June), W_{p7} (July), and W_{p8} (August). Then, we averaged those dependent variables into two parameters of W_{p4-5} and W_{p6-8}. The VIF of these two new parameters was less than 1.5, which suggests that they are independent variables. In agreement with Eqs. 1 and 2, the impact of pasture drought (measured by W_p) on AGB$_8$ is estimated by the signs of the regression coefficients. Equations 1 and 2 represent the impact of W_p on AGB$_8$ using stepwise multiple linear regression:

$$\mathrm{AGB}_8 = 18.1 + 0.12W_{p4-5} + 0.24W_{p6-8} \quad (R^2 = 0.30, p = 0.013) \tag{1}$$

$$\mathrm{AGB}_8 = 19.8 + 0.29W_{p6-8} \quad \left(R^2 = 0.32, p = 0.010\right) \tag{2}$$

The model indicates that W_p during June–August have significant impact on AGB$_8$; however, the regression coefficient during the April–May was not significant. As a result,

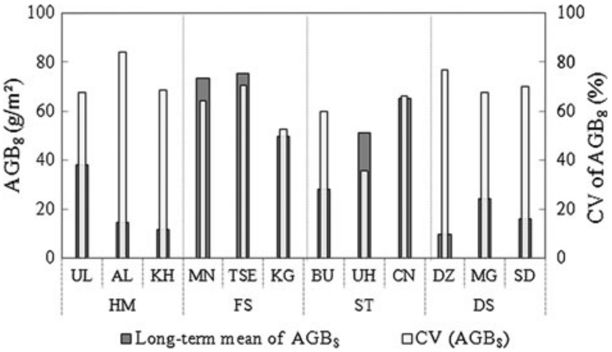


Fig. 6 Long-term mean pasture aboveground biomass (AGB$_8$) and its variability for the twelve grassland stations (Abbreviations of the station name were shown in Fig. 1) during 1974–2010. AGB$_8$ is averaged AGB$_8$ per vegetation zone, CV is coefficient of variation as calculated from average and standard deviation of AGB$_8$

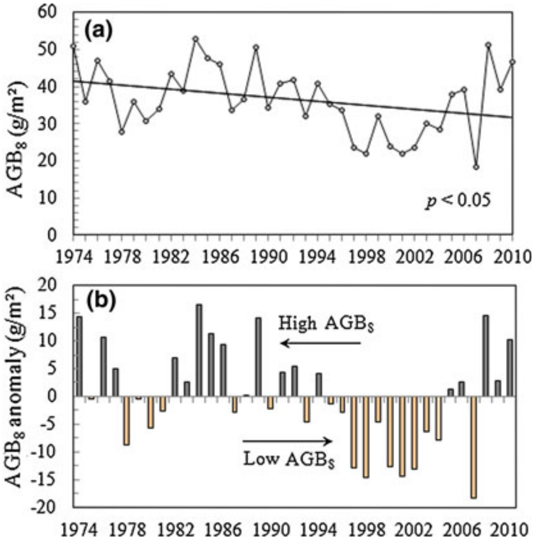


Fig. 7 The time series of averaged pasture plant aboveground biomass (AGB_8) (**a**) and its anomalies (**b**) during 1974–2010 over the twelve stations

the spring months W_{p4-5} were excluded from the next analysis (Eq. 2) due to their low relative contributions. As seen from the R^2 (Eq. 1), consecutive drought conditions have a significant influence on AGB_8 in Mongolia, and the W_p contribution during the growing period was 30 %. The R^2 from Eq. 2 shows that AGB8 was more sensitive to the occurrence of droughts during June–August ($R^2 = 0.32$, $p = 0.010$) (as seen in 2000–2002 and 2007), which is reasonable because of grass heading, flowering, and maturity stages occur during this period, making grasses particularly sensitive to moisture availability. This result is consistent with study of Nandintsetseg et al. (2010), which have reported 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 in the Mongolian steppe.

4 Conclusions

This study explored the frequency, duration, and severity of meteorological and pasture droughts in the four main vegetation zones of Mongolia using SPI, W_p, and PDSI drought indices, respectively. We also considered the spatio-temporal variability of pasture production, and the influence of drought on its productivity. To our knowledge, this is the first attempt to identify pasture drought events in Mongolia using the estimated soil moisture anomalies index, which was validated using long-term soil moisture observations available in the region. W_p was highly correlated with the precipitation anomalies, thereby demonstrating its efficiency compared with the widely used PDSI. This study highlighted W_p can be used to identify pasture drought frequency, duration, and severity, and has potential for application in Mongolia. It was found that all indices show a significant ($p < 0.05$) increase in the frequency and severity of growing-season droughts during the 2000s across the four vegetation zones (except high mountain) in Mongolia. Overall, 35–37 (SPI) meteorological, 27–29 (W_p) and 16–21 (PDSI) pasture droughts were identified over the four vegetation zones in Mongolia. Most of these events (26–30 events by SPI, 16–18 by W_p, and 8–11 events by PDSI) occurred on a one-month timescale. Moreover, the moderate droughts were the most frequently occurred over all four zones. The longest and severe pasture drought events lasted for 6–8 months (spanned for two growing season) in the forest steppe and high mountain zones during 2000–2001 and 2006–2007. The frequency of the short-term meteorological droughts was observed relatively greater than pasture droughts; however, the pasture droughts were more persistent and severe than meteorological droughts.

The impact of pasture drought (measured by W_p) on pasture production indicates that consecutive droughts during the growing season have contributed significantly to the reduction in pasture production. Results indicated that 32 % of the lower pasture productions were recorded when drought occurred during June–August as seen in 2000–2002 and 2007. The results showed that the W_p index is best correlated with pasture production anomalies than PDSI. Therefore, it would be an appropriate index for measuring and monitoring pasture droughts, and predicting pasture production in regions where moisture is the main limiting factor. These findings are relevant for both decision-makers and herders.

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