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DOES GRAZING AFFECT THE RESPONSES OF RANGELAND VEGETATION TO DROUGHTS?

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ABSTRACT

Grazing and drought are the major drivers of pasture degradation in Mongolia. It is important to understand how these two drivers interact and influence rangeland ecosystem services that support food supply for the entire nation. This study aimed to examine the effects of drought, grazing, and their interaction on aboveground plant biomass (AGB) in the semi-arid steppe zone of Mongolia, using a 21 year (2000-2020) dataset on air temperature, precipitation, and aboveground biomass. Aboveground biomass surveys were conducted across the zone within a non-grazed fenced area and a comparable grazed area outside the fence. The Standardized Precipitation-Evapotranspiration Index (SPEI) was calculated to assess drought conditions, using air temperature and precipitation. To assess the effects of drought, grazing, and their interaction on aboveground biomass, linear mixed effect models were used. Results showed that the interaction between grazing and the intensity of drought was highly significant (t-value = 5.73, $p < 0.001$), indicating that the response of aboveground biomass to the intensity of drought differed between grazed and non-grazed areas in the current year. The negative effect of droughts on AGB in non-grazed plots was twice as strong as for grazed plots. The interaction between the previous year's intensity of drought and grazing was highly significant (t-value = 3.24, $p < 0.01$), indicating that the response of aboveground biomass to the previous year's intensity of drought differed between grazed and non-grazed areas. The previous year's intensity of drought had a negative effect (not significant) on aboveground biomass in the non-grazed plots while there is no significant effect in the grazed plots. My research indicates that grazing modulates the response of aboveground biomass to drought. Therefore, grazing should be considered when designing management strategies for rangelands under future climate change scenarios.

Key words: aboveground biomass, grazing, drought, overgrazing

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1. INTRODUCTION

Mongolia is a landlocked country in Central Asia that has a great variety of landscapes. Rangelands cover about 80% of Mongolia's territory (Batima et al. 2000; Nakano et al. 2020) and they have been used for nomadic animal husbandry for thousands of years (Hanks 2010). About 77% of the total Mongolian territory is affected by desertification (Nyamtseren et al. 2015). According to the National Report on Rangeland Health of Mongolia, out of 1,500 monitoring sites, 58% of sites were in a degraded state in 2016 (Densambuu et al. 2018). Nowadays, about 30% of Mongolians engage in animal husbandry. In 1990, the Mongolian economic system changed from a centrally planned economy to a market driven economy, and the number of livestock grew rapidly, reaching 70 million heads in 2019, almost three times the 1990 level (NSO 2019). In addition to the increasing number of livestock, the climate in Mongolia is getting drier and climate-related extreme events, such as droughts, are becoming more frequent (MET 2018).

Without proper pasture management, grazing by millions of livestock, in combination with a dry climate and frequent droughts are the major causes of pasture degradation in Mongolia (Indree & Dorjgotov 2013). Therefore, numerous studies have been carried out on the effects of drought (Munkhtsetseg et al. 2007; Shinoda et al. 2010; Nandintsetseg & Shinoda 2013; Shinoda et al. 2014; Natsagdorj & Munkhbat 2020) and grazing on Mongolian grasslands (Indree & Dorjgotov 2013; Khishigbayar et al. 2015; Na et al. 2018; Ahlborn et al. 2020). However, our understanding of how these two drivers interact is relatively poor, and insufficient information is available on the recovery capacity of land after disturbances, in the presence or absence of grazing. Hence it is important not only to study the impact of drought and grazing on the vegetation independently but to study them simultaneously to better understand their interactions.

In this study, I will examine the resilience of grasslands in the semi-arid steppe zone of Mongolia after a disturbance (drought), and whether the response varies depending on the area being grazed or not.

1.1 Climate and droughts in Mongolia

The climate of Mongolia is continental due to being isolated from the oceans and characterized by the high fluctuation of temperature and low precipitation (Jambaajamts 1989). The annual mean temperature is 0.2°C (long-term average 1981-2010), the winter (December to February) average temperature is -20°C, and the summer (June to August) average temperature is 18°C. The 0°C isotherm of annual mean temperature is along the northern border of the desert steppe zone and lays north of 46° latitude. In winter, the absolute minimum temperature is -54°C, while in summer the absolute maximum temperature is 45°C (NAMEM 2017). Thus, the climate in Mongolia is harsh.

As in many other parts of the world, the climate in Mongolia has changed considerably during recent decades. For example, the annual mean near-surface temperature has increased by 2.2°C in the period 1940-2015 (MET 2018). Similarly, climate-related extreme events such as drought and dzud have become more frequent. However, annual precipitation has not changed significantly during the same period, when only a 7% decrease was detected (MET 2018).

Drought is a natural hazard characterized by low precipitation, which is below normal and extended over months, seasons, or even longer periods (WMO 2006). Many researchers have conducted drought studies since the 1970s (Natsagdorj & Munkhbat 2020), using different methods and indices to assess drought. Due to climate change, drought frequency and intensity have increased in Mongolia, especially since 2000 (Nandintsetseg & Shinoda 2013; MET 2018; Natsagdorj & Munkhbat 2020). In particular the drought years 2000, 2002, and 2015 had a large impact on the socio-economy of the country (MET 2018).

1.2 Responses of vegetation to drought

Plant responses to drought differ depending on their life form, species, and structure (Eziz et al. 2017). Herbaceous annual plants are more sensitive to drought than woody plants and respond more quickly to drought; however, drought tolerance varies depending on drought intensity and biomass allocation (Eziz et al. 2017). For example, annual plants are more resistant to low-intensity drought, while perennial plants are more resistant to high-intensity drought and recover faster than annual plants due to their strong, large root systems (Shinoda et al. 2010). Another study showed that the timing of the drought can influence its impact: intense spring droughts reduced soil water content in the upper level of the soil profile and subsequently reduced total herbage production by 20 to 40% (Heitschmidt et al. 2005). Furthermore, experiments that simulated vegetation responses to drought showed similar results with significant reductions in aboveground biomass which recovered quickly in the late summer (Munkhtsetseg et al. 2007; Shinoda et al. 2010). These studies showed that droughts had only a small effect on the below ground biomass which was not severely damaged by drought (Shinoda et al. 2010).

1.3 Responses of vegetation to grazing

The rapid livestock increase after 1990 raised grazing pressure on pastures of Mongolia and resulted in a 34% increase in grazing over the period 1996–2015 compared to the previous two decades (1976–1995) (Nandintsetseg et al. 2021). Although overgrazing is one of the drivers that can accelerate grassland degradation (Liu et al. 2013; Wick et al. 2016), vegetation responses differ depending on grazing intensity (Pulungan et al. 2019; Li et al. 2021) and grazer density (Austrheim et al. 2014; Pulungan et al. 2019), and some studies have reported that species diversity decreased with an increase in grazer density. Therefore, grazing could enhance the positive and negative influences on ecosystem services through biodiversity (Li et al. 2021). In general, grazing has a negative impact on aboveground biomass (Bat-Oyun et al. 2016; Takatsuki et al. 2018; Fan et al. 2019; Li et al. 2021), while species richness increases at intermediate levels of grazing (Pulungan et al. 2019).

Grazing is the main driver of vegetation dynamics, but in some cases, its effects can be overridden by climate. For example, changes in the aboveground biomass of palatable plants in grazed areas were primarily controlled by rainfall intensity in June of the current year, and secondarily by livestock numbers in summer in the semi-arid grasslands of Mongolia (Nakano et al. 2020).

Although droughts and grazing are important drivers of vegetation dynamics in Mongolia, there is still little research considering their combined effects and a poor understanding of how ecosystems respond to the combined effects of drought and grazing (Ruppert et al. 2015). Therefore, understanding the implications of disturbance in grassland ecosystems is a critical issue in both nature conservation and human economic development in Mongolia (Nakano et al. 2020).

1.4 Project objectives

The goal of this study is to examine the resilience of grasslands in the semi-arid steppe zone of Mongolia after a disturbance (drought), and whether the response varies depending on the area being grazed or not. To address this goal, monitoring data of the steppe zone of Mongolia was analysed to assess the impact of drought on biomass and the recovery capacity of the vegetation after a drought. To be able to address the interactions between drought and grazing, areas were chosen where comparable data for grazed and non-grazed sites were available.

The objectives of this study are: (1) to identify drought conditions during 2000-2020, and (2) to examine the effect of drought conditions in the current year on aboveground biomass production in areas currently subjected to grazing or where grazing has been excluded, and (3) to test whether the previous year's drought better explains the biomass responses. Knowledge on the recovery capacity of a grazing area and a better understanding of the interactions between grazing and droughts in Mongolia will help develop sustainable management practices under future climatic scenarios.

Within the framework of the above objectives, the following research questions were developed.

1. What are the drought conditions during the study period?
2. Does grazing influence the response of aboveground biomass to droughts?
3. Does plant biomass recovery after drought differ when grazing is excluded?

2. METHODS

2.1 Study area

The Mongolian territory can be categorized into five climatic regions based on the aridity index, consisting of humid, sub-humid, semi-arid, arid, and hyper-arid regions from north to south (Nyamtseren et al. 2018; Fig. 1A). In addition, the Mongolian territory can be further divided based on landscape, into six main, and 11 sub-ecological zones (Doljin 2016; Fig. 1B). The ecological zones are based on latitudinal spatial variations of the landscape, altitudinal belts of the mountainous landscape, and depression of intermountain valleys (Doljin & Yembuu 2021). Among all ecological zones, the steppe is the largest, comprising 34.2% of the territory (Fig. 1C), and is further divided into three subzones: meadow steppe, steppe, and dry steppe. The steppe belongs to the semi-arid climatic region.

In the current study, I will focus on the semi-arid steppe zone that covers the vast plains of the Eastern Mongolian, Middle Khalkha plateaus, narrowing to the west and extending to the southern foothills of the Khankhukhii Mountains (Doljin & Yembuu 2021).

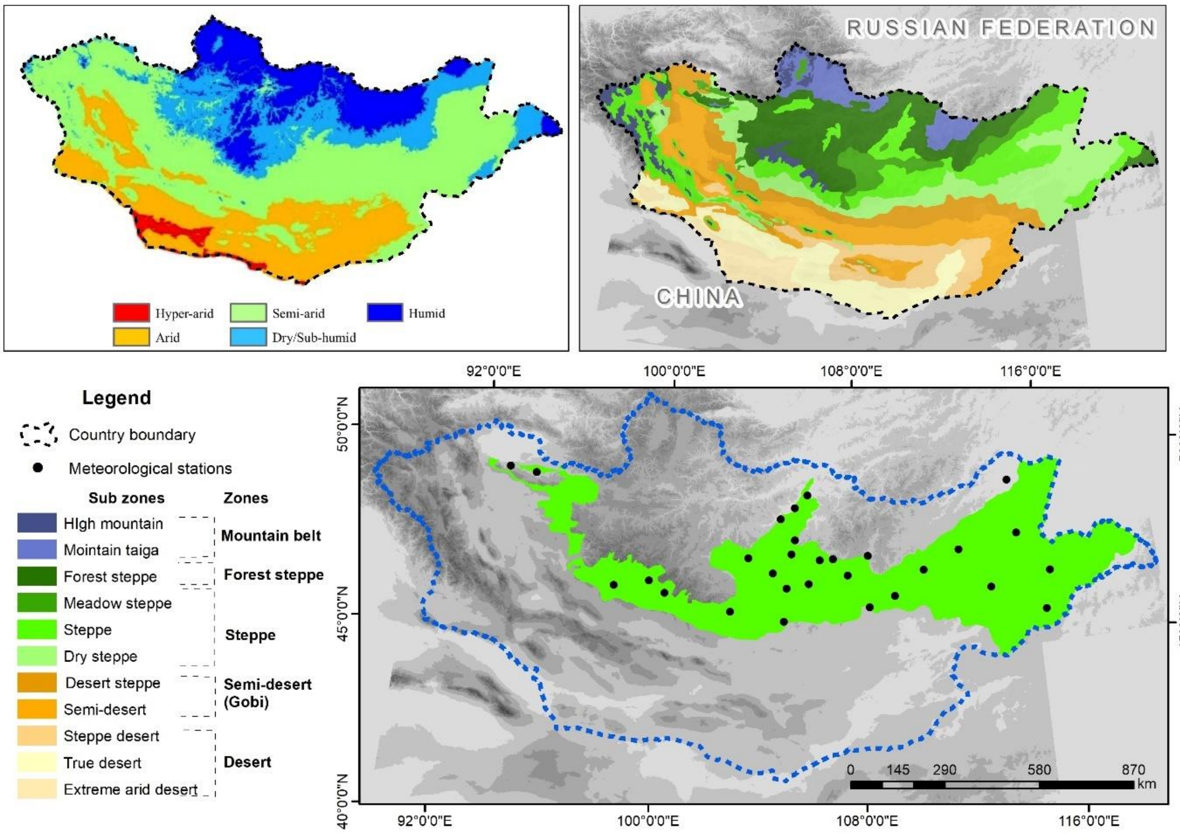

Figure 1. Study area A. Climatic region based on aridity index (Source: Nyamtseren et al. 2018); B. Ecological zones of Mongolia; C. Steppe zone of Mongolia and geographical distribution of meteorological stations in the steppe zone (indicated by black dots).

2.2 Data collection

Sites from the semi-arid steppe zone from the National Agency of Meteorology and Environmental Monitoring's (NAMEM) database were used in this study. Meteorological (air temperature and precipitation) and aboveground biomass (AGB) data have been measured and collected by local meteorological officers, coded and sent to NAMEN through the internet within a certain time and recorded in a meteorological notebook which is sent to NAMEM the following month. Data quality has been checked by the Information and Research Institute of Meteorology, Hydrology, and Environment of Mongolia (IRIMHE). The monitoring network includes 29 meteorological stations distributed in the semi-arid steppe zone in Mongolia (Fig. 1C). In this study, monthly average air temperature, precipitation, and aboveground biomass (AGB) (2000-2020) from this network were used.

2.3 Data measurements

2.3.1 Air temperature

In Mongolia, near-surface air temperature (here air temperature) is measured in two different ways: a) using a thermometer in a Stevenson screen which protects instruments from outside sources, while allowing air to circulate freely around them, and b) automatic weather stations (AWS) at 2 meters' height (Fig. 2). In cases where the automatic station is interrupted, measurements should be made by an observer using a thermometer.

At each meteorological station, the air temperature is measured eight times during the day (at 02:00, 05:00, 08:00, 11:00, 14:00, 17:00, 20:00 and 23:00 local time) and recorded by observation. After observations, the recorded data are transmitted to NAMEM using meteorological codes. The unit used for temperature measurements is degrees Celsius (°C). The automatic meteorological stations currently used in Mongolia are semi-automatic. In other words, the measurements are performed continuously and automatically, but later recorded, coded, and transmitted to NAMEM by the observer.

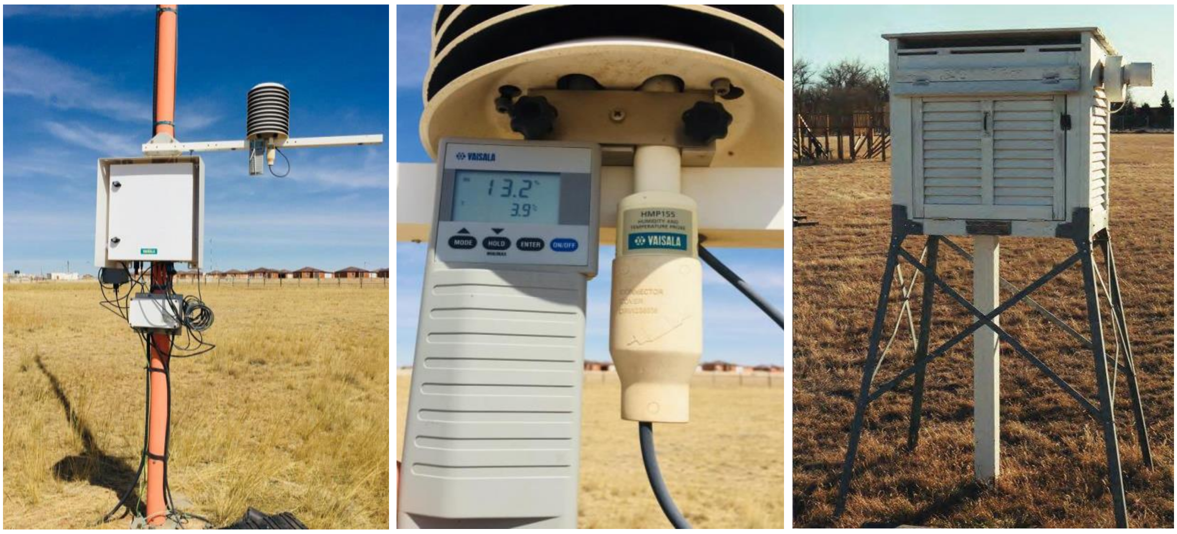

Figure 2. From left: MAWS301, the automatic weather station's data logger; an air temperature sensor (photos: G. Odbayar, B. Byambadorj, 2019); and a Stevenson screen (photos from Ryberg et al. 2009).

2.3.2 Precipitation measurement

The rain gauge is operated manually by the observer and measures the volume of precipitation collected in a vessel with a standardized size (Fig. 3). Rainwater enters through the orifice and accumulates in the cylindrical vessel. The amount of precipitation is measured using a rain-measuring glass. The scale is graduated in millimetres based on the size of the rain gauge orifice. The observer takes measurements using the rain-measuring glass.

Figure 3. Photos of the Tretyakov rain gauge. (Photos: from Ryberg et al. 2009).

2.3.3 Measurement of aboveground biomass

At each meteorological station, vegetation data was collected during the plant growing season to monitor plant growth in two comparable areas, fenced and unfenced (Fig. 4). At each site, a 25 m × 25 m area was fenced with a fence tall enough to exclude large animals. The sampling area outside the fence was similar in size and was surrounded by natural small stones for recognition.

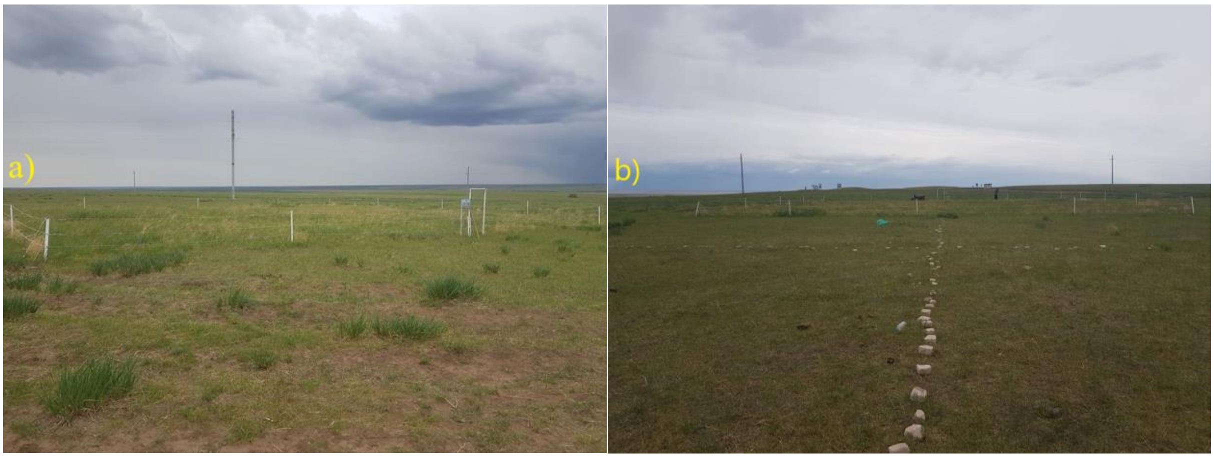

Figure 4. An example of a sampling site at Khalkhgol station. (a) A 25 x 25 m exclosure, here the fenced plot is viewed from the south; (b) unfenced plot viewed from the west.

The same sampling procedure was carried out within and outside the fence. The area was divided into four blocks (Fig. 5), and within each of the four blocks, aboveground biomass (AGB) was collected in a 1 m^2 sampling plot. The sampling started in spring when average vegetation height had reached 3 cm and stopped in autumn when plants had completely withered after the plant growing season. The AGB samples were air-dried and the total AGB was calculated from the combined 4 m^2 and subsequently converted into c/ha. The sampling was made on the 4th, 14th, 24th days of each month within the fenced plots (Fig. 5), but only on the 25th day of each month at the grazed sites.

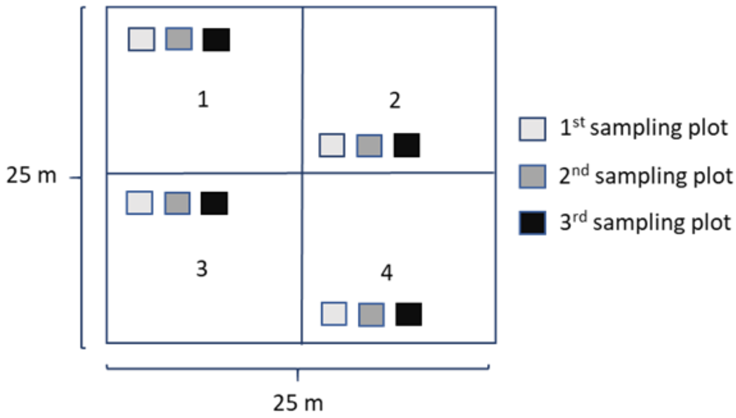

Figure 5. Sampling procedure for aboveground biomass in the fenced plot at each study area within a month. In unfenced plots, only the 1st sampling plot was collected.

2.4 Calculation of the drought index

The Standardized Precipitation Evapotranspiration Index (SPEI) is a drought index based on precipitation and potential evapotranspiration (PET) (Vicente-Serrano et al. 2010). The SPEI uses the monthly difference between precipitation and potential evapotranspiration, and it represents a climatic water balance (Thornthwaite 1948) that is calculated at different time scales to obtain the SPEI. SPEI has six classes and they correspond to conditions from extreme drought to wet (Table 1) according to Vicente-Serrano et al. (2010). See details on calculating SPEI in Appendix 1.

Table 1. Drought classification based on the Standardized Precipitation Evapotranspiration Index (SPEI). (Source: Vicente-Serrano et al. 2010).

SPEI values	Wet/Drought category
≥ 0.5	Wet
-0.49 – 0.49	Near normal
-0.99 – - 0.50	Mild drought
-1.49 – -1.00	Moderate drought
-1.99 – -1.50	Severe drought
≤ -2.0	Extreme drought

SPEI index was calculated using the R statistical program, package SPEI (http://cran.r-project.org/web/packages/SPEI) developed by Beguería and Vicente-Serrano, 2017. PET was calculated using the Thornthwaite equation for one month (SPEI1) and three months (SPEI3) intervals.

2.5 Data analysis

2.5.1 Description of drought conditions during the study period

To assess drought conditions, SPEI was calculated for two different time scales for each site and each year, that is one-month (SPEI1) and three-months (SPEI3). To explore which values of SPEI1 and SPEI3 better detected the effects of drought on pasture production, Pearson's linear correlation was calculated to assess the correlation between the different values of SPEI1, SPEI3, and aboveground biomass. The average values of SPEI1 June-August and SPEI3 in August performed better and obtained more similar patterns and was more strongly correlated with aboveground biomass than any other time indices of SPEI3 and SPEI1. For all stations, the average correlation coefficient between the AGB and SPEI3 of August and the average of SPEI1 June-August was around 0.5, while the remaining correlation coefficients were 0.16-0.45. Hence, SPEI3 in August and the average of June-August SPEI1 are both useable. For further analyses in the current study, average values of SPEI1 in June-August ($SPEI1_{J-A}$) were used.

Within the study period, the area of the semi-arid steppe affected by drought was assessed by $SPEI1_{J-A}$. The drought affected area was calculated as the percentage of stations (out of 29 stations) showing indications of drought.

To assess drought duration within the season, I used monthly SPEI1 values in June, July, and August. Drought duration was defined as the number of months with drought. That is one, two, and three months for June to August, and the number of events were counted for each station for drought frequency for the period 2000-2020.

2.5.2 Aboveground biomass trend

A linear trend analysis was carried out on the aboveground biomass for both non-grazed and grazed plots. These trends were then related to the drought index ($SPEI1_{J-A}$). Within a year, the AGB of 24th of August in the non-grazed plots and AGB of 25th of August in the grazed plots was considered the maximum biomass for each year. Therefore, out of 29 meteorological stations in the semi-arid steppe zone, data from 15 stations was used due to data quality and data availability.

2.5.3 Effects of drought and grazing on aboveground biomass

The effects of drought, grazing, and their interaction on the plant aboveground biomass in the current and the following year were analysed using the linear mixed effect models (LMM) at the significance level of $p < 0.05$. In the models, I included as response variable the aboveground plant biomass in a specific year, and as predictor variables the interaction between the intensity of drought in the same or the previous year, and grazing. The interaction enables testing of whether the responses of aboveground biomass to the intensity of drought depends on the presence or absence of grazing. I included the effect of year and the identity of the station as crossed random factors in the model, to account for non-independence in the data (i.e., measurements were taken within the same year for all stations, and repeatedly within the same station). Thus, the models were:

aboveground biomass ~ intensity of drought*grazing + (1|year) + (1|station)

Statistical analyses were performed in the R statistical program, using the *lme4* package (https://cran.r-project.org/web/packages/lme4/index.html) (Bates et al 2015).

3. RESULTS

3.1 Drought condition

3.1.1 Drought extent, intensity, frequency, and duration

During the study period, the semi-arid steppe zone has experienced droughts in most years at some sites but with different intensities, duration, and spatial distribution. For example, in some years most areas were affected by droughts in April-September, in some years only in August-September, and in some years only a certain part of the region was affected by drought while the rest experienced no drought. The semi-arid steppe zone experienced extensive droughts in 2002 and 2007 (Fig. 6) covering almost 70% of the steppe zone with 2.3% extreme, 24-28% severe, 24-25% moderate, and 12.6-14.9% mild drought. The least intense drought occurred in 2012-2013 which covered 4.6-5.7% of the zone with mild to moderate drought.

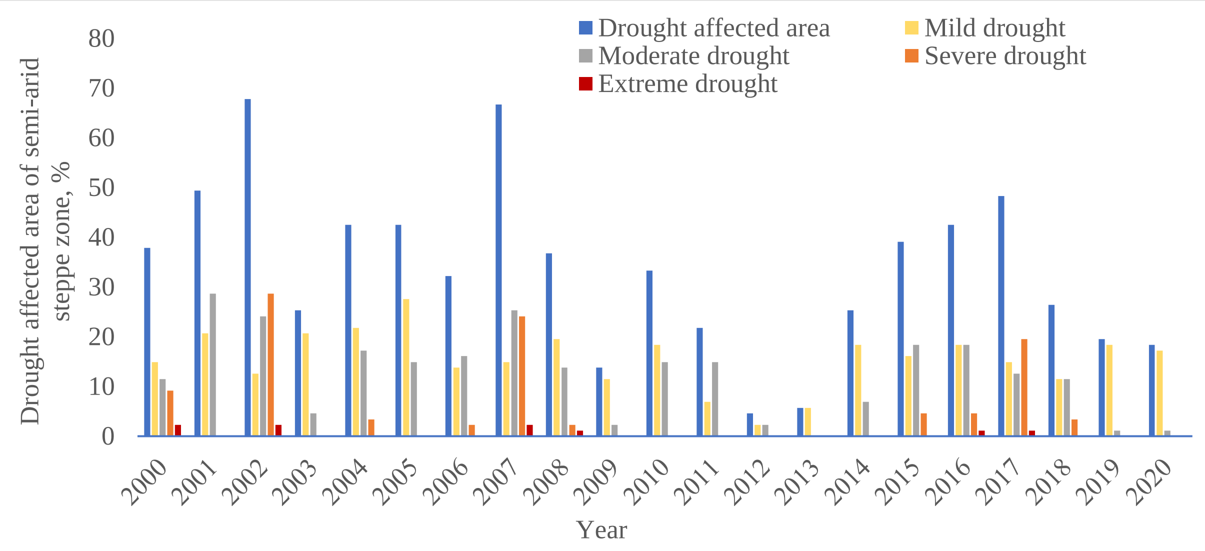

Figure 6. Percentage of meteorological stations in the semi-arid steppe zone in Mongolia that show indications of drought using SPEI1$_{J\text{-}A}$ averaged over 29 stations in 2000-2020.

During the study period, the semi-arid steppe zone was mostly affected by mild to moderate drought. There were severe and extreme droughts 10 times or less.

During the first decade of the study period (2000-2010) the frequency and intensity of droughts was higher than in the following decade (2011-2020; Fig. 7). The period characterized by wet years was 2012-2013 and for dry years 2002 and 2007 (Fig. 7), with other years characterized by normal or near-normal conditions in the steppe zone.

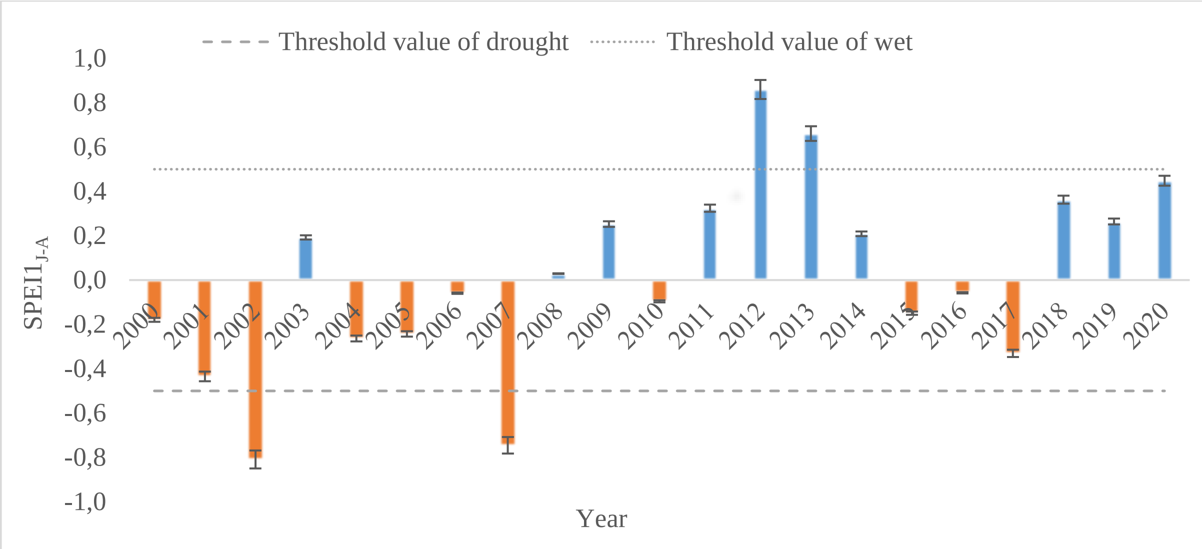

Figure 7. $SPEI1_{J-A}$ averaged over 29 stations for the study period, 2000-2020. The dashed horizontal line shows the threshold value of the drought (orange bars), the dotted line shows the threshold value of the wet condition (blue bars) as described in Table 1**Table**.

Drought frequency based on $SPEI1_{J-A}$ during the study period showed that most areas were affected by drought 3-4 times and there were indications that drought in the semi-arid steppe zone occurred two times every 10 years or once in every five years during the study period.

Most places were affected by drought events 20 times during the last 21 years. One-month duration droughts occurred 7-13 times, two-month droughts occurred 1-7 times and three-month droughts 1-4 times in the period 2000-2020. This shows that droughts lasting for two and three months in a row were infrequent.

3.2 Aboveground biomass trend in the steppe zone

Between the years 2000 and 2020, the aboveground biomass pattern was similar in the non-grazed and grazed plots. Both had a trend with increasing biomass, but the plots protected from grazing had more biomass (Fig. 8). As can be seen from Figure 8, the difference in biomass between non-grazed and grazed plots was larger in wet years (2012, 2013, 2014, 2020) and reached almost the same level in drought years (2000, 2001, 2004, 2007).

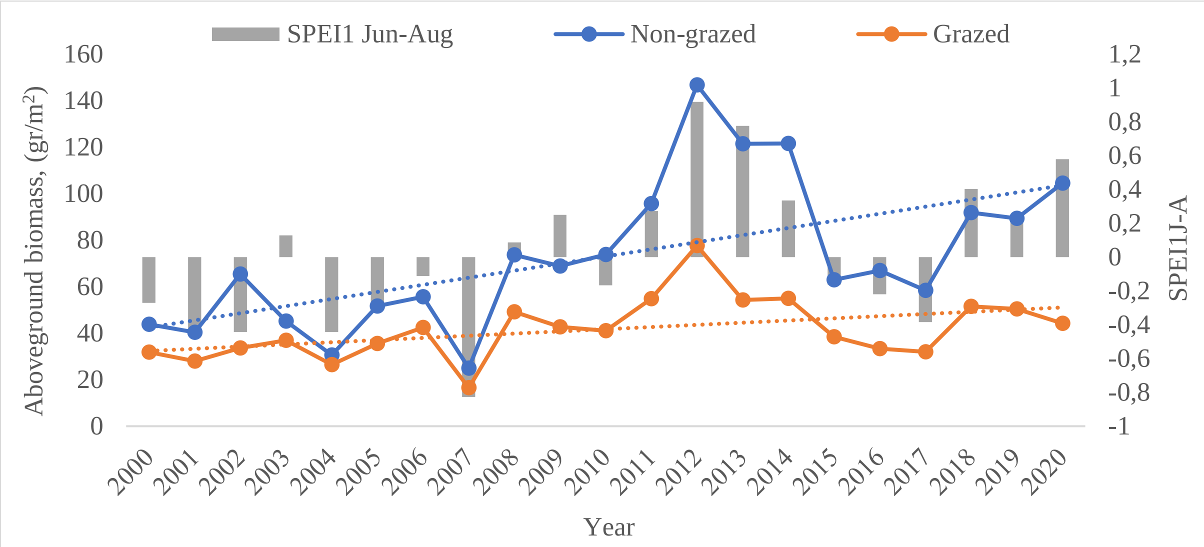

Figure 8. Aboveground biomass in grazed and non-grazed plots (left y-axis) and drought condition (right y-axis) trend, AGB and SPEI1$_{J\text{-}A}$ were averaged over 15 stations for 2000-2020.

In addition, the aboveground biomass fluctuation was highly dependent on drought conditions, especially in non-grazed plots.

3.3 The effect of drought and grazing on biomass

The relationship between the current year's drought intensity and aboveground biomass was negative in both non-grazed and grazed plots. However, the strength of the response differed depending on whether the area was being grazed or not (Fig. 9). From the graph, we can see that the response of biomass to drought was stronger in the non-grazed plot than in the grazed plot.

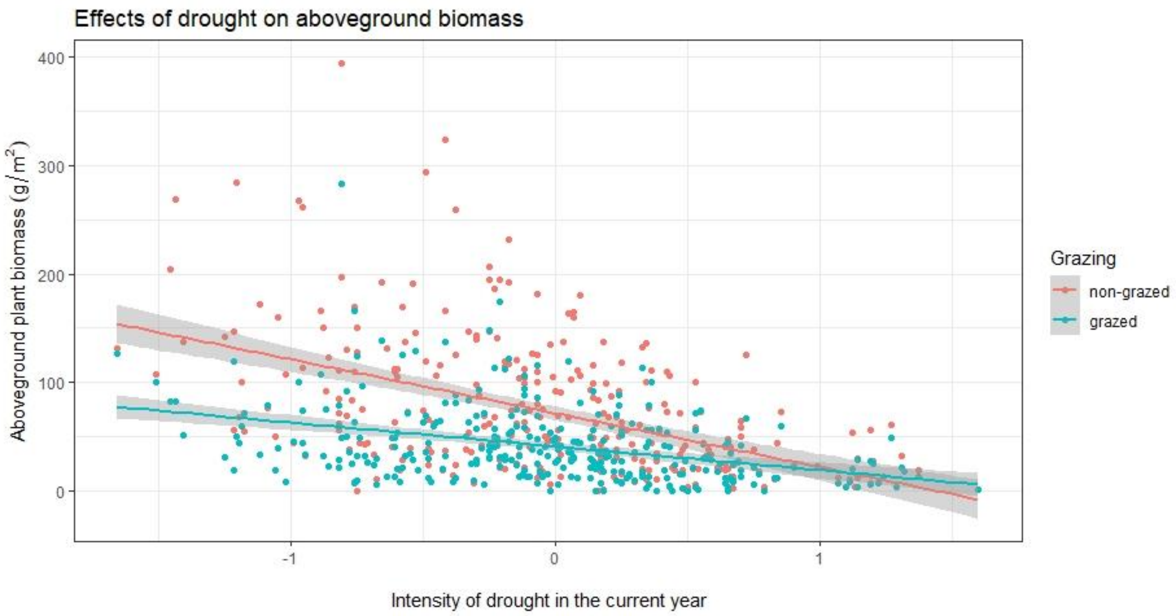

Figure 9. Effect of drought on aboveground biomass in the grazed and non-grazed plot in the current year.

A linear mixed effect model (LMM) was used to test the combined effect of drought and grazing on the plant aboveground biomass. The model showed that the interaction between grazing and the intensity of drought was highly significant in the current year (LMM; t-value = 5.73, $p < 0.001$), indicating that the response of aboveground biomass to the intensity of drought differed between grazed and non-grazed areas.

However, the strength of this effect on non-grazed plots is twice as strong as for grazed plots (the estimate in this model (-4.46) is twice as big as in the model for grazed areas (-2.20)).

A similar pattern was found when the relationship between the previous year's drought (drought intensity) and the aboveground biomass was observed (Fig. 10). The previous year's drought intensity had a negative effect on the current year aboveground biomass in the non-grazed plot while there is no effect in the grazed plot.

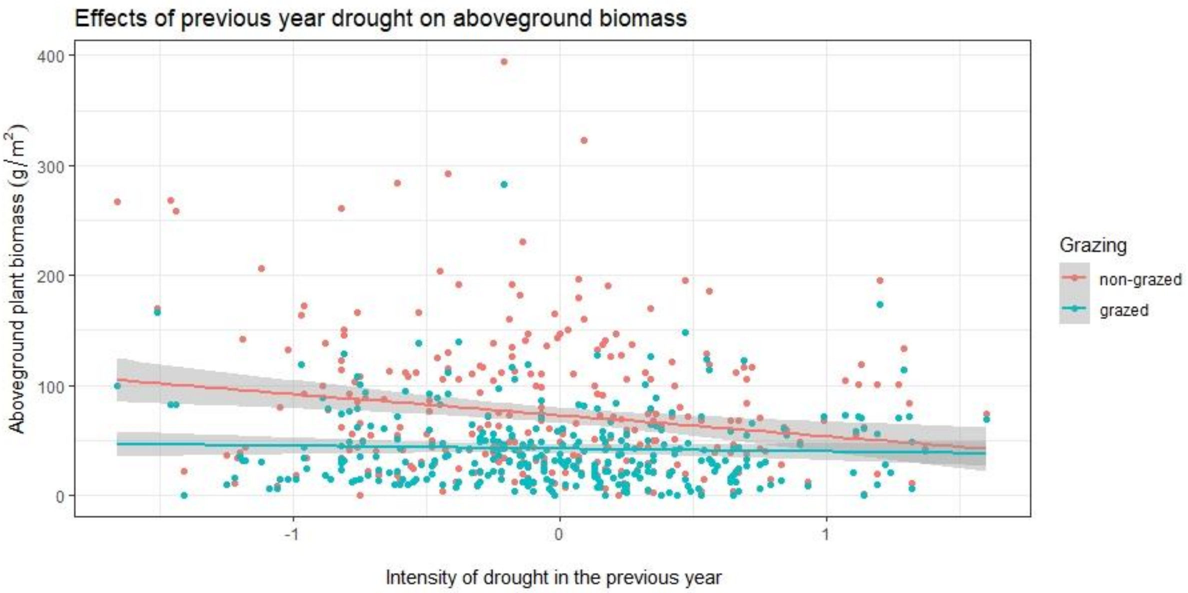

Figure 10. The previous year's effect of drought on aboveground biomass in the grazed and non-grazed plot.

To test the combined effects of the previous year's drought intensity and grazing, a similar model (LMM) was used. The result showed that the interaction between the previous year's intensity of drought and grazing was highly significant (t-value = 3.24, $p < 0.01$), indicating that the response of aboveground biomass to the previous year's intensity of drought differed between grazed and non-grazed areas.

When the effect of the previous year's drought intensity on the aboveground biomass in the non-grazed and grazed plots were separately tested with LMM, the result showed that the effect of the previous year's drought intensity does not influence biomass in the grazed plots (t-value = 0.16, $p = 0.87$) and has a small impact on biomass in the non-grazed plot as it is not statistically significant, although marginal (t-value = -1.86, $p = 0.06$).

The summary of the test results is shown in Table 2. The interaction of drought and grazing was significant for both the current and previous year's drought, while the impact of the previous year's drought was not significant for AGB. For the current year, impact of drought was significant for both grazed and non-grazed plots.

Table 2. Results of the linear mixed effect model for the effects of current year drought, grazing and their interaction on AGB, and the effects of previous year drought, grazing and their interaction on AGB during the study period. The p-value is significant when < 0.05.

	Current year			**Previous year**		
	P value	**T value**	**Estimates**	**P value**	**T value**	**Estimates**
Drought*Grazing~AGB (total)	< 0.001	5.73	-4.58	< 0.01	3.24	-1.23
Drought~AGB (grazed)	< 0.001	-9.4	-2.23	0.87	0.16	0.5
Drought~AGB (non-grazed)	< 0.001	-9.04	-4.45	0.06	-1.86	-1.1

4. DISCUSSION

4.1.1 Drought condition

In the past, both the frequency and severity of drought have increased in Mongolia (Nandintsetseg & Shinoda 2013; MET 2018; Natsagdorj & Munkhbat 2020; Nandintsetseg et al. 2021). Most of these studies were based on long-term data which started during the period 1940-1975 and used different drought indices, including SPEI, to assess drought conditions. The increase of drought conditions was intense in the 2000s (Natsagdorj & Munkhbat 2020), and drought in 2000 and 2002 together with 2015 caused significant socio-economic losses in the country (MET 2018). In general, intensities of drought comparable to those observed since 2000 have not occurred between 1961 and 1999 (Natsagdorj & Munkhbat 2020). Increasing drought intensity is slightly higher in central and eastern Mongolia than in other regions. The increase in drought conditions has particularly occurred in the forest-steppe and eastern steppe regions (Natsagdorj & Munkhbat 2020; Nandintsetseg et al. 2021).

In this study, the drought condition decreased slightly in the second half of the study period (2011-2020) compared to the first decade (2000-2010); the most extensive and intense drought occurred in 2002 and 2007 in the semi-arid steppe zone in Mongolia. Therefore, when the 2000s were considered the driest period of 1961-2020 (Natsagdorj & Munkhbat 2020), the decreasing trend of drought in 2000-2020 can be in line with previous studies.

Moreover, most of the drought events occurred within one month with a mild to moderate intensity in Mongolia in 1965-2010, while the longest and most severe pasture drought occurred during 2000–2001, 2006–2007, and 2017 (Nandintsetseg & Shinoda 2013, Natsagdorj & Munkhbat 2020). My results agreed with these.

4.1.2 Biomass trend

Some studies have shown that drought frequency and heat stress on pasture were increasing, at the same time plant, aboveground biomass in non-grazed plots have increased in Mongolia (Bat-Oyun et al. 2016; Natsagdorj & Munkhbat 2020). However, when the multi-year series of aboveground biomass data were divided into two sections, 1974-2002 and 2003-2015, two distinct trends became apparent, a decline in the first period and growth in the second period (Natsagdorj & Munkhbat 2020). This is in line with the results of my research that aboveground biomass has slightly increased in both grazed and non-grazed plots during 2000-2020.

The increase in aboveground biomass may result from the constant levels of rainfall since 2008, and at the same time, the plant growing season has become slightly longer resulting in increased temperature that influences the vegetation (Natsagdorj & Munkhbat 2020). On the other hand, overgrazing has led to changed vegetation composition resulting in reduced palatable plants and increased unpalatable plants (Natsagdorj & Munkhbat 2020). Nevertheless, the total aboveground biomass of pasture vegetation may increase.

The difference between non-grazed and grazed plots biomass increased in wet years and reached almost the same level in the drought years in this study. This is in line with another study in Mongolia, in which grazing significantly reduced aboveground biomass in the wet years compared to the drought years (Bat-Oyun et al. 2016).

4.1.3 Effects of drought and grazing on aboveground biomass

The combined effects of current year drought and grazing had a significant negative influence on the aboveground biomass, and it was stronger when the vegetation was protected from grazing (Fig. 9). The difference between grazed and non-grazed plots increased in wet years but almost disappeared in severe drought conditions (Fig. 8). The decline of the aboveground biomass as a response to drought was more pronounced when the area was protected from grazing. Thus, the aboveground biomass in the grazed plot was more resilient to drought than in the non-grazed plot. This means grazing has affected the response of vegetation to drought. However, how they affect each other is complex and a better explanation may be found at a more detailed level of biomass.

Since this study looked exclusively at total biomass it is not possible to interpret the results at the species level. Studies have shown that species diversity is generally higher under moderate levels of grazing due to grazers suppressing dominant species (Pulungan et al. 2019). On the other hand, under a long-term heavy grazing regime (overgrazing), grazing has affected species composition resulting in changes from palatable to unpalatable species (Bat-Oyun et al. 2016).

5. CONCLUSIONS

- The SPEI index was useful in assessing drought conditions and had a good relationship with aboveground biomass in the non-grazed plots.
- Within the study period, a trend was identified that the aboveground biomass slightly increased while drought conditions slightly decreased in the steppe zone.
- The drought significantly reduced aboveground biomass, and the combined impact of the current year drought intensity and grazing on aboveground biomass were significant. Therefore, grazing affected the response of aboveground biomass to drought.

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APPENDIX I

The **Standardized Precipitation Evapotranspiration Index (SPEI)** is a drought index based on precipitation and, potential evapotranspiration (PET) (Vicente-Serrano et al. 2010). Temperature is included in the PET component. SPEI is based on a precipitation-based drought index, the standardized precipitation index (SPI). The SPEI uses the monthly difference between precipitation and PET, and it represents a climatic water balance (Thornthwaite 1948) that is calculated at different time scales to obtain the SPEI. The SPEI identifies both wet and dry conditions (Vicente-Serrano et al. 2010).

SPEI uses the Thornthwaite equation (Thornthwaite 1948) which is the simplest approach to calculate PET (mm) and only requires data on monthly average temperature.

$$PET = 16K\left(\frac{10T}{I}\right)^{m} \qquad (1)$$

Where T is the monthly-mean temperature (°C); I is a heat index calculated as the sum of 12 monthly index values *i*; the latter being derived from mean monthly temperature using the formula:

$$i = \left(\frac{T}{5}\right)^{1.514} \qquad (2)$$

m is a coefficient depending on *I*; $m = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.79 \times 10^{-2}\,I + 0.492$; and *K* is a correction coefficient computed as a function of the latitude and month:

$$K = \left(\frac{N}{12}\right)\left(\frac{NDM}{30}\right) \qquad (3)$$

Here *NDM* is the number of days of the month and *N* is the maximum number of sun hours, which is calculated using $N = \left(\frac{24}{\pi}\right)\omega_s$, where ω_s is the hourly angle of sun rising, which is calculated using $\omega_s = arccos(-tan\varphi tan\delta)$, where φ is the latitude in radians and δ is the solar declination in radians, calculated using $\delta = 0.4093sen\left(\frac{2\pi J}{365}\right) - 1.405$, where J is the average Julian day of the month.

With a value for PET, the difference between the precipitation *P* and *PET* for the month *i* is calculated using the following equation.

$$D_i = P_i - PET_i \qquad (4)$$

which provides a simple measure of the water surplus or deficit for the analysed month. The calculated D_i values are aggregated at different time scales. The difference $D_{i,j}^k$ in a given month *j* and year *i* depends on the chosen time scale *k*. For example, the accumulated difference for one month in a particular year *i* with a 12-month time scale is calculated

$$X_{i,j}^k = \sum_{l=13-k+j}^{12} D_{i-1,l} + \sum_{l=1}^{j} D_{i,l}, \qquad \text{If } j < k \tag{5}$$

And

$$X_{i,j}^k = \sum_{l=j-k+1}^{j} D_{i,l}, \qquad \text{if } j \geq k, \tag{6}$$

where $D_{i,l}$ is the P – PET difference in the first month of year *i*, in millimeters. The log-logistic distribution is used to transform the original values for standardizing the D series to obtain the SPEI. The probability density function of a three-parameter log-logistic distributed variable is expressed as

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \tag{7}$$

where α, β, and γ are scale, shape, and origin parameters, respectively, for D values in the range ($\gamma > D < \infty$). The probability distribution function of the D series, according to the log-logistic distribution, is given by

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \tag{8}$$

With $F(x)$ the SPEI can easily be obtained as the standardized values of $F(x)$. For example, following the classical approximation of Abramowitz and Stegun (1965),

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{9}$$

where $W = \sqrt{-2\ln(P)}$ for $P \leq 0.5$, P being the probability of exceeding a certain D value, $P = 1 - F(x)$. If $P > 0.5$, then P is replaced by $1 - P$ and the sign of the resultant SPEI is reversed. The constants are: C_0=2.515517, C_1=0.802853, C_2=0.010328, d_1=1.432788, d_2=0.189269, d_3=0.001308. The average value of the SPEI is 0, and the standard deviation is 1. The SPEI is a thus standardized variable, and it can therefore be compared with other SPEI values over time and space. A SPEI of 0 indicates a value corresponding to 50% of the cumulative probability of D, according to a Log-logistic distribution.