Journal of Arid Environments 70 (2007) 94–110

Journal of Arid Environments

www.elsevier.com/locate/jaridenv

Pasture yield response to precipitation and high temperature in Mongolia

E. Munkhtsetseg*, R. Kimura, J. Wang, M. Shinoda

Arid Land Research Center, Tottori University, Hamasaka 1390, Tottori 680-0001, Japan

Received 29 May 2006; received in revised form 1 November 2006; accepted 30 November 2006

Abstract

Animal-available pasture biomass has been observed and recorded for the past few decades to assess the crucial impact of pasture conditions on pastoral livestock husbandry, which is one of the major industries in Mongolia. This database provided a unique, useful basis for the present correlation analysis between seasonal measures of meteorological variables and pasture yield at three sites in southern Mongolia. Precipitation in July exhibited a high correlation with pasture yield, whereas high temperatures in June and July demonstrated a considerable negative correlation. Consequently, a reduction in precipitation with an increase in high temperature results in a lower yield, whereas sufficient precipitation with a reduction in high temperature results in greater production. The study also attempted to establish a new aridity index. The pasture yield correlated closely with the new aridity index. This implies that aridity has the potential to restrain grass growth in Mongolia.

Keywords: Animal-available pasture biomass; Aridity index; Desert ecosystems; Mongolian grassland

1. Introduction

Water stress is the most crucial environmental stress for vegetation in dry lands due to the low amount of precipitation and high rate of evapotranspiration. The high variability in frequency and amount of rainfall, combined with high evaporative demand, create restraints for vegetation growth and yield in semi-arid and arid regions. Meteorological

---

*Corresponding author. Tel.: +81 857 21 7031; fax: +81 857 29 6199.
E-mail address: munkhuu@alrc.tottori-u.ac.jp (E. Munkhtsetseg).

doi:10.1016/j.jaridenv.2006.11.013

analyses of precipitation are common in the assessment of drought occurrence and aridity, whereas there have been few studies on dry-spell events and high temperature. It is possible that the frequency and length of dry spells affect vegetation growth without a significant reduction in the seasonal precipitation. Several studies have addressed the influence of dry spells on vegetation growth in semi-arid and arid regions. Reddy (1983) pointed out that crop production potential is influenced not only by rainfall but also by variability, such as dry spells in India. Barbe and Lebel (1997) noted that lasting drought is associated with an increase in dry-spell events, rather than with a decrease in the mean event rainfall, whereas Shinoda et al. (1999) demonstrated that a reduced frequency of continuous rainfall characterized the drought conditions in the Sahelian region. Lal et al. (1998) found that prolonged dry spells negatively affected vegetation growth in India. Barron et al. (2003) reported that maize growth in east Africa was affected by dry spells. Single and multiple dry-spell events, coupled with high temperatures, appear to intensely influence vegetation growth as high temperatures have resulted in a reduction in fertility (Polowick and Sawhney, 1985), lower yields (Argarman, 1983; Lomas, 1988, 1992; Morrison and Stewart, 2002), incomplete phenological phases (Matsumoto et al., 2003) and increased surface resistance (Kimura et al., 2005). Moreover, it is vital to explore the impact of high temperature on vegetation growth as air temperature has been elevating due to climate change.

Mongolia has reason to be concerned about climate change as air temperature has increased over the past 60 years by 1.6 °C (Batima et al., 2005). Most published studies have assessed the impact of inter-annual precipitation changes on vegetation growth in Mongolia. Kondoh and Kaihotsu (2003) found a significant correlation between summer precipitation and the Normalized Difference Vegetation Index (NDVI) in the grasslands of Mongolia. Ni (2003) noted that grass-species richness was positively correlated with precipitation and aridity index (mean annual precipitation divided by mean air temperature plus 10 °C) in southeast Mongolia. Miyazaki et al. (2004) revealed that precipitation in July had the largest influence on vegetation growth in central Mongolia. Zhang et al. (2005) reported a significant difference in yield between drier and moister years and found that air temperature stress-degree-day had a prevailingly negative effect on vegetation growth in northeastern Mongolia. However, neither of these studies investigated the impact of high temperature on pasture yield in Mongolia. The aim of this study was to assess the pasture yield variation due to precipitation and high temperatures. The most common correlation analysis was applied to the time series of pasture yield and climatic variables to assess how individual climatic variables or their combinations relate to the variability of pasture yield. It should be noted that unique, long-term (30-year) databases of yield and climatic variables made it possible to conduct such a statistical analysis. Furthermore, we attempted to establish a new aridity index for the grasslands of Mongolia.

2. Materials and methods

2.1. Site descriptions and materials

Three sites (Mandalgovi, Sainshand and Dalanzadgad) situated in the desert-steppe zone, in the southern part of Mongolia, were selected for this study (Fig. 1). Vegetation features were low yield, a short growing period and sparse vegetation coverage. The

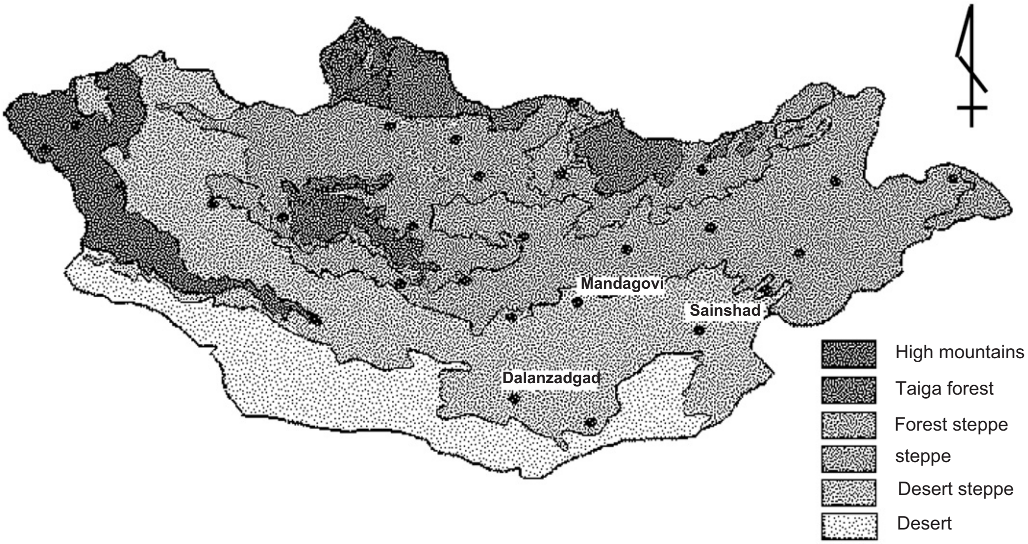

Fig. 1. Vegetation zone map.

dominant grass type covering all the sites was cool-season C3 plants, including species such as *Stipa glareosa* and *Artemisia frigida*. The soil type was brown soil, according to the soil classification system of Mongolia (Nogina, 1978, 1989).

The climatic variables, including maximum/minimum temperatures and precipitation for 1971–2000, were collected by the Institute of Meteorology and Hydrology in Mongolia. The pasture yield (dry biomass) was measured at the local plant observation sites near the meteorological stations for the same period. Fences protected the vegetation in each plant site from grazing. The measurements were performed at 10-day intervals, beginning when the grass height exceeded 3 cm and continuing until the grass reached the senescence stage. The grass biomass was measured in four plots with areas of 1 m^2, while leaving a biomass under a height of 1 cm to assess the animal-available biomass. This is why the measured biomass is called animal-available biomass in Mongolia. There were several gap years in the pasture yield data. Some of the gaps were due to no measurements being taken when the plant heights were less than 3 cm, which was related to low vegetation growth that was attributed to bad climatic conditions during the growing period. Such gaps were considered to have lower yields and were assumed to be equal to 10 kg ha^{-1}. Monthly dry biomass yield will be referred to as dry biomass and seasonal maximum as pasture yield in the following sections.

2.2. Quantification of high temperatures

To assess the impact of high temperatures on grass yield, the high temperature was quantified by occurrence and variation. As expressed in Eq. (1), the high temperatures (H_i) were quantified during a month of the growing season as the sum of the differences between daily maximum temperature ($T_{\max}$) and a threshold temperature (T_{cr}), when a daily maximum temperature exceeded a threshold value on a dry day, i.e. $(T_{\max}-T_{\mathrm{cr}})>0$

and $P = 0$ (P-precipitation)

$$H_i = \sum_{i=1}^{n} (T_{\max} - T_{\mathrm{cr}}), \quad i = 1, \ldots, n. \tag{1}$$

Here, n is the number of days in a month of a growing season.

2.3. Estimation of threshold value

It was necessary to define a threshold above which a temperature value is considered to be a high (extreme) temperature for vegetation growth. The procedure suggested by Morrison and Stewart (2002) was used to determine the threshold value (T_{cr}). A flowchart for determining threshold temperature is provided in Fig. 2. Pasture yield (Y) was assumed to be reduced by H_i, as expressed in

$$Y = Y_{\max} - bH_i, \tag{2}$$

where $Y_{\max}$ is the intercept representing potential yield, and b is a slope angle.

A least squares optimization procedure was applied to a 28–30-year pasture yield database to determine the best values for $Y_{\max}$, b and H_i. This value of H_i was used with $T_{\max}$ to obtain T_{cr} using Eq. (1). The process was iterative and terminated when an estimate of T_{cr} resulted in the lowest sum of the squares of the deviation between the calculated (Y_{est}) and observed yields (Y).

3. Results and discussion

3.1. Monthly variations of precipitation, temperature, dry days and pasture yield

Monthly changes in mean air temperature (T_{mean}) and precipitation (P), averaged from 1971 to 2000 with standard deviations (SDs) during the growing season, are presented in Fig. 3. Monthly maximums of precipitation were recorded in July at Dalanzadgad and Sainshand. A monthly maximum of precipitation was recorded in August at Mandalgovi. The mean air temperatures (T_{mean}) exhibited a peak in July at all the sites.

Monthly variations of dry biomass with SDs are presented in Fig. 4. The seasonal maximum biomass occurred in August at Mandalgovi, whereas the maximum occurred in September at the other two sites. The biomass increased rapidly from June (70 kg ha^{-1}) to August (270 kg ha^{-1}) and then remained nearly constant in September (260 kg ha^{-1}) at Mandalgovi. The seasonal maximum timing and small decline in September at Mandalgovi were also seen in central Mongolia (Miyazaki et al., 2004). A rapid increase occurred from June (50 kg ha^{-1}) to July (130 kg ha^{-1}) at Sainshand, with a slight increasing trend until September (160 kg ha^{-1}). The dry biomass increased almost constantly at Dalanzadgad from May (30 kg ha^{-1}) to September (110 kg ha^{-1}).

Fig. 5 shows a monthly time series of the number of no precipitation days (NPD), averaged from 1971 to 2000 with SDs. The monthly minimum NPD occurred in July with the highest standard deviation. In contrast, the monthly maximum NPD occurred in May with the lowest standard deviation.

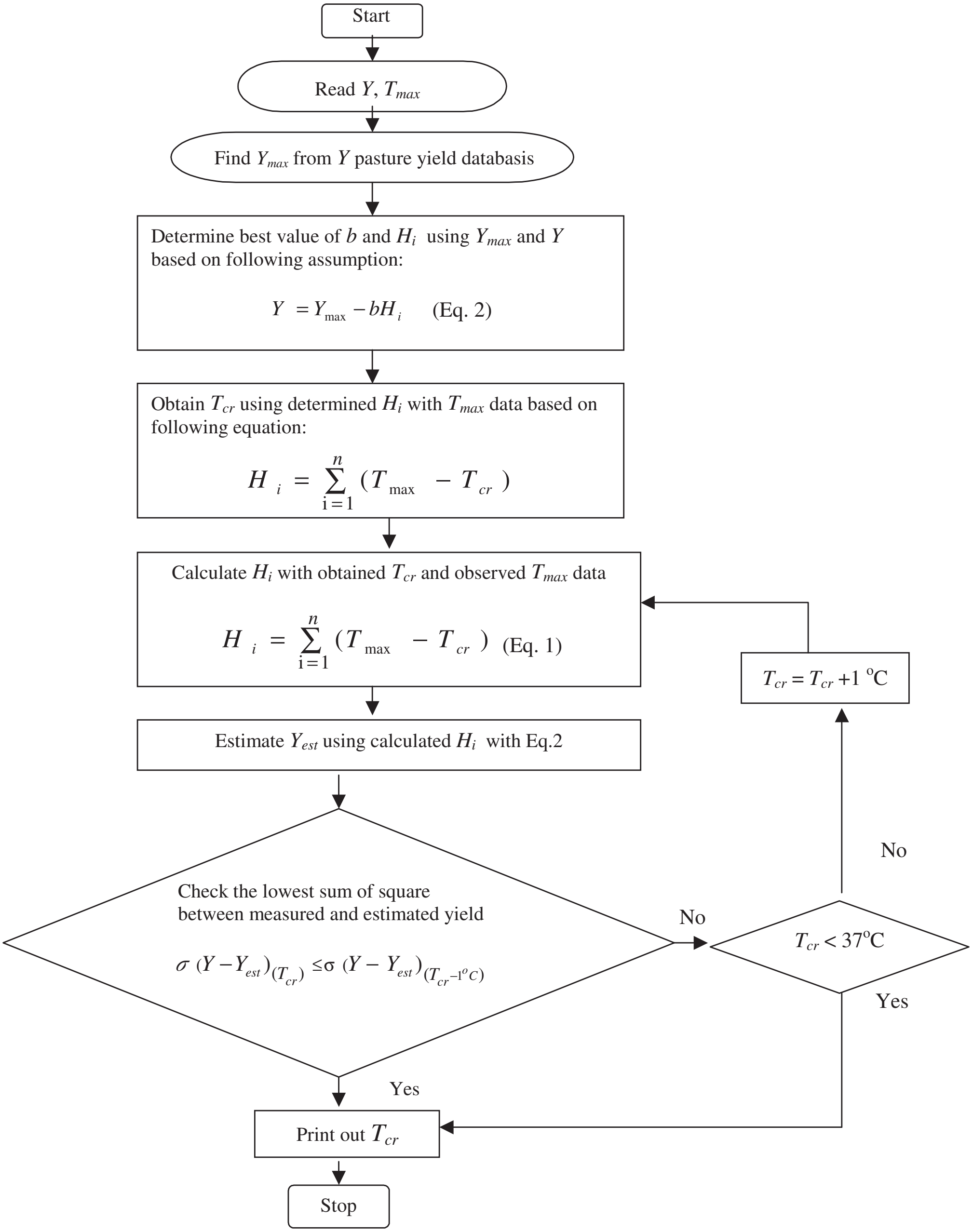

Fig. 2. Flowchart for determining a threshold temperature.

3.2. Relationship between precipitation and pasture yield

Table 1 represents the correlation coefficients between precipitation and pasture yield. This analysis used 28-year data points with a degree of freedom (27). The lower limits for

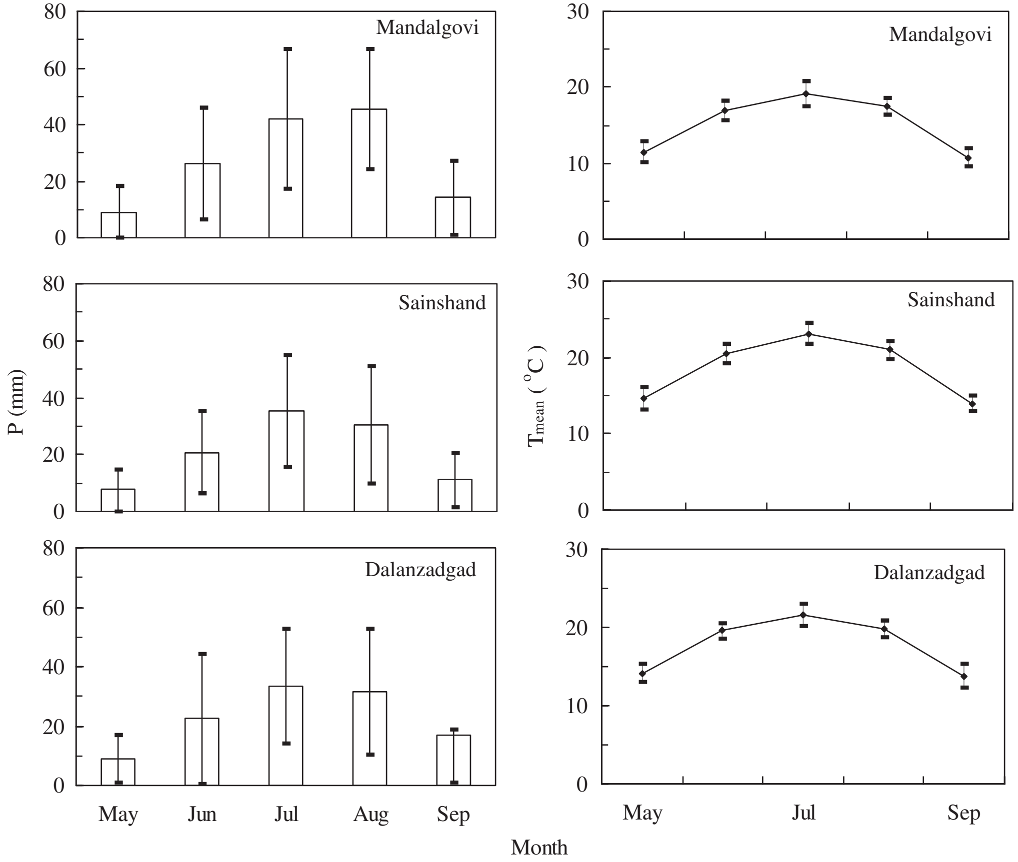

Fig. 3. Seasonal variations of mean temperature (T_{mean}) and precipitation (P) with standard deviations.

significant correlation were 0.479 and 0.375 at the 99% and 95% confidence levels, respectively. Fig. 6 illustrates the relationship between precipitation in July ($P7$) and pasture yield (Y). The results revealed that $P7$ influenced grass growth, which is consistent with the findings in central Mongolia (Miyazaki et al., 2004). Fig. 7 illustrates the relationship between NPD and pasture yield. The NPD in July negatively influenced pasture yield.

3.3. *Response of pasture yield to high temperature*

Table 2 lists the variables of the estimated T_{cr} and averaged H_i from 1971 to 2000 with SDs. The estimated threshold temperatures (T_{cr}) for grass differed from site to site and month to month, although all the sites belong to the desert-steppe zone. This difference among estimated thresholds can be partly explained by plant adaptation to different climatic conditions. Individual plants adjust their physiology and development in response to changes in their environment (Howe and Brunner, 2005). The best measure for evaluation of the importance of an adaptive trait is to assess its effect on fitness, or on well-documented components of fitness, such as seed production, germination, survival and

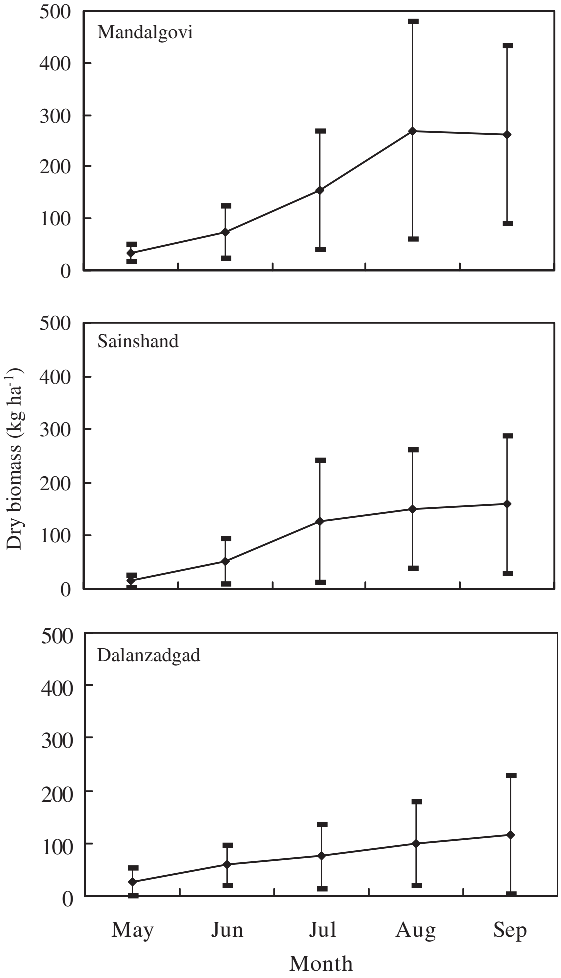

Fig. 4. Seasonal variations of dry biomass with standard deviations.

vegetative biomass (Orr, 1998; Schluter, 2001; Kaweski and Ebert, 2004; Howe and Brunner, 2005). It is likely that a higher T_{mn} corresponds to a high T_{cr}, whereas a lower T_{mn} corresponds to a low T_{cr} (Fig. 8). This implies that grasses that are subjected to a higher mean air temperature are more adapted to high temperatures than those that are subjected to a lower mean air temperature, and so they are more capable of surviving under extremely high temperatures.

Table 3 lists the correlation coefficients between H_i and monthly pasture yield. There were no correlations between the high temperatures and pasture yield at Mandalgovi, with the exception of the correlation between the high temperature in June and dry biomass in July. This may be related to climatic features at Mandalgovi, which is located near the boundary of the transition between steppe and desert-steppe zones. Moreover, Mandalgovi is located at higher latitude than the other two sites, which may be the cause of heat weakness at the site. A slight negative correlation was noticed between the

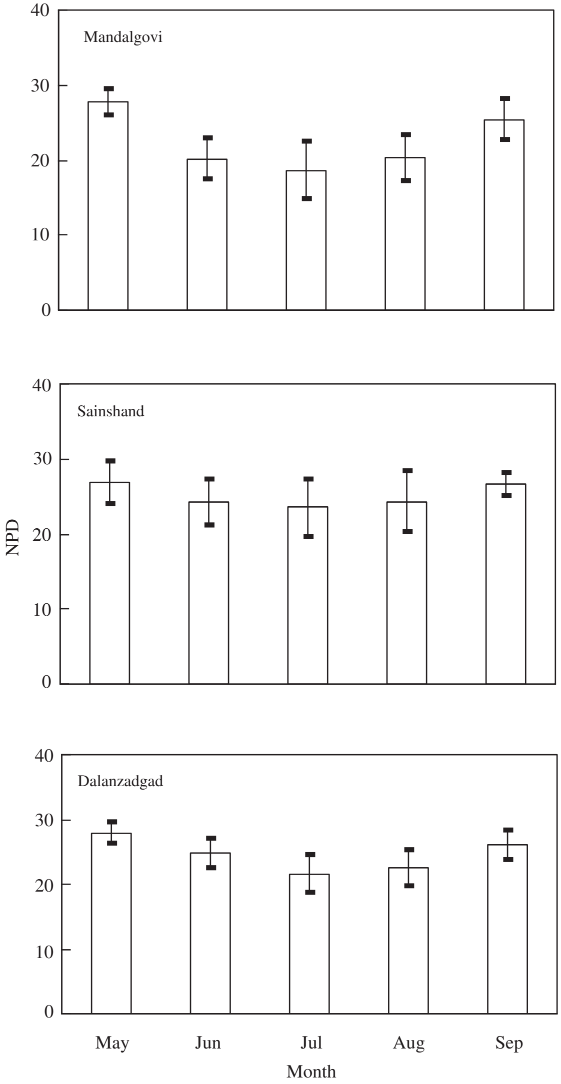

Fig. 5. Seasonal variations of no precipitation days (NPD) with standard deviations.

high temperature in July (H_i 7) and pasture yield at all the sites, whereas no correlation was observed between the high temperature in June (H_i 6) and pasture yield. The H_i depends not only on high temperatures, but also on the frequency of NPD (Eq. (1)). As discussed earlier, the NPD in July has negative effects on pasture yield, which might be resulted that grasses are more responsive to H_i 7 than H_i 6. Accordingly, pasture yield is sensitive to high temperatures in July and may explain why the threshold temperature in July is consistently lower than in June.

The correlations between high temperature and mean temperature are presented in Table 4. Significant positive correlations were found between high temperature and mean temperature. However, no significant correlations were found between mean temperature

Table 1
Correlation matrix of precipitation and pasture yield[a]

Site name	Precipitation	Dry biomass					Pasture yield
		May	June	July	August	September	
Mandalgovi	May	0.46	0.29	0.06	0.22	0.08	0.15
	June		0.02	0.18	0.14	0.05	0.13
	July			**0.64**[c]	**0.69**[c]	**0.42**[b]	**0.60**[c]
	August				0.02	0.07	0.01
	September					0.15	0.01
Sainshand	May	0.27	0.12	0.15	0.25	0.32	0.25
	June		0.08	0.16	0.21	0.20	0.28
	July			**0.45**[b]	**0.60**[c]	**0.57**[c]	**0.62**[c]
	August				0.28	0.23	0.23
	September					**0.45**[b]	**0.41**[b]
Dalanzadgad	May	0.30	0.29	0.34	0.39	0.34	0.39
	June		0.32	0.36	**0.46**[b]	**0.47**[b]	**0.50**[c]
	July			**0.46**[b]	**0.42**[b]	0.36	**0.52**[c]
	August				0.03	0.01	0.05
	September					0.03	0.07

[a] The bold values are significant correlation coefficient.
[b] The 95% significance level.
[c] The 99% significance level.

and pasture yield, whereas negative correlations were found between high temperature and pasture yield. It is likely that high temperatures were responsible for reducing the pasture yield.

3.4. Aridity index

3.4.1. Yield response to aridity in southern Mongolia

Essentially, aridity indices are based on a supply and demand concept of the water-balance equation. For a given region, the annual mean evapotranspiration and run-off rates are regulated primarily by the amount of available energy (the demand) and precipitation (the supply). Therefore, a new aridity index (AI) was established as in Eq. (3); precipitation (P) is the supply and H_i is the demand in southern Mongolia

$$\mathrm{AI} = \frac{P7}{H_i\,6 + H_i\,7}, \tag{3}$$

where $P7$ is the precipitation in July in mm, whereas $H_i\,6$ represents the high temperatures in June and $H_i\,7$ the high temperatures in July.

It is well known that aridity alters vegetation growth. Therefore, the relationships between the new aridity index and pasture yield were examined. The pasture yield (Y) correlated much more closely with AI (associated with combination of $P7$ and H_i) (Fig. 9) than with $P7$ only (Fig. 6). This implies that aridity has the potential to restrain grass growth in southern Mongolia. The results indicate that the pasture yield is enhanced by precipitation and limited by high temperature. Consequently, a little precipitation in July

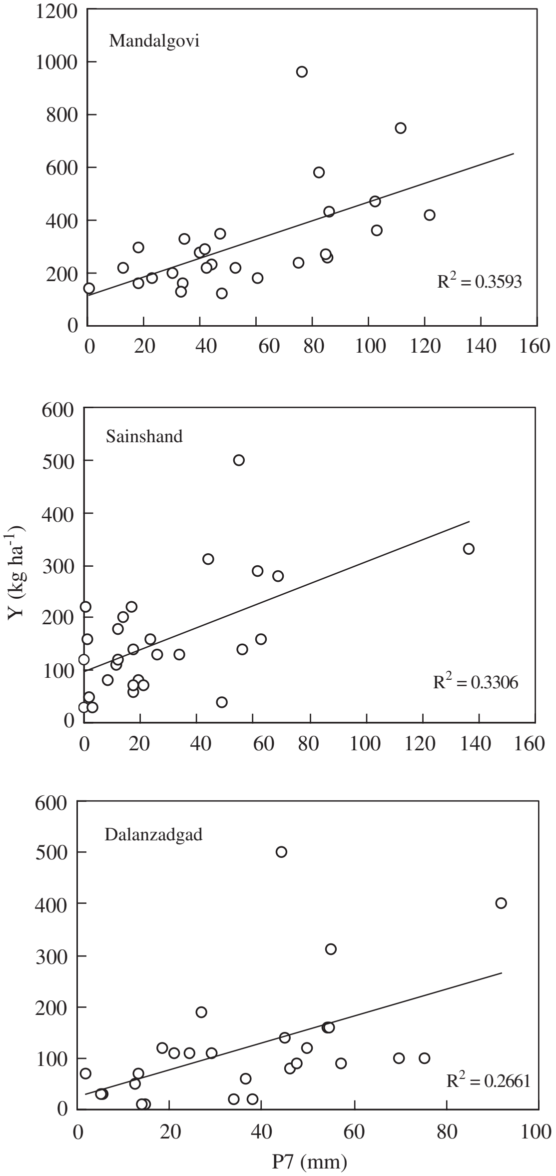

Fig. 6. Relationships between pasture yield (*Y*) and precipitation in July (*P*7).

(*P*7) with an increased high temperature (H_i) results in a lower yield, whereas sufficient precipitation in July (*P*7) with a reduced high temperature (H_i) results in greater production.

3.4.2. Vegetation zonal characteristics of the relationships between yield and aridity

To apply the new aridity index to zonal characteristics, 15 sites in different vegetation zones were selected (Table 5). Seasonal precipitation (P_r) was applied to the new aridity

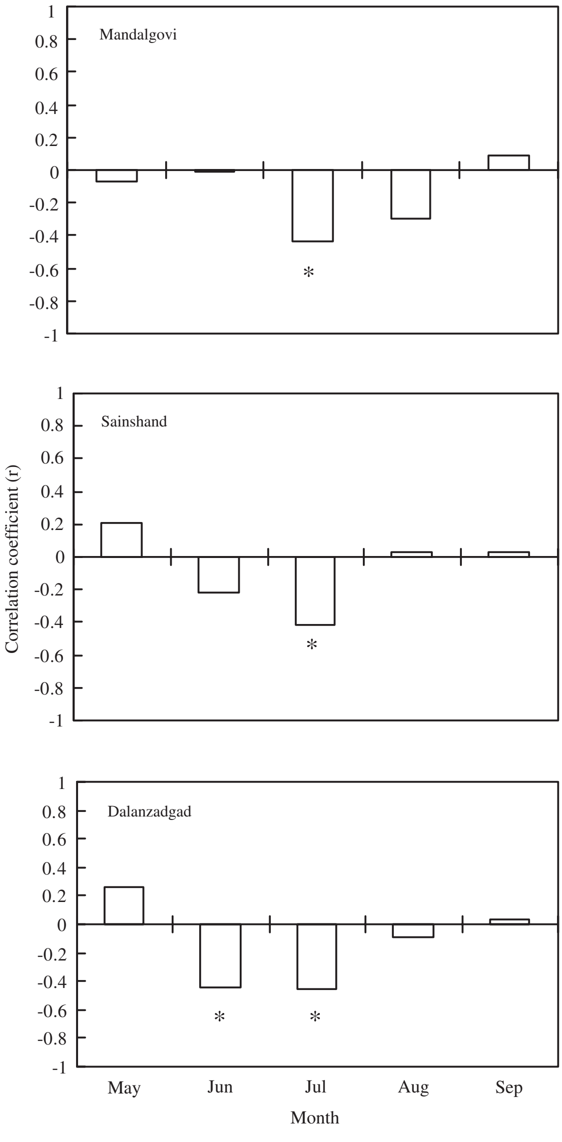

Fig. 7. Autocorrelations of monthly no precipitation days (NPD) for pasture yield (Y). *The 95% significance level. **The 99% significance level.

index formula, as seasonal and annual precipitations are the primary factors that control the spatial distribution of plant activity (Ni and Zhang, 2000; Ni, 2003). The threshold temperature of 30 °C at Dalanzadgad that resulted in the highest correlation between the pasture yield and aridity index was used as the threshold temperature for the 15 sites. Some sites exhibited $H_i = 0$, which makes it difficult to calculate the aridity index (P_r/H_i). Therefore, the new aridity index formula (Eq. (3)) was modified as in Eq. (4). A linear-regression analysis using the least-squares method determined an additional coefficient

Table 2
Determined threshold temperatures among sites

Site name	Month	Determined threshold temperature, (°C) (T_{cr})	H_i averaged from 1971 to 2000	Standard deviation (SDs)
Mandalgovi	June	29.0	7.5	6.7
	July	26.0	49.0	32.0
Sainshand	June	33.0	4.7	5.7
	July	28.0	76.0	37.3
Dalanzadgad	June	30.0	6.4	5.4
	July	30.0	18.4	16.6

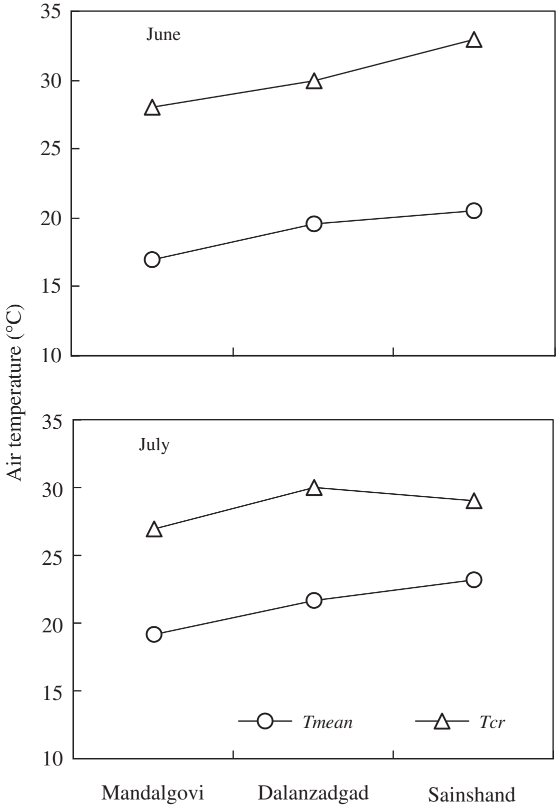

Fig. 8. Threshold temperature (T_{cr}) and their corresponding mean temperature (T_{mean}).

that was equal to 10

$$\mathrm{AI}_z = \frac{P_r}{10 + H_i}, \tag{4}$$

$$H_i = H_i\,6 + H_i\,7, \tag{5}$$

Table 3
Correlation matrix of high temperature and pasture yield[a]

Site name	High temperatures (H_i)	Dry biomass				Pasture yield (Y)
		June	July	August	September	
Mandalgovi	June	−0.365	**−0.572**[c]	−0.360	−0.269	−0.337
	July		−0.353	−0.325	−0.210	−0.342
Sainshand	June	−0.163	−0.286	−0.294	−0.275	**−0.382**[b]
	July		**−0.415**[b]	**−0.540**[c]	**−0.458**[b]	**−0.614**[c]
Dalanzadgad	June	−0.155	−0.362	−0.319	−0.321	**−0.393**[b]
	July		**−0.497**[b]	**−0.417**[b]	−0.379	**−0.455**[b]

[a] The bold values are significant correlation coefficient.
[b] The 95% significance level.
[c] The 99% significance level.

Table 4
High temperature vs. mean temperature[a]

Site name	High temperatures (H_i)	Mean temperature (T_{mean})	
		June	July
Mandalgovi	June	**0.641**[c]	**0.569**[c]
	July		**0.812**[c]
Sainshand	June	0.366	**0.448**[b]
	July		**0.958**[c]
Dalanzadgad	June	**0.626**[c]	**0.452**[b]
	July		**0.779**[c]

[a] The bold values are significant correlation coefficient.
[b] The 95% significance level.
[c] The 99% significance level.

where AI_z is the new aridity index for zonal, P_r represents the total precipitation from May to September, and H_i is the sum of high temperatures in June and July.

To evaluate the sensitivity of AI_z to different hydrological conditions, the relationships between pasture yield and AI_z in a wet year (1993) and a dry year (1999) are illustrated in Fig. 10. The pasture yield is closely correlated with AI_z in both the selected years, whereas precipitation exhibits a lower correlation with pasture yield in a dry year. The new aridity index ranged from 6 to 13 in a wet year but decreased to 0.6–4 in a dry year in the desert-steppe zone (Table 6). In a wet year, aridity indices varied between 21 and 48 for the forest steppe and 24–30 for the steppe zones; in a dry year, aridity indices dropped to 3–12. These results showed that aridity in the forest-steppe, steppe and desert-steppe zones were able to be estimated by this new approach. However, the new aridity index was not applied to the estimation of aridity in taiga forest and high mountain zones, which have a higher soil–water capacity as a result of a colder climate regime than in forest steppe, steppe and deserts steppe zones.

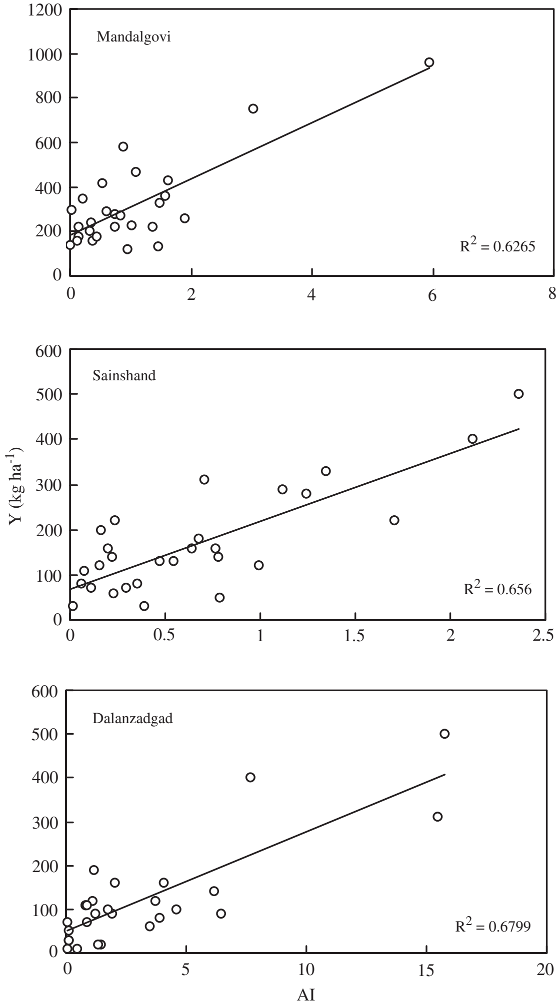

Fig. 9. Relationships between pasture yield (*Y*) and new aridity index (AI) in southern Mongolia.

4. Conclusions

The relationships between climate variables and pasture yield were examined using a long-term database based on southern Mongolia. A significant positive correlation was found between precipitation in July and pasture yield. A considerable negative correlation was observed between high temperature (in June and July) and pasture yield. Pasture yield correlated well with a combination of precipitation and high temperature, much more than with their individual values. These results indicated that the pasture yield is enhanced by precipitation and limited by high temperature. Consequently, a reduction in precipitation with an increase in high temperature results in a lower yield, whereas sufficient precipitation with a reduction in high temperature results in greater production. The study also attempted to establish a new aridity index. The pasture yield correlated

Table 5
Locations of study sites

Vegetation zone	Site name	Lon (deg. min)	Lat (deg. min)	Elev (m)
Forest steppe	Sukhbaatar	106°18′	50°23′	626
	Uliastai	96°82′	47°75′	1751
	Erdenemandal	101°38′	48°53′	1509
Steppe	Dashbalbar	114°38′	49°55′	705
	Arvaiheer	102°78′	46°27′	1813
	Hujirt	102°77′	46°90′	1662
	Choibalsan	114°60′	48°07′	759
	Bayanhongor	100°68′	46°13′	1859
Desert steppe	Hovd	91°65′	48°02′	1405
	Dalanzadgad	104°42′	43°58′	1462
	Mandalgovi	106°28′	45°77′	1393
	Sainshand	110°12′	44°90′	936
	Gurvantes	101°00′	43°20′	1726
	Saihan-Ovoo	103°90′	45°45′	1319
	Zereg	92°82′	47°13′	1152

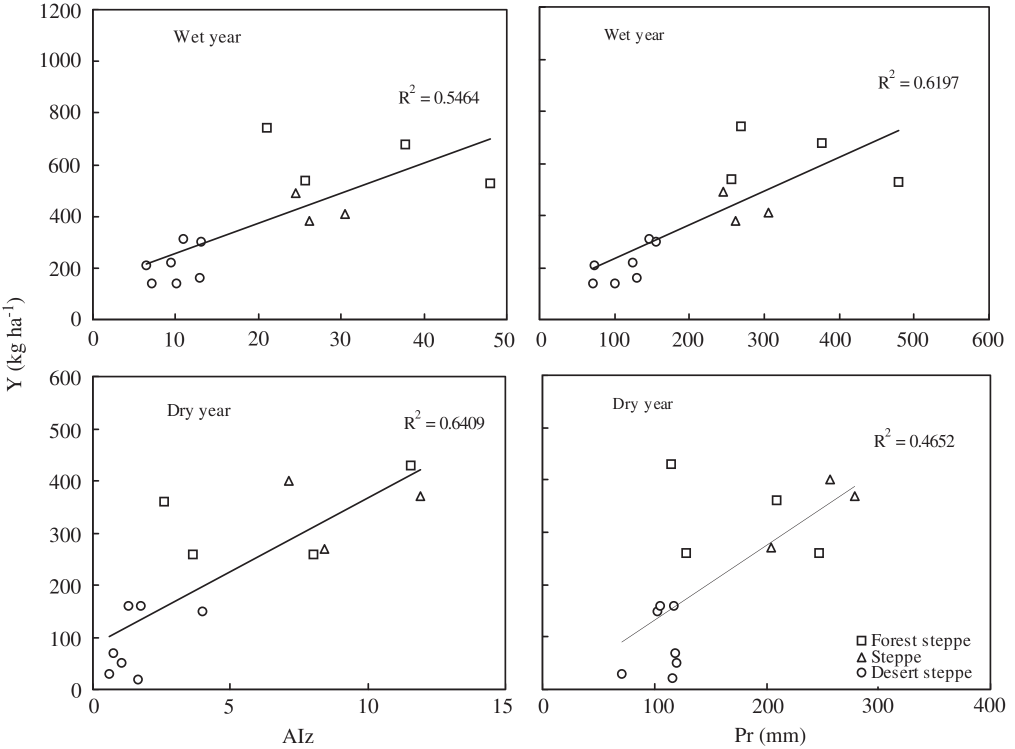

Fig. 10. Relationships among pasture yield (Y), new aridity index (AI_z), and seasonal precipitation (P_r) in the different vegetation zones in Mongolia.

Table 6
Sensitivity of aridity index with comparative changes in pasture yield for wet and dry years

Vegetation zone	Pasture yield (Y) (kg ha^{-1})		Aridity index (AI_z)		Precipitation (P_r) (mm)	
	Wet year (1993)	Dry year (1999)	Wet year (1993)	Dry year (1999)	Wet year (1993)	Dry year (1999)
Forest steppe	360–1170	260–450	21–48	3–12	257–479	115–247
Steppe	280–490	270–400	25–30	8–12	245–305	204–280
Desert steppe	140–400	20–160	6–13	0.6–4	70–156	70–120

closely with the new aridity index, which implies that aridity has the potential to restrain grass growth in Mongolia. The new aridity index was sensitive to dry and wet climatic conditions among different vegetation zones, which demonstrates the usefulness of the new aridity index for predictions of aridity. However, the new aridity index was not applied to the estimation of aridity in taiga forest and high mountain zones, which have a higher soil–water capacity as a result of a colder climate regime than in forest steppe, steppe and desert-steppe zones.

Acknowledgements

The authors would like to express their gratitude to students of the Arid Land Research Center, Tottori University, and researchers of the Institute of Meteorology and Hydrology, Mongolia, for their advice and discussions regarding this research.

References

Argarman, E., 1983. Effect of temperature and pollen source on fertilization, fruit set and abscission in avocado. M.Sc. Thesis, Hebrew University of Jerusalem, Rehovot, Israel.

Barbe, L.L., Lebel, T., 1997. Rainfall climatology of the HAPEX-Sahel region during the years 1950–1990. Journal of Hydrology 188–189, 43–73.

Barron, J., Rockström, J., Gichuki, F., Hatibu, N., 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. Journal of Agricultural and Forest Meteorology 117, 23–37.

Batima, P., Natsagdorj, L., Gomboluudev, P., Erdenetsetseg, B., 2005. Observed climate change in Mongolia. AIACC Working Paper, vol. 12, pp. 12–16.

Howe, G.T., Brunner, A.M., 2005. An evolving approach to understanding plant adaptation. New Phytologist 167, 1–5.

Kaweski, T.J., Ebert, D., 2004. Conceptual issues in local adaptation. Ecology Letters 7, 1225–1241.

Kimura, R., Fan, J., Zhang, X., Takayama, N., Kamichika, M., Matsuoka, N., 2005. Evapotranspiration over the grassland field in Liudaogou Basin of the Loess Plateau, China. Journal of Acta Oecologica 29, 45–53.

Kondoh, A., Kaihotsu, 2003. Preliminary analysis on the relationship between vegetation activity and climatic variation in Mongolia (in Japanese). Journal of Arid Land Studies 13 (2), 147–151.

Lal, M., Singh, K.K., Srinivasan, G., Rathore, L.S., Naidu, D., Tripathi, C.N., 1998. Growth and yield responses of soybean in Madhya Pradesh, India to climate variability and change. Journal of Agriculture and Forest Meteorology 93, 53–70.

Lomas, J., 1988. An agrometeorological model for assessing the effect of heat stress during the flowering and early fruit set on avocado yields. Journal of American Society for Horticultural Science 113 (1), 172–176.

Lomas, J., 1992. Analysis of the effect of heat stress during flowering on the yield of avocado under Mediterranean climatic conditions. Journal of Agricultural and Forest Meteorology 59, 207–216.

Matsumoto, M., Ohta, T., Irasawa, M., Nakamura, T., 2003. Climate change and extension of the *Ginkgo biloba* L. growing season in Japan. Global Change Biology 9, 1634–1642.

Morrison, M.J., Stewart, D.W., 2002. Heat stress during flowering in summer Brassica. Crop Science 42, 797–803.

Miyazaki, S., Yasunari, T., Miyamoto, T., Kaihotsu, I., Davaa, G., Oyunbaatar, D., Natsagdorj, L., Oki, T., 2004. Agrometeorological conditions of grassland vegetation in central Mongolia and their impact for leaf area growth. Journal of Geophysical Research 109, D22106.

Ni, J., 2003. Plant functional types and climate along a precipitation gradient in temperate grasslands, north-east China and south-east Mongolia. Journal of Arid Environments 53, 501–516.

Ni, J., Zhang, X.S., 2000. Climate variability, ecological gradient and the Northeast China Transect (NECT). Journal of Arid Environments 46, 313–325.

Nogina, N.A. (Ed.), 1978. Soil Survey of the Main Natural Zones of Mongolia. Nauka, Moscow, p. 275 (in Russian).

Nogina, N.A., 1989. Specific features of soils and soil formation processes in the central Asian facies (taiga, steppe, desert). Soil Sciences 9, 5–14 (in Russian).

Orr, H.A., 1998. The population genetics of adaptation: the distribution of factors fixed during adaptive evolution. Evolution 52, 935–949.

Polowick, P.L., Sawhney, V.K., 1985. Temperature effects on male fertility and flower and fruit development in *Capsicum annuum* L. Scientia Horticulturae 25 (2), 117–127.

Reddy, S.J., 1983. Agroclimatic classification of the semi-arid tropics III. Characteristics of variables relevant to crop production potential. Journal of Agricultural and Forest Meteorology 30, 269–292.

Schluter, D., 2001. Ecology and the origin of species. Trends in Ecology and Evolution 16, 372–380.

Shinoda, M., Okatani, T., Saloum, M., 1999. Diurnal variations of rainfall over Niger in the west African Sahel: a comparison between wet and drought years. International Journal of Climatology 19, 81–94.

Zhang, Y., Munkhtsetseg, E., Kadota, T., Ohata, T., 2005. An observational study of ecohydrology of a sparse grassland at the edge of the Eurasian cryosphere in Mongolia. Journal of Geophysical Research 110, D14103.