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Interannual variation in the climate and above-ground biomass of *Leymus chinense* steppe and *Stipa grandis* steppe in the Xilin river basin, Inner Mongolia, China

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We evaluated the relationship between variability in climate and variability in primary production and efficiencies of water use of *Leymus chinense* steppe and *Stipa grandis* steppe during 1980–89. On average, annual precipitation was 313·3 mm, while peak above-ground live biomass (PALB) and peak standing crop (PSC) were 182·68 $g.m^{-2}$ and 193·48 $g.m^{-2}$ for *L. chinense* steppe, 144·43 $g.m^{-2}$ and 152·12 $g.m^{-2}$ for *S. grandis* steppe. The coefficient of variation (CV) in annual precipitation was 22%, while the CV in PALB and PSC were 29% and 26% for *L. chinense* steppe, 24% and 25% for *S. grandis* steppe. Rain-use efficiency was 6·3 $kgDM.ha^{-1}mm^{-1}year^{-1}$ for *L. chinense* steppe and 4·9 for *S. grandis* steppe, using PSC as the estimate of ANPP. Monthly and seasonal patterns of precipitation were as important as annual precipitation in determining responses of these two steppes.

Keywords: primary production; rain-use efficiency; grasslands; *Leymus chinense*; *Stipa grandis*; Eurasia steppe; Inner Mongolia; temperate semi-arid climate

Introduction

Leymus chinense (syn. *Aneurolepidium chinense*) steppe is the dominant vegetation type in the eastern Eurasia steppe zone where the climate is semi-arid and sub-humid, while *Stipa grandis* steppe is the dominant vegetation in the middle Eurasia steppe zone where climate is semi-arid (Wu, 1980). Both *L. chinense* steppe and *S. grandis* steppe provide good forage for livestock and are used mainly as natural grazing lands (Zhao *et al.*, 1988). The importance of these grasslands to the local economy demands that

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we understand the relationship between climate and primary productivity of *L. chinense* steppe and *S. grandis* steppe over long-term time domain, in addition to studying spatial variation in primary production relative to climate (Wang & Jiang, 1982; Jiang, 1988).

Climate, soil texture, grazing and cultivation are important controls on spatial patterns of primary production and soil organic matter of grasslands. Spatial patterns of net primary production of grasslands are strongly correlated with gradients of annual precipitation at the regional and global scales (Noy-Meir, 1973; Lauenroth, 1979; Le Houérou, 1984; Sala *et al.*, 1988). Noy-Meir (1973) proposed the inverse soil texture hypothesis: primary production in arid and semi-arid regions is higher in coarse texture soils than in fine texture soils. Very few field ecological works have focused on the long-term dynamics of primary productivity (Towne & Owensby, 1984; Smoliak, 1986; Le Houérou *et al.*, 1988; Lauenroth & Sala, 1992). Information on interannual variation in primary production is essential for us to determine the stocking rates of grasslands for rangeland ecosystem management on the one hand, and to understand the response of grassland ecosystems to possible CO_2-induced climate change on the other hand.

In this study we examined long-term data sets of climate and above-ground biomass of *L. chinense* steppe and *S. grandis* steppe during 1980–89 in the Xilin river basin within the Unesco/MAB Xilingol Steppe Biosphere Reserve, Inner Mongolia Autonomous Region, China (Fig. 1). Our objectives were two-fold: (1) to determine temporal variabilities in precipitation, temperature, primary production and efficiencies of water use; and (2) to establish quantitative relationship between primary production and key climate variables in the domain of time.

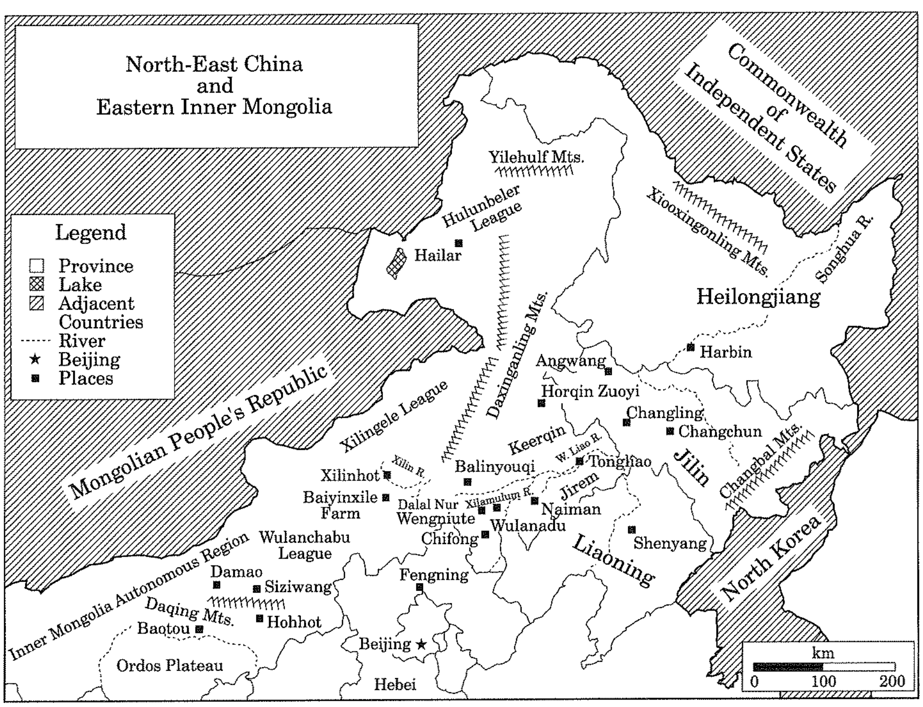

Figure 1. Geographical location of the Xilin river basin and study sites. (after National Research Council, 1992)

Study sites and methods

Study sites

L. chinense steppe and *S. grandis* steppe are dominant typical steppe in the Xilin river basin (Li *et al.*, 1988). Two permanent experiment sites (25 ha each) for *A. chinense* steppe and *S. grandis* steppe were established in 1979 at the Baiyinxile Livestock Farm, approximately 60 km south-east of Xilinhot (Fig. 1). The *S. grandis* site is about 6 km west of the *L. chinense* site.

Climate in the Xilin river basin is a continental middle temperate semi-arid climate. Winter is usually cold and dry, while summer is generally warm and wet (Chen, 1988). The average annual mean temperature and annual precipitation in the period of 1980–89 were 0·02°C and 313·3 mm, respectively (Fig. 2). Stable snow cover exists from the end of November to March. The non-frost period lasts about 102–136 days. Grass plants initiate growth at the end of April and continue growing until September, a growing season of about 150 days (Jiang, 1985).

Leymus chinense *site*

This site is located in a smooth wide plain with low hills on the 2nd-level basalt platform, approximately 1200 m in altitude. Low hills occur with a relative height of 20–30 m with < 5° slope. Of 86 species of flowering plants that belong to 28 families and 67 genera in the site, there are 11 grass species (Jiang, 1985). The xeric rhizomonous grass *L. chinense* (Trin.) Tzvelev (syn. *Aneurolepidium chinense* (Trin.) Kitagava) is the edificato species, and *S. grandis* Smirnov, *Koeleria pyramidara* (Lam.) P. Beauv (syn. *K. cristata* (L.) Link) and *Agropyron cristatum* (L.) Gaertn. are dominant species. Community cover is about 30–40% and may reach 60–70% in wet years.

The soil is dark chestnut (Mollisol) and the soil depth is usually over 100 to 150 cm (Wang & Cai, 1988). The A horizon reaches 20–30 cm deep. There is no distinct

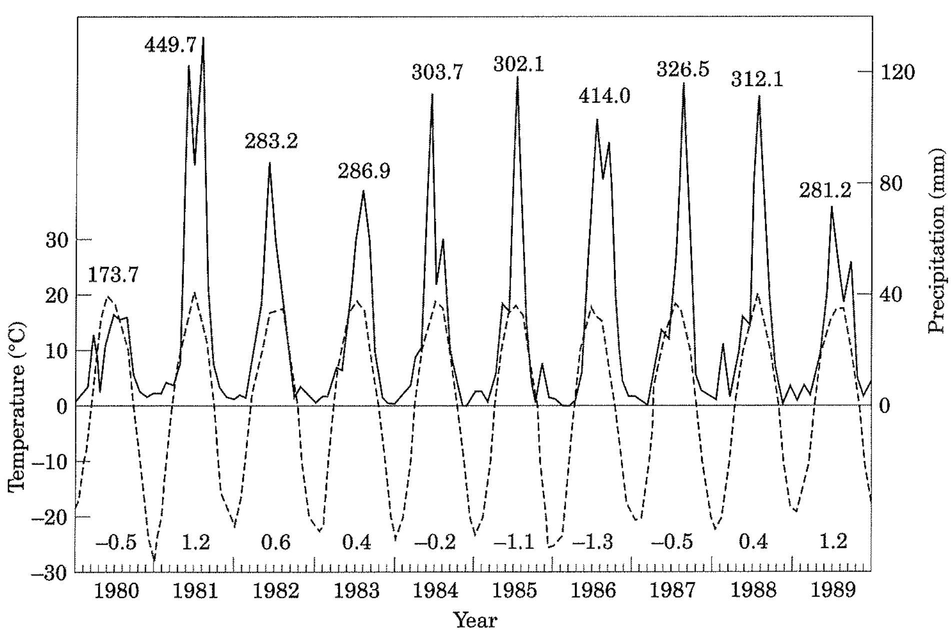

Figure 2. Monthly precipitation (|——|) and monthly mean temperature (|– – –|) in 1980–89.

$CaCO_3$ layer in the soil profile. Soil textures average 21% clay, 19% silt and 60% sand, litter covers the soil surface and no soil erosion occurs.

Stipa grandis *site*

This site with 52 species of flowering plants is located in a open high plain on the 1st-level basalt platform approximately 1130 m in altitude. *S. grandis* is the edificato species, other dominant species are *Artemisia commutata* and *Aneurolepidium chinense*, and accompanying species are *Agropyron cristatum*, *Koeleria pyramidara*, *Heteropappus altaicus* (Willd.) Novopokr., *Artemisia frigida* Willd. and *Kengia squarrosa* (Trin.) Pecker (syn. *Cleistogenes squarrosa* (Trin.) Keng). Community cover is usually about 25%, and may reach 50% on wet years.

Soil is typically chestnut (Mollisol) and soil depth is less than 1 m (Wang & Cai, 1988). The A horizon is about 20 cm deep. A clear $CaCO_3$ layer occurs below 50 cm. On average, soil texture is 21% clay, 30% silt and 49% sand.

Methods

Vegetation sampling

In the fenced sites of *L. chinense* steppe and *S. grandis* steppe, field sampling began in early May and ended in mid-October, at intervals of about 2 weeks. Five 1-m^2 quadrats were randomly placed at each sampling date. Cover, density, growth height and phenological phases of each species were recorded. Above-ground biomass of individual species was measured by the harvest technique. Plant materials were clipped to the ground surface, and litter on the harvested quadrats was collected. At the laboratory, the clipped plant material was separated into live and standing-dead parts, which were weighed as the fresh weight of live biomass and standing dead, respectively. These plant materials were then oven-dried at 65°C and dry weights of live biomass and standing dead were measured (Wang, 1989). The vegetation sampling has been conducted since 1980. In 1987–89, only measurement on above-ground live biomass was made, so no standing dead data are available.

Data analysis

The climate data set includes monthly precipitation, monthly minimum/maximum/mean temperature in 1980–89 from the local weather station. Principal component analysis was used to detect monthly patterns in precipitation, minimum and maximum temperature. Principal components were derived from the covariance matrices of climate variables (SAS, 1985). The coefficient of variation (CV) was used as the index of variability.

There are many methods of estimating annual above-ground net primary productivity (ANPP) (Singh *et al.*, 1975). We used both peak above-ground live biomass (PALB) and peak standing crop (PSC, derived from peak live biomass plus standing dead) as crude estimates of ANPP of *L. chinense* steppe and *S. grandis* steppe, as they are relatively simple and practical. Regression analysis was used to establish quantitative relationship between climate variables and PALB and PSC of *L. chinense* steppe and *S. grandis* steppe. Such climatic variables were used in the linear regression analysis as annual precipitation, total precipitation in April–September, total precipitation in May–September, monthly precipitation, annual mean temperature, average temperature in April–September, and monthly minimum and maximum temperature. Forward/backward/stepwise model selection algorithms were used to select those climatic variables that were statistically significant in relation to PALB and PSC (SAS, 1985).

Rain-use efficiency is the ratio of ANPP to annual precipitation in $kgDM.ha^{-1}.mm^{-1}$ $year^{-1}$ (Le Houérou, 1984). Water-use efficiency was defined as the ratio of ANPP to actual evapotranspiration (AET) during the growing season (April–September) in $mgDM.g^{-1}H_2O$ (Sims & Singh, 1978). Local weather data indicate that the measured monthly potential evaporation during April–September is always greater than monthly precipitation, so it is reasonable to assume that AET is equal to precipitation during the growing season. The Production to Rain Variability Ratio (PRVR), which is the ratio of CV of annual primary production to CV of annual precipitation, was used to evaluate the significance of the relationship between the variability of primary production and the variability of annual precipitation (Le Houérou *et al.*, 1988).

Results and discussion

Interannual variation in temperature and precipitation

Temperature in 1980–89

Mean annual minimum temperature ranged from −10·0°C in 1980 to −6·3°C in 1989, with an average value of −7·6°C. The coefficient of variation (CV) in annual minimum temperature was −15%. In the principal component analysis of monthly minimum temperature, the first principal component (PC1) accounts for 41·5% of variance and the second principal component (PC2) for 20·7% of variance (Fig. 3(a)). The minimum temperature in January and February contribute most to PC1. The minimum temperatures in January and February were −32·2°C and −30·8°C in 1980 but −26·3°C and −22·7°C in 1989, respectively. The minimum temperature in March and November contribute most to PC2. The minimum temperatures in March and November were −21·1°C and −15·3°C in 1980 but −14·3°C and −22·5°C in 1981, respectively. There seems to be no clear patterns or clusters in these 10 years as shown in Fig. 3(a). PCA indicated that minimum temperature is not an important factor in controlling primary production, although it is important in controlling plant distribution (Woodward, 1987).

The mean annual maximum temperature varied from 6·4°C in 1986 to 8·9°C in 1989, with a mean of 7·7°C and a CV of 11%. In the principal component analysis of monthly maximum temperature, PC1 accounts for 33·7% of variance and PC2 for 24·4% of variance (Fig. 3(b)). The maximum temperatures in November, January and April contribute most to PC1. The maximum temperatures in November, January and April in 1980 were 2·6°C, −8·9°C and 3·7°C, while those in 1981 were −7·7°C, −18·1°C and 14°C, respectively. The maximum temperatures in April and July contribute most to PC2. Years 1989 and 1982 had higher maximum temperatures in April (i.e. 14·4°C in 1989 and 14°C in 1982), but lower maximum temperatures in July (i.e. 24·2°C in 1989 and 23·1°C in 1982). In 1980 there were low maximum temperatures in April (3·7°C), but the highest maximum temperatures in July (30·5°C). The high maximum temperature in April provides suitable temperature conditions for grass plants to initiate growth earlier, resulting in a longer plant-growing season. The higher maximum temperature in July increases potential evapotranspiration and thus less water is available for plant growth. Both PC1 and PC2 indicated the maximum temperature in April is very important. The average value of the maximum temperature in April is 11°C and its coefficient of variation is 26%, the largest CV observed during the growing season. These results indicate that the monthly maximum temperature is more important than the monthly minimum temperature in influencing primary production.

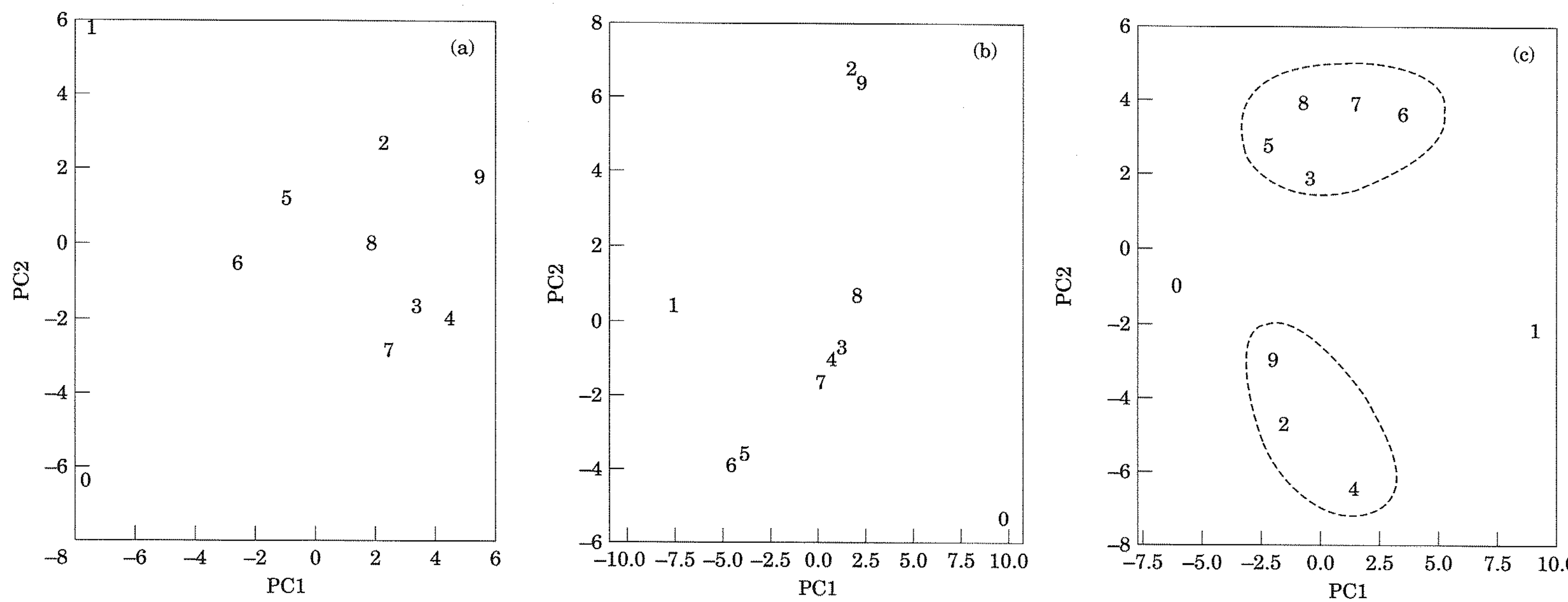

Figure 3. Scatter diagram of years in the first two principal components. (a) monthly minimum temperature; (b) monthly maximum temperature; (c) monthly precipitation. (The number is the last digit of year, i.e. 0 = 1980, 1 = 1981, 2 = 1982, 3 = 1983, 4 = 1984, 5 = 1985, 6 = 1986, 7 = 1987, 8 = 1988, 9 = 1989).

Precipitation in 1980–89

Annual precipitation varied from 173·7 mm in 1980 to 449·7 mm in 1981, with a mean of 313·3 mm (Fig. 2). On the average, 89% of annual precipitation occurs in the period of April–September. The coefficient of variation (CV) in annual precipitation was 22%. Low annual precipitation and large interannual variation in rainfall on the Xilin river basin indicate that water is the dominant controlling factor for the magnitude and variation of above-ground biomass and primary production of *L. chinense* steppe and *S. grandis* steppe.

Coupland (1950) declared rainfall events of less than 8–10 mm as ecologically unimportant, while Sala & Lauenroth (1982) claimed that even small rain events are ecologically significant. Rainfall events were mostly small and varied greatly in intensity (Fig. 4). Rainfall events of ≥ 5·0 mm occurred mostly in April–September, accounting for 24·6% of total rainfall events. Rainfall events of ≥ 10·0 mm occurred mostly in June–September, accounting for 11·2% of total rainfall events. Large rainfall events occurred on only one day in June 1981 (50 mm), May 1982 (32·9 mm), June 1982 (27·5 mm), June 1984 (34·0 mm), July 1985 (34·3 mm) and August 1986 (30·9 mm).

In the principal component analysis of monthly precipitation, PC1 accounts for 35·8% of variance and PC2 for 32·7% of variance (Fig. 3(c)). PC1 indicates a gradient of annual precipitation, as 1980 is the driest year and 1981 is the wettest year (Fig. 2). Precipitation in August and June contribute positively to PC1. Precipitation in August and June was highest in 1981 (133·1 mm and 123·5 mm) but lowest in 1980 (30·8 mm and 25·2 mm). The coefficients of variation in precipitation in June and August were 58% and 46%, respectively. Precipitation in June contributes negatively to PC2 but precipitation in July and August contributes positively to PC2. PC2 indicated a clear pattern in precipitation during the growing season. There was a high level of precipitation in June and April but low precipitation in July and August in 1982, 1984 and 1989, while there was high precipitation in July and August and low precipitation in June and April in 1983, 1985, 1986, 1987 and 1988. The seasonal difference (Spring *vs.* Summer) in precipitation may have significant effects on the magnitude and variation of primary production of *L. chinense* and *S. grandis* steppe. PCA indicated that monthly and seasonal precipitation patterns are as important as annual precipitation in determining precipitation patterns (Fig. 3(c)).

The magnitude and variation of primary production

Peak above-ground live biomass of *L. chinense* steppe (PALBa) occurred in the period between late July and late August. PALBa varied considerably from 90·31 g.m^{-2} in 1980 to 242·0 g.m^{-2} in 1988 (Fig. 5). The mean of PALBa is 182·68 g.m^{-2} and the coefficient of variation (CV) in PALBa is 29%. Standing dead material occurred by the early June, depending on soil water condition and precipitation. Peak standing crop of *L. chinense* steppe (PSCa) in 1980–86 ranged from 106·93 g.m^{-2} in 1980 to 252·61 g.m^{-2} in 1982, with a mean of 193·48 g.m^{-2} and a CV of 26% (Fig. 5).

Peak above-ground live biomass of *S. grandis* steppe (PALBs) occurred in mid-August to early September. PALBs varied from 79·08 g.m.$^{-2}$ in 1980 to 198·60 g.m^{-2} in 1981 (Fig. 5). The mean of PALBs is 144·43 g.m^{-2} and the coefficient of variation (CV) in PALBs is 24%. Peak standing crop of *S. grandis* steppe (PSCs) in 1980–86 ranged from 92·7 g.m^{-2} in 1980 to 206 g.m^{-2} in 1981, with a mean of 152·12 g.m^{-2} and a CV of 25% (Fig. 5).

On average, peak above-ground live biomass and peak standing crop of *L. chinense* steppe were 127% and 129% higher than those of *S. grandis* steppe, respectively. This supports the inverse soil texture hypothesis (Noy-Meir, 1973), as the dark chestnut soil of *L. chinense* steppe (60% sand) has more coarse soil texture than the chestnut soil of *S. grandis* steppe (49% sand). There were more available water in the coarse textured soil of *L. chinense* steppe than in the soil of *S. grandis* steppe (Li, 1988). However, the ratio of PALB of *L. chinense* steppe over PALB of *S. grandis* steppe varied considerably over time, ranging from 88% (17·25 g.m^{-2} lower) in 1989 to 183% (100·32 g.m^{-2} higher) in 1985, with a CV of 21% (Fig.5). The ratio of PSC of *L. chinense* steppe over PSC of *S. grandis* steppe in the period of 1980–86 also varied over time, ranging from 89% (19·16 g.m^{-2} lower) in 1984 to 176% (101·95 g.m^{-2} higher) in 1985, with a CV of 20% (Fig.5). These varying interannual differences in PALB and PSC indicate that interannual variation in climate had strong but different effects on *L. chinense* steppe and *S. grandis* steppe.

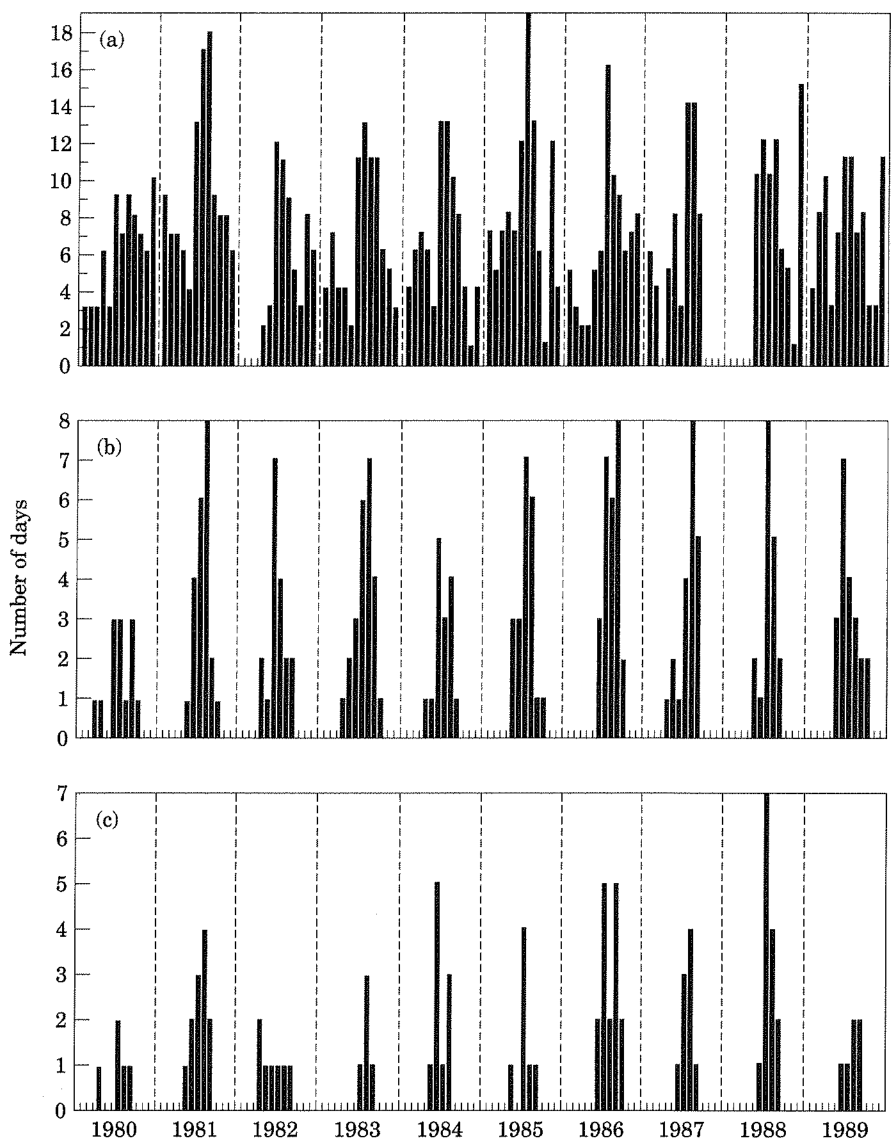

Figure 4. Frequency distribution of rainfall events at various levels of precipitation (a) ≥ 0·10 mm; (b) ≥ 5·0 mm; (c) ≥ 10·0 mm.

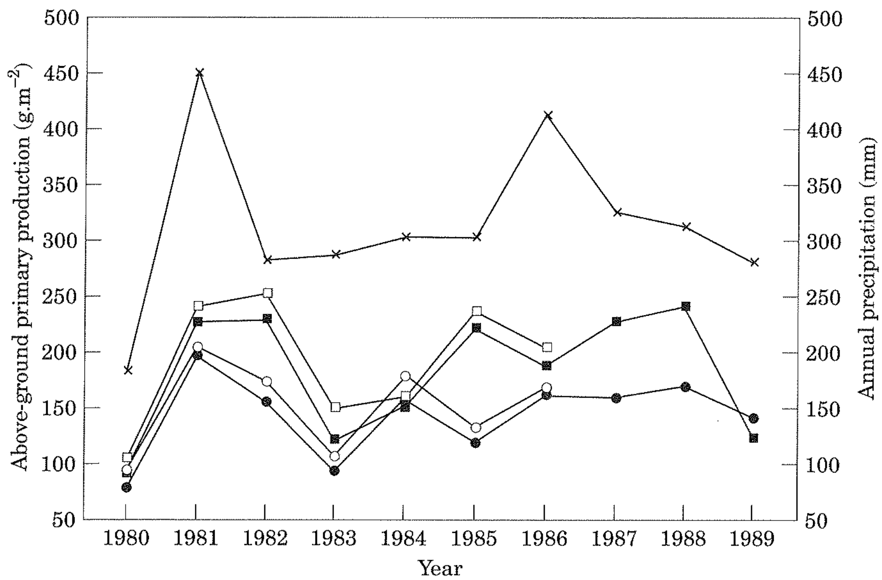

Figure 5. Interannual variation in peak above-ground live biomass (PALB) and peak standing crop (PSC) of both *L. chinense* steppe and *S. grandis* steppe. PALBa (–■–) and PSCa (–□–) — *L. chinense* steppe; PALBs (–●–) and PSCs (–○–) — *S. grandis* steppe (* = precipitation).

Le Houérou *et al.* (1988) and Noy-Meir (1973) found that variability of primary production in arid and semi-arid zones is much greater in fine-textured top soils than in coarse-textured top soils, and larger in shallow than deep soils. However, dark chestnut soil of the *L. chinense* site is more coarse-textured and deeper than typical chestnut soil of the *S. grandis* site. The coefficient of variation in PALB of the *L. chinense* site (29%) is greater than the CV in PALB of the *S. grandis* site (24%) in 1980–89, and the coefficient of variation in PSC of *L. chinense* steppe (CV = 26%) is larger than the CV in PSC of *S. grandis* steppe (CV = 25%) in 1980–86. The fact that variabilities of PALB and PSC of *L. chinense* steppe were larger than those of *S. grandis* steppe should be attributed to the differences in species composition and species responses to intraseasonal patterns and interannual variation of precipitation and temperature, rather than to the differences in soil texture and depth.

Relationship between climate and primary production

Temperature, PALB and PSC

The linear regression analysis indicated that the mean annual minimum temperature, average minimum temperature during April–September, average monthly minimum temperature, mean annual maximum temperature and average maximum temperature during April–September were not significantly correlated with PALB and PSC of *L. chinense* steppe and *S. grandis* steppe at $\alpha = 0{\cdot}05$ level. The monthly maximum temperature in April (MXT4) accounted for 44% of interannual variation of PALB of *S. grandis* steppe (PALB = 57·60 + 7·89*MXT4; $r^2 = 0{\cdot}44$; $p = 0{\cdot}0353$; $n = 10$); 56% of interannual variation of PSC of *S. grandis* steppe (PSC = 57·06 + 9·15*MXT4; $r^2 = 0{\cdot}56$; $p = 0{\cdot}0542$; $n = 7$) and 57% of interannual variation of PSC of *L. chinense* steppe (PSC = 66·44 + 12·23*MXT4; $r^2 = 0{\cdot}57$; $p = 0{\cdot}0489$; $n = 7$). The monthly maximum temperature in May (MXT5) accounted for 39% of interannual variation of

PALB of *L. chinense* steppe (PALB = 705·98 – 27·20*MXT5; r^2 = 0·39; p = 0·0518; n = 10).

Precipitation and peak above-ground live biomass (PALB)

Annual precipitation accounted for about 34% of variability in PALB of *L. chinense* steppe but was not significantly related to PALB at α = 0·05 level (Fig. 6(a)). Although significant at α = 0·05 level, total precipitation in the growing season accounted for only 41% of variability in PALB (Fig. 6(b)). Precipitation in July was significantly correlated to PALB of *L. chinense* steppe at α = 0·05 level (Fig. 6(c)).

Annual precipitation and precipitation in the growing season seem to have a linear relationship with PALB of *S. grandis* steppe (Fig. 7). Annual precipitation accounted for 64% of the variability of PALB of *S. grandis* steppe (Fig. 7(a)), total precipitation during April–September for 72% of interannual variation (Fig. 7(b)), and total precipitation during May–September for 69% of interannual variation (Fig. 7(c)). PALB of *S. grandis* steppe was not significantly correlated to any of monthly precipitation variables at α = 0·05 level.

Precipitation and peak standing crop (PSC)

Annual precipitation accounted for 40% of variability in PSC of *L. chinense* steppe in 1980–86 (Fig. 8(a)). The total precipitation during April–September accounted for 46% of variability in PSC of *L. chinense* steppe (Fig. 8(b)). Monthly precipitation in May (R5) accounted for 50% of interannual variation of PSC of *L. chinense* steppe (Fig. 8(c)). However, PSC had no significant linear relationship with both annual precipitation and the total precipitation during April–September at α = 0·05 level, or with monthly precipitation at α = 0·05 level.

Annual precipitation accounted for 62% of variability in PSC of *S. grandis* steppe in 1980–86 (Fig. 9(a)). The total precipitation during April–September accounted for 70% of variability in PSC (Fig. 9(b)). However, precipitation in June accounted for 84% of variability in PSC (Fig. 9(c)). A 1-cm increase in precipitation in June will result in 9·60 g.m^{-2} increase in PSC of *S. grandis* steppe. Monthly precipitation in June (R6) and July (R7) was significantly correlated to PSC of *S. grandis* steppe (PSC = 50·49 + 9·84*R6 + 4·68*R7; r^2 = 0·97; p = 0·0011; n = 7).

Efficiencies of water use

PALB as the estimate of ANPP and efficiencies of water use

In *L. chinense* steppe, rain-use efficiency (RUE, kgDM.ha^{-1}mm^{-1}year^{-1}) ranged from 4·3 in 1983 to 8·2 in 1982 (Fig. 10). The mean of RUE was 5·7 kgDM.ha^{-1}mm^{-1} year^{-1} and the CV in RUE was 26%. Water use efficiency (WUE, mgDM.g^{-1}H_2O) varied between 0·47 in 1983 and 0·86 in 1982, with a mean of 0·63 mgDM.g^{-1}H_2O and a CV of 24% (Fig. 10).

In *S. grandis* steppe, rain-use efficiency (RUE, kgDM.ha^{-1}mm^{-1}year^{-1}) ranged from 3·3 in 1983 to 5·5 in 1982, with a mean of 4·4 kgDM.ha^{-1}mm^{-1}year^{-1} and a CV of 16% (Fig. 10). Water-use efficiency (WUE, mgDM.g^{-1}H_2O) varied between 0·37 in 1983 and 0·58 in 1982, with a mean of 0·49 mgDM.g^{-1}H_2O and a CV of 14% (Fig. 10).

On average, RUE of *S. grandis* steppe is about 77% of RUE of *L. chinense* steppe, and WUE of *S. grandis* steppe is 78% of WUE of *L. chinense* steppe. Variations in RUE and WUE of *L. chinense* steppe were larger than those of *S. grandis* steppe (Fig. 10).

The Production to Rain Variability Ratio is 1·32 for *L. chinense* steppe and 1·09 for *S. grandis* steppe, respectively.

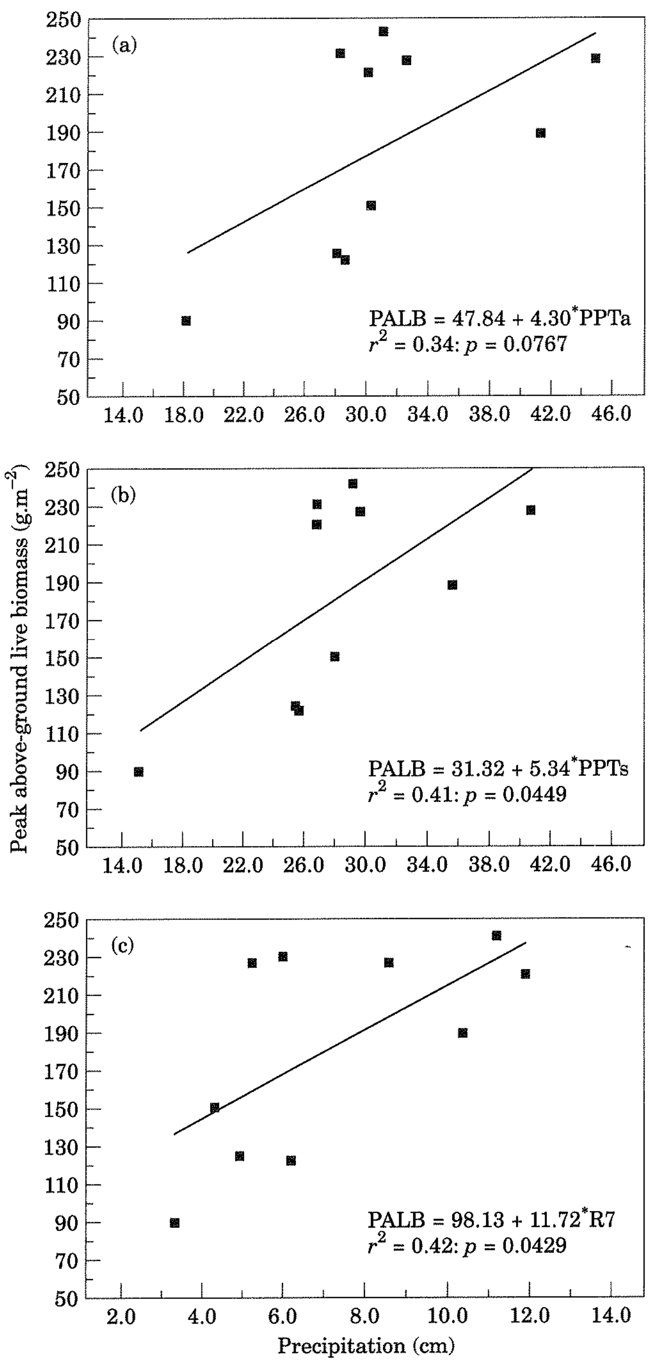

Figure 6. The relationship between precipitation and peak above-ground live biomass of *L. chinense* steppe, (a) annual precipitation; (b) precipitation between April and September; (c) precipitation in July.

PSC as the estimate of ANPP and efficiencies of water use

Rain-use efficiency (RUE, kgDM.ha^{-1}mm^{-1}year^{-1}) of *L. chinense* steppe varied from 4·9 in 1986 to 8·9 in 1982 (Table 1). The mean and the coefficient of variation in RUE

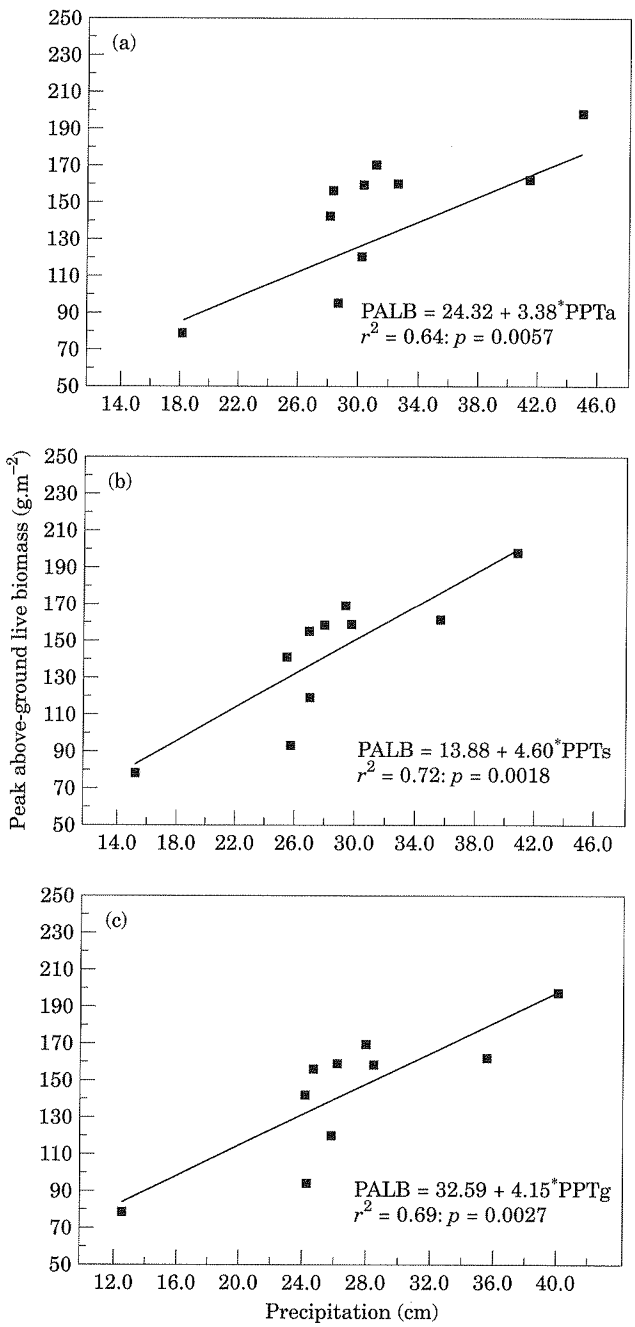

Figure 7. The relationship between precipitation and peak above-ground live biomass of *S. grandis* steppe, (a) annual precipitation; (b) total precipitation during April–September; (c) total precipitation during May–September.

are 6·3 kgDM.ha^{-1}mm^{-1}year^{-1} and 23%, respectively. Water-use efficiency (WUE, mgDM.g^{-1}H_2O) varied from 0·57 in 1984 to 0·94 in 1982 (Table 1). The mean of WUE is 0·69 mgDM.g^{-1}H_2O and the CV in WUE is 21%.

Rain-use efficiency (RUE, kgDM.ha^{-1}mm^{-1}year^{-1}) of *S. grandis* steppe ranged from 3·7 in 1983 to 6·2 in 1982 (Table 1). The mean of RUE is 4·9 kgDM.ha^{-1}mm^{-1}year^{-1} and the CV in RUE is 18%. Water-use efficiency (WUE, mgDM.g^{-1}H_2O) ranged from 0·41 in 1983 to 0·65 in 1982 (Table 1). The mean and the coefficient of variation in WUE are 0·52 mgDM.g^{-1}H_2O and 16%, respectively.

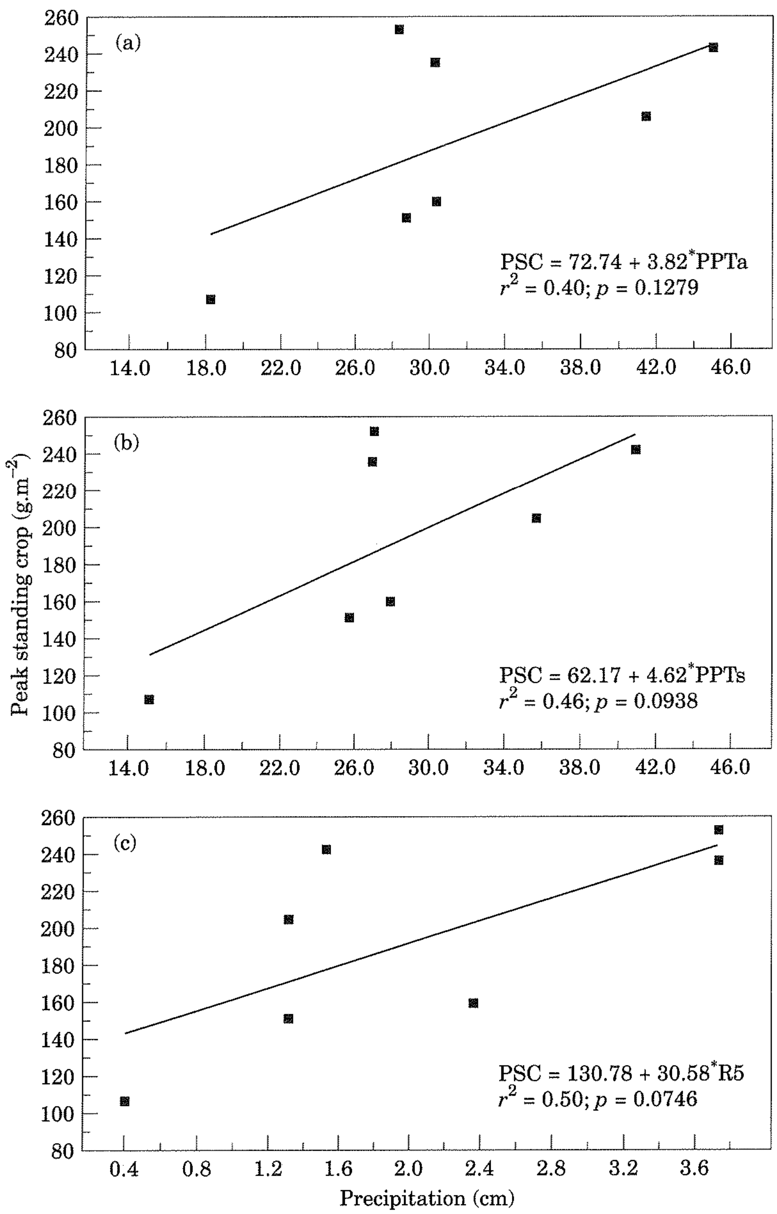

Figure 8. The relationship between precipitation and peak standing crop of *L. chinense* steppe, (a) annual precipitation; (b) total precipitation during April–September; (c) precipitation in May.

On average, RUE of *S. grandis* steppe is about 79% of RUE of *L. chinense* steppe, and WUE of *S. grandis* steppe is 74% of WUE of *L. chinense* steppe. Variations in RUE and WUE of *L. chinense* steppe were larger than those of *S. grandis* steppe (Table 1). The Production to Rain Variability Ratio (PRVR) is 1·18 for *L. chinense* steppe and 1·14 for *S. grandis* steppe, respectively. Both *L. chinense* steppe and *S.grandis* steppe had higher RUE and lower PRVR values, compared with the average value of 77 series data (RUE = 4·0 and PRVR = 1·5) from the world arid lands (Le Houérou *et al.*, 1988).

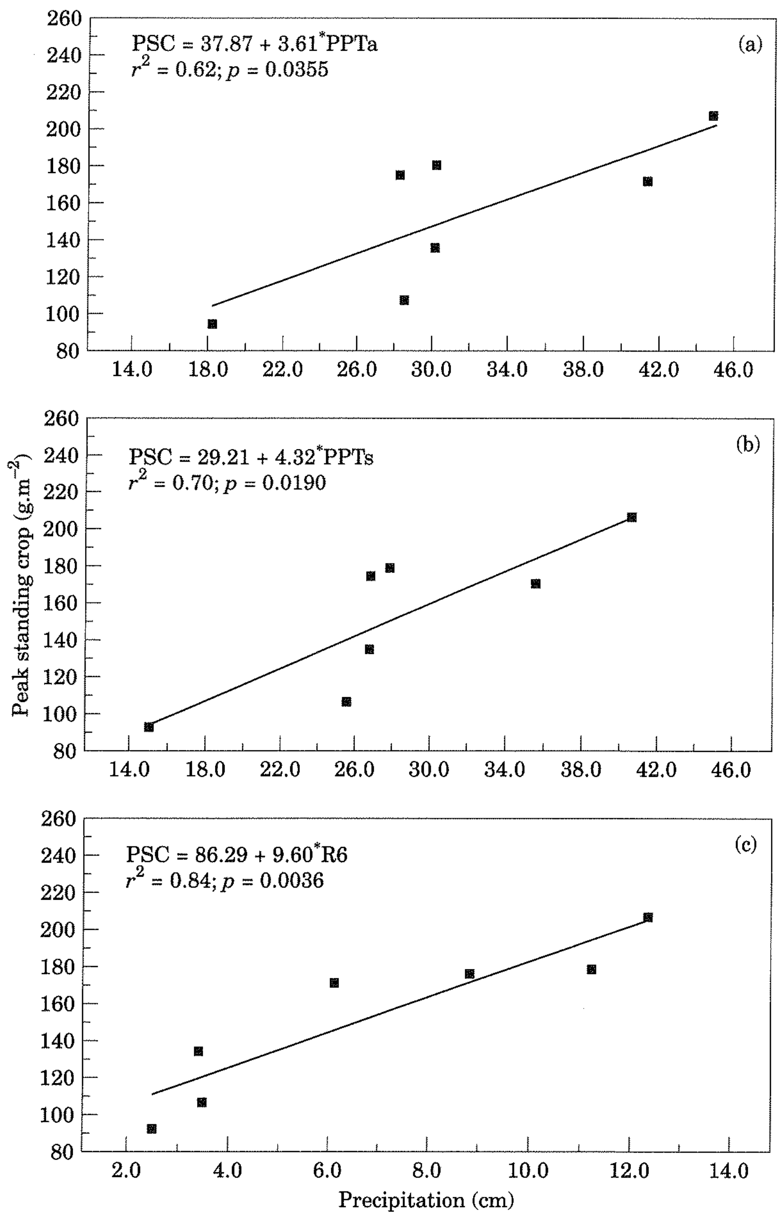

Figure 9. The relationship between precipitation and peak standing crop of *S. grandis* steppe, (a) annual precipitation; (b) precipitation between April and September; (c) precipitation in June.

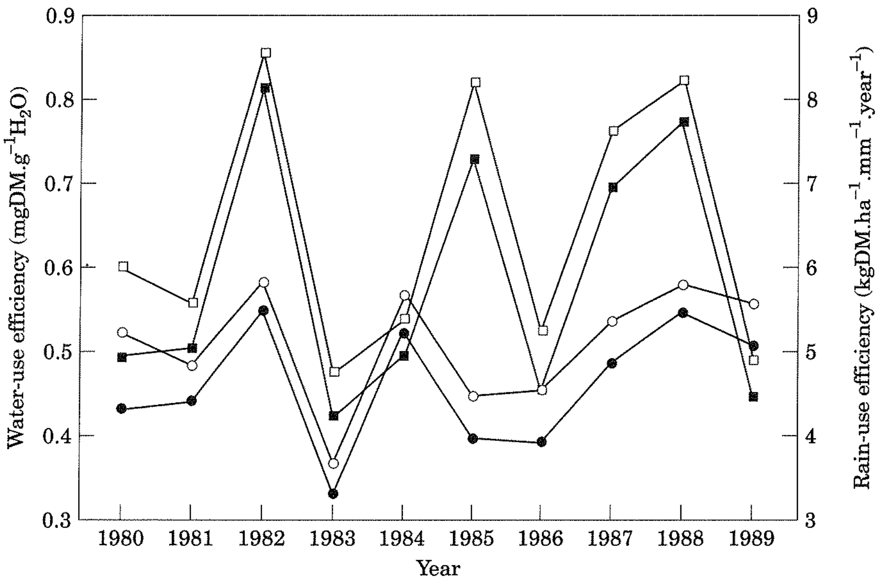

Figure 10. Rain-use efficiency (RUE) and water-use efficiency (WUE) of *L. chinense* and *S. grandis* steppe, using peak above-ground live biomass (PALB) as estimate of above-ground net primary production (ANPP >. RUEa (-■-) and WUEa (-□-) — *L. chinense* steppe; RUEs (-●-) and WUEs (-○-) — *S. grandis* steppe.

Table 1. *Rain-and water-use efficiencies (RUE), using peak standing crop (PSC) as estimate of above-ground net primary production (ANPP)*

	L. chinense site		*S. grandis* site	
Year	RUE	WUE	RUE	WUE
1980	6·2	0·71	5·3	0·61
1981	5·4	0·59	4·6	0·51
1982	8·9	0·94	6·2	0·65
1983	5·3	0·59	3·7	0·41
1984	5·3	0·57	5·9	0·64
1985	7·8	0·88	4·4	0·50
1986	4·9	0·57	4·1	0·48
mean	6·3	0·69	4·9	0·52
CV (%)	23	21	18	16

Summary

There were large interannual variations in temperature and precipitation in the period of 1980–89 in the Xilin river basin. Monthly and seasonal patterns of temperature and precipitation are as important as annual temperature and precipitation. Correspondingly, there were large interannual variations in peak above-ground live biomass, peak standing crop, rain-use efficiency and water-use efficiency of both *L. chinense* steppe and *S. grandis* steppe. The coefficient of variation in annual precipitation (22%) was lower than the coefficients of variation in PLAB of *L. chinense* steppe (29%) and *S. grandis* steppe (24%). Variations in annual precipitation and monthly precipitation

patterns are the key factors that control the magnitude and interannual variation of primary production of *L. chinense* and *S. grandis* steppe over time.

On average, peak above-ground live biomass, peak standing crop, rain-use efficiency and water-use efficiency of *L. chinense* steppe (182·68 $g.m^{-2}$, 193·38 $g.m^{-2}$, 6·3 $kgDM.ha^{-1}mm^{-1}year^{-1}$ and 0·69 $mgDM.g^{-1}H_2O$) were higher than those of *S. grandis* steppe (144·43 $g.m^{-2}$, 152·12 $g.m^{-2}$, 4·9 $kgDM.ha^{-1}mm^{-1}year^{-1}$ and 0·52 $mgDM.g^{-1}H_2O$, probably due to soil texture difference. The coefficients of variation in PALB, PSC, RUE and WUE of *L. chinense* steppe (29%, 26%, 23% and 21%) were also larger than those of *S. grandis* steppe (24%, 25%, 18% and 16%). Annual precipitation accounts for much higher percentages of interannual variations in PALB and PSC of *S. grandis* steppe ($r^2 = 0{\cdot}64$ for PALB and $r^2 = 0{\cdot}62$ for PSC) than those of *L. chinense* steppe ($r^2 = 0{\cdot}34$ for PALB and $r^2 = 0{\cdot}40$ for PSC). This difference in response to interannual variation in precipitation between *L. chinense* steppe and *S. grandis* steppe should be attributed to the difference in species composition. Therefore, quantitative analysis on the response of *L. chinense* steppe and *S. grandis* steppe to intra-annual and interannual variations of climate at population level is required if we want to understand the relationship fully between temporal variability in primary production of these plant communities and temporal variability in climate.

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