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Effects of rainfall amount and frequency on vegetation growth in a Tibetan alpine meadow

Baocheng Zhang · Junji Cao · Yanfen Bai · Xuhui Zhou · Zhigang Ning · Songjie Yang · Lin Hu

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Abstract Over the past decades, rainfall amount and frequency changed considerably on the Tibetan Plateau. However, how altered rainfall pattern affects vegetation growth and phenology in Tibetan alpine grasslands is poorly understood. In this study, we investigated the long-term effects of rainfall amount and frequency on production (i.e., aboveground biomass, AGB) and phenology of three perennial plants in a Tibetan alpine meadow from 1994 to 2005. Growth period (i.e., the dates from greening to senescence) was referred to plant phenology here. Our results showed that annual precipitation and total rainfall from large events ($\geq$ 5 mm per day) were mainly distributed in the growing season, which increased significantly from 1994 to 2005 with more increment in May and July (p<0.05). Total AGB and growth periods of three plants were linearly correlated with annual precipitation and total rainfall from large events, but have insignificant correlations with total rainfall from small events (< 5 mm per day) and rainfall frequency (including small, large, and all events). The results suggest that aboveground plant production and phenology are

Baocheng Zhang, Junji Cao, Yanfen Bai and Xuhui Zhou are contributed equally to this work

B. Zhang · J. Cao
State Key Lab of Loess and Quaternary Geology, Institute of Earth Environment,
Chinese Academy of Sciences, Xi'an 710075, China

B. Zhang (✉) · X. Zhou (✉)
Coastal Ecosystems Research Station of the Yangtze River Estuary, Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, The Institute of Biodiversity Science, Fudan University, Shanghai 200433, China
e-mail: bczhang09@gmail.com
e-mail: zxuhui14@fudan.edu.cn

Y. Bai
Cold and Arid Regions Environmental and Engineering Research Institute,
Chinese Academy of Sciences, Lanzhou 730000, China

Z. Ning
Shaanxi Changqing National Natural Reserve, Yang County, Shaanxi Province 723300, China

S. Yang · L. Hu
College of Agriculture and life sciences, Ankang University, Ankang 725000, China

more sensitive to changes in large rainfall events (≥ 5 mm per day) than small events (< 5 mm per day) in the alpine meadow ecosystems.

1 Introduction

As a consequence of anthropogenic buildup of CO_2 and other greenhouse gases in the atmosphere and the resulting global warming, precipitation frequency and amount are predicted to largely alter with great possibility of extreme events in the 21th century due to shifting patterns of air circulation and hydrologic cycling (Huntington 2008; IPCC 2007). Changes in precipitation pattern may considerably affect ecosystem structure and functions (Dougherty et al. 1996; Golluscio et al. 1998; Miranda et al. 2009; Weltzin et al. 2003; Yahdjian and Sala 2006). Duration, amount and frequency of rainfall events can significantly influence water availability (Loik 2007; Noy-Meir 1973; Schwinning and Ehleringer 2001). Large rainfall events would increase moisture availability more easily than small ones. Plant production thus would benefit more from large than small events, particularly in the growing season with relatively high temperature (Weltzin et al. 2003). Availability of soil water may also influence leaf bud flush (Blum 1996), senescence (Barr et al. 2007; Jolly and Running 2004), and then growth period (Grogan and Schulze 2012). The growth period refers to a time that a plant species grows from greening to senescence. In many ecosystems, shifting growth period induced by changes in precipitation patterns could obviously influence plant production by changing individual competion and community stability (Churkina and Running 1998; Churkina et al. 2005; Muller 1978; Zhou et al. 2001).

One of the approaches to understand precipitation effects is to characterize the patterns of ecosystem processes along natural precipitation gradients. These studies found that plant production (mainly aboveground net primary production (ANPP) or aboveground biomass (AGB)) was positively correlated with changes in precipitation along spatial gradients (Bai et al. 2008; Fang et al. 2005; Gao et al. 2009; Huxman et al. 2004; Munkhtsetseg et al. 2007; Shackleton 1999; Sneva 1982; Yang et al. 2009; Zhou et al. 2009). The effects of precipitation were more significant when mean annual rainfall was less than 600 mm (Austin et al. 2004; Noy-Meir 1973; Sala et al. 1988).

Another important approach is, at the local scale, to use long-term site-specific observation data to understand the effects of precipitation on ecosystem processes, although there are effects of confounding factors to some degree (Swemmer et al. 2007). However, most studies suggested that AGB was primarily responsive to the seasonal timing and magnitude of rainfall, instead of annual precipitation amount (Fay et al. 2000; Robertson et al. 2009). Increased variability in growing-season rainfall led to reduced AGB in grassland ecosystems (Fay et al. 2003). In addition, large rainfall events can penetrate root-zone soil and increase soil water potentials enough for the plants to keep turgor during leaf flush (Blum 1996), while water deficit may accelerate leaf senescence (Barr et al. 2007; Jolly and Running 2004). In the agriculture system, crop yield increased with the lengths of growth period (Liu et al. 2010; Tao et al. 2006; Wang et al. 2008). But an increase in the length of growth period reduced aboveground biomass in the northern hardwood forest (Muller 1978). Furthermore, different plant species may respond specifically to rainfall events (Golluscio et al. 1998; Jenerette et al. 2008). Plant productivity and phenology (e.g., growth period) may also respond differently to climate variability at different times of year (Craine et al. 2012). Effects of amount and frequency of large rainfall events (≥ 5 mm) on vegetation growth and phenology may be different from those of small ones (< 5 mm). Thus, how amount and frequency of large and small rainfall events affect plant growth and phenology is poorly understood, especially in Tibetan alpine meadows.

There is still a debate on primary production and climate factors on the Tibetan Plateau. Previous studies showed that plant production was mainly determined by rainfall (Wang et al. 2009; Yang et al. 2010; Yang et al. 2008), solar radiation (Piao et al. 2006), temperature (Piao et al. 2006; Xu et al. 2011; Zhang et al. 2009) and their combined effect in the Tibetan alpine meadows (Luo et al. 2004; Zhong et al. 2010). Few studies have examined responses of growth period and plant production to large and small rainfall events in the Tibetan plateau. Grassland ecosystems cover approximately 1.2×10^6km^2 in Tibetan plateau, where alpine meadows account for 35 % of the area (Cao et al. 2004) and play a key role in local ecological environment (Bai et al. 2012) and animal husbandry (Zhou et al. 2001). In an alpine meadow ecosystem, grassland utilization was determined by the amount of AGB and its carrying capacity to support livestock production (Fay et al. 2000; Yahdjian and Sala 2006; Yang et al. 2009). Therefore, we examined the effects of precipitation amount and frequency on production and phenology of three perennial plants in an alpine meadow from 1994 to 2005. In this study, the objectives were to examine patterns of rainfall pattern (i.e., amount and frequency of large (≥ 5 mm) and small (< 5 mm) rainfall events) and their effects on AGB and growth period of three dominant forages. We hypothesized that total rainfall from large events (≥ 5 mm) would significantly affect AGB and growth periods of plant species compared to that from small events (< 5 mm).

2 Materials and methods

2.1 Study site

The study area, Husbandry Meteorology of Qumalai county observation station (HMQS), was located on the southeast Tibetan Plateau (34.08º N, 95.47º E) with a typical continental plateau climate, which have a larger diurnal variation (cold and dry) and strong radiation (Xu et al. 2011). The mean annual air temperature is −2.2 °C with frost occurring at any time of the year. Recent mean annual precipitation ranges from 323 to 545 mm with an average of 390 mm. The HMQS is a typical alpine meadow ecosystem, which is dominated by perennial grasses, such as *Festuca vubra*, *Kobresia pygmaea*, *Poa pratensis*, *Carex tristachya*, *Kobresia humilis*, and *Korbresia Capillifolia*. These plant species maintain the integrity of alpine meadow (Zhao 2009) and provide high-quality forages for livestock (Long et al. 1999).

2.2 Experimental protocol

The study site, 100×100 m^2 in area, has been fenced to prevent grazing since 1986. Aboveground biomass was measured once a year during the study period. At the HMSQ, four plots (1×1 m^2) were randomly harvested all aboveground biomass to ground level at the end of August each year (peak biomass usually in August). Biomass samples were oven-dried at 65 °C to constant mass and the average was considered as aboveground biomass (AGB) in alpine meadows (China Meteorological Administration 1993; Yang et al. 2010).

Growth period, the dates from the greening to senescence, was used to represent plant phenology. The date of first greening is defined as the date that 10 or more percent of the perennial forages turns green, and the date of senescence is referred to the date that the two thirds or more percent of the perennial forages becomes yellow (State Meteorological Administration 1993). We mainly recorded the growth periods of three dominant species Festuca (*Festuca rubra*), Kobresia (*Kobresia pygmaea*), and Bluegrass (*Poa pratensis*) from 1994 to 2005.

Daily rainfall events are categorized as large (≥ 5 mm) and small (< 5 mm) ones. Total rainfall from large events is the annual accumulation as well as that from small events. Precipitation frequency is total days with all rainfall events as well as frequency with large (≥ 5 mm) and small rainfall events (< 5 mm).

2.3 Statistical analysis

Effects of rainfall patterns on alpine meadow production were analyzed by the following three steps. Firstly, we calculated the change rate of every month's rainfall frequency and amount from 1994 to 2005. Secondly, correlations between rainfall pattern (i.e., amount and frequency) and growth period of three dominant grasses were conducted by Pearson correlation analysis and stepwise regression analysis. Finally, we examined relationships of rainfall pattern (frequency and amount) with AGB and growth period. All statistical analyses were performed using SPSS 13.0 for Windows (SPSS Inc., Chicago, Illinois, USA 2004).

3 Results

3.1 Trends of rainfall pattern

From 1994 to 2005, annual mean temperature, rainfall and total rainfall from large events (≥ 5 mm) were shown in Fig. 1a,b,c. Annual rainfall amount increased significantly with a rate of 12.09 mm/year over the study period ($p<0.05$), while total rainfall from large events (≥ 5 mm) increased marginally with a rate of 13.29 mm/year ($p=0.054$). In contrast, annual mean temperature, annual rainfall frequency (Fig. 1e) and total rainfall from small events (< 5 mm) did not display the distinct trend over time ($p>0.2$). Frequency of large rainfall (≥ 5 mm) and small events (< 5 mm) increased significantly over time with an increase rate of 1.9 day/year ($p<0.001$) and a decrease one of 1.97 day/year ($p<0.054$), respectively (Fig. 1d, f).

The monthly changes in rainfall pattern (i.e., the slope of the linear regression) from 1994 to 2005 were diverse for annual, large, and small events (Table 1). Frequency of annual rainfall and small events increased in May but decreased in November over time as well as annual rainfall in August ($p<0.05$), while that of large events did not showed the significant trend ($p>0.05$). Amount of annual rainfall and large events increased significantly in May and July from 1994 to 2005, while amount of small events decreased in November ($p<0.05$, Table 1).

3.2 Effects of rainfall patterns on growth periods

The growth periods of the three perennial forages—Festuca, Kobresia and Bluegrass - increased significantly with total amount of annual rainfall and large events ($p<0.05$, Figs. 2a,b,c and 3a,b,c), while they did not change with total rainfall frequency ($p>0.6$, Fig. 2d, e, f) and small rainfall event (data not shown). Only the growth periods of Festuca showed a significant increase with the frequency of large rainfall events (≥ 5 mm) ($p<0.05$, Fig. 3f), when those of Bluegrass increased marginally with frequency of large rainfall events ($p=0.08$, Fig. 3d). Growth periods of all three plants did not change significantly with frequency of annual rainfall and small events (< 5 mm) as well as those of Kobresia with frequency of large rainfall events ($p>0.10$, Fig. 3e).

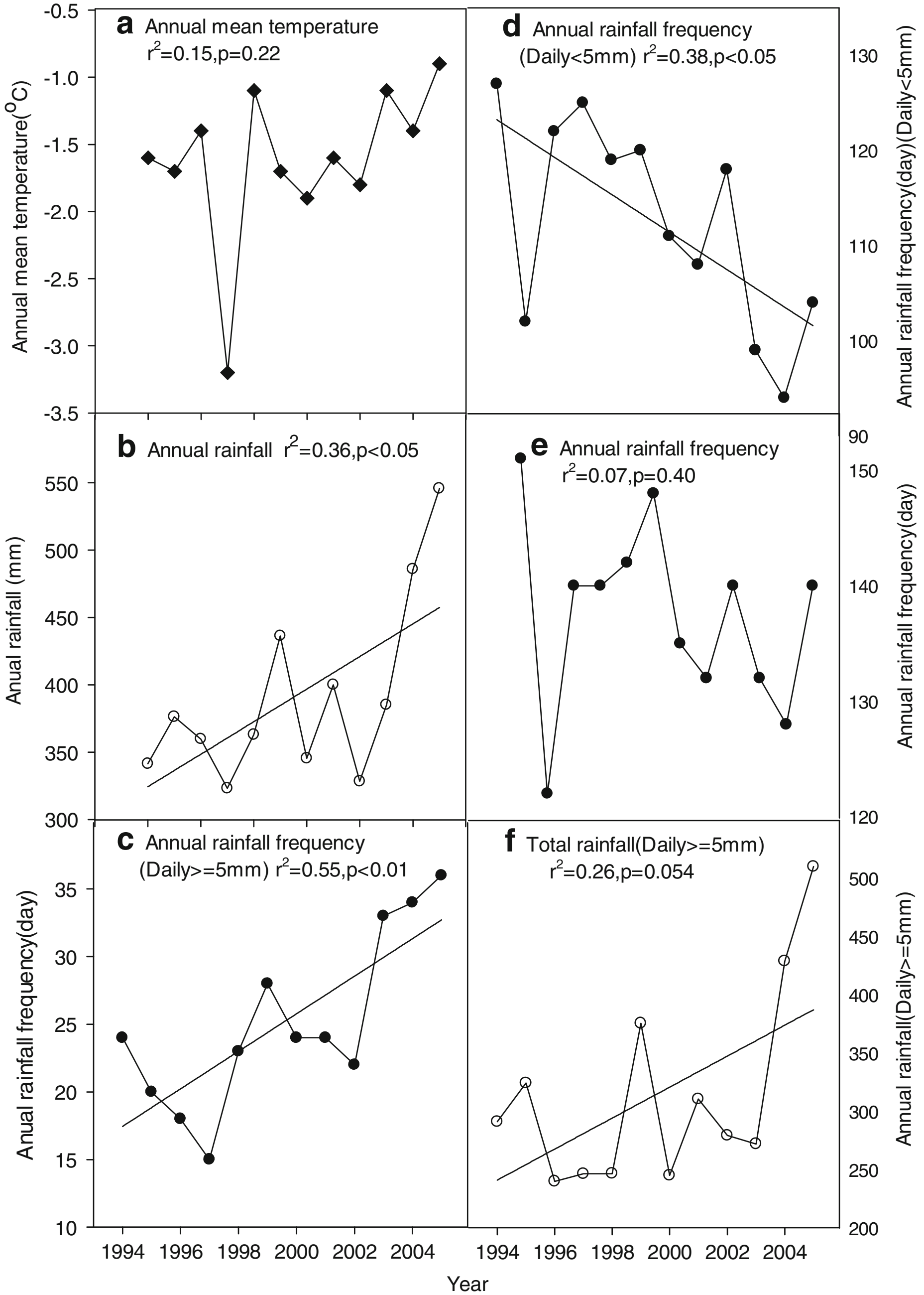

Fig. 1 Annual mean temperature (**a**), annual rainfall (**b**), rainfall frequency of annual (**c**), large events (≥ 5 mm per day, **d**), and small events (< 5 mm per day, **e**), and total rainfall from large events (**f**) from 1994 and 2005

Table 1 The change trend (i.e., the slop of the linear regression over time) in rainfall pattern from 1994 to 2005

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall frequency												
RF<5	−0.14	−0.15	0.04	−0.42	0.56[c]	0.11	−0.34	0.32	−0.14	0.14	−0.57[a]	−0.04
RF≥5	0	0	0	0.1	0.16	0.06	0.24	0.3	0.22	0.06	0.07	0
ARF	−0.14	−0.12	0.04	−0.37	0.70[b]	0.19	0.06	0.68[c]	0.1	0.19	−0.50[b]	−0.04
Rainfall Amount												
RA<5	−0.12	0.046	0.12	−0.09	1.15	0.64	−0.44	1.37	0.28	0.18	−0.60[a]	−0.16
RA≥5	0	0	0	0.21	1.11[a]	1.42	6.23[a]	3.04	−0.71	−1.09	−0.29	−0.17
ARA	−0.03	0.21	0.04	0.12	2.26[b]	2.05	5.80[b]	0.32	−0.14	−0.11	−0.58	−0.33

Unit is day/year for rainfall frequency and mm/year for rainfall amount

RA<5 - Rainfall Amount (Daily<5 mm); RA≥5 - Rainfall Amount (Daily≥5 mm); ARF-Annual Rainfall Frequency; RF<5-Rainfall frequency (Daily<5 mm); RF≥5-Rainfall frequency (Daily ≥5 mm); ARA - Annual Rainfall Amount

[a] represents significance at the 0.01 level

[b] at the 0.05 level

[c] at the 0.1 level

3.3 Effects of rainfall patterns on aboveground biomass (AGB)

The AGB of the Tibetan alpine meadow increased significantly with a rate of 4.92 gm^{-2} $year^{-1}$ from 1994 to 2005 (p=0.05), and showed a synchronized increase with annual rainfall amount with a rate of 0.38 $g.mm^{-1}$ (r^2=0.66, p<0.001, Fig. 4a). However, the frequency of annual rainfall did not have a significant correlation with AGB (p>0.8, Fig. 4d).

The AGB of the alpine meadow increased marginally with total rainfall and frequency from large events (≥ 5 mm) (Fig. 4c,f), while the total rainfall amount and frequency from small events (< 5 mm) did not show the significant effects on AGB (p>0.05, Fig. 4b, e; Table 2). Higher rainfall frequency of large events (≥ 5 mm) may promote more grassland production compared with that of small events (< 5 mm). The sensitive coefficient of AGB with the changes in large rainfall frequency (i.e., the slope of the linear regression) was 2.65 $g.m^{-2}.day^{-1}$ (Fig. 4f).

3.4 Relationship between growth period and AGB

The correlations between grassland AGB, rainfall pattern, and growth period by person Pearson correlation were shown in Table 2. The total AGB was correlated significantly with the growth periods of three dominant plants (r^2≥0.54, p<0.01). In addition, regression coefficient of Festuca was maximum, followed by Bluegrass and Kobresia (Fig. 5).

4 Discussion

In the area of Tibetan alpine meadows, the total rainfall amount have an increasing trend from 1994 to 2005 as well as total rainfall from large events (≥ 5 mm, Fig. 1), whereas the

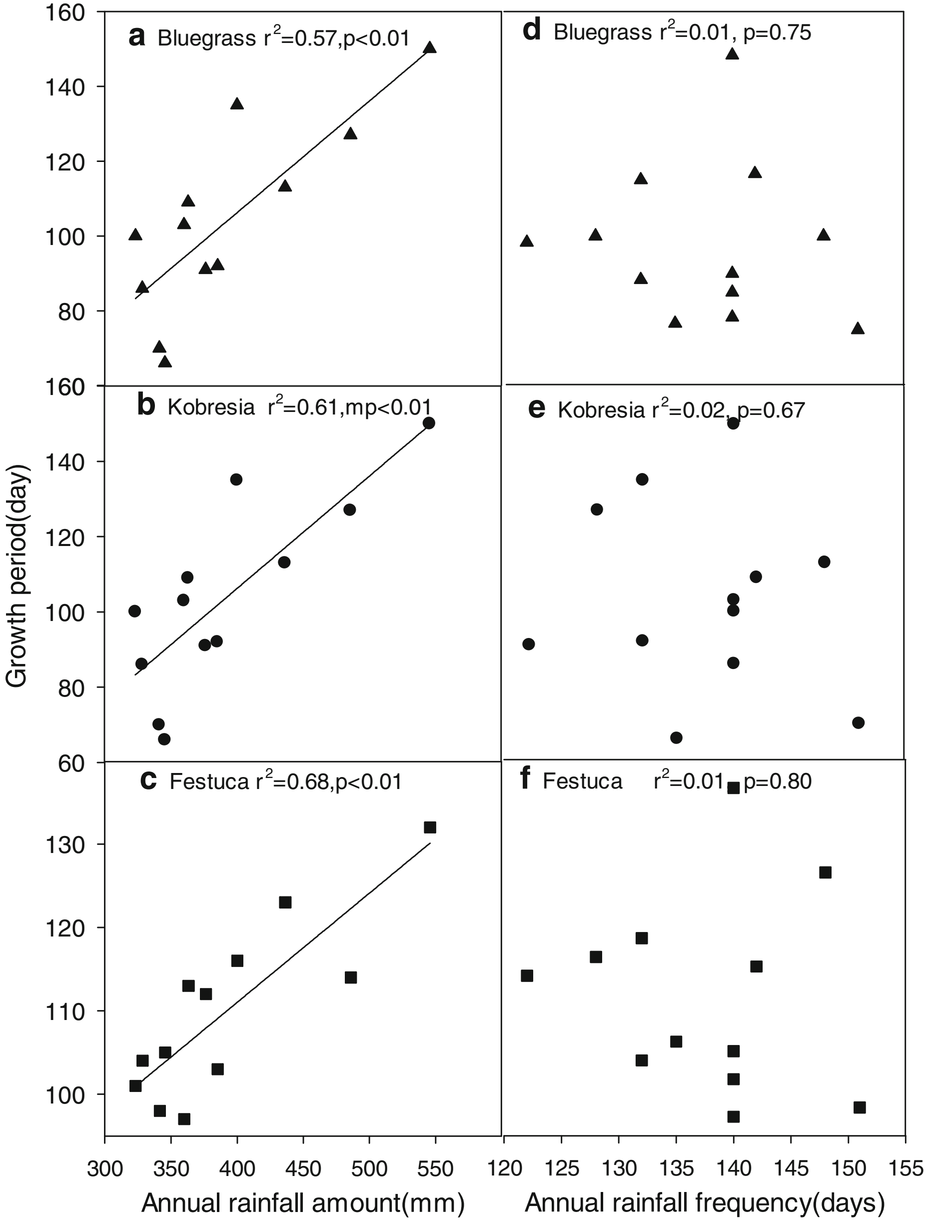

Fig. 2 Relationships of annual rainfall amount and frequency with growth periods of three dominant forage grasses—Festuca (**a**, **d**), Kobresia (**b**, **e**) and Bluegrass (**c**, **f**)—from 1994 to 2005

trend of small events (< 5 mm) was not significant ($p>0.1$). Furthermore, the frequency of large rainfall events presented an increasing trend, while the small ones showed a decrease over time. This implied that the increase in precipitation mainly resulted from large rainfall events (≥ 5 mm) (Fig. 1b, c), which are usually regarded as effective rainfall (Munson et al. 2010; Wei et al. 2008).

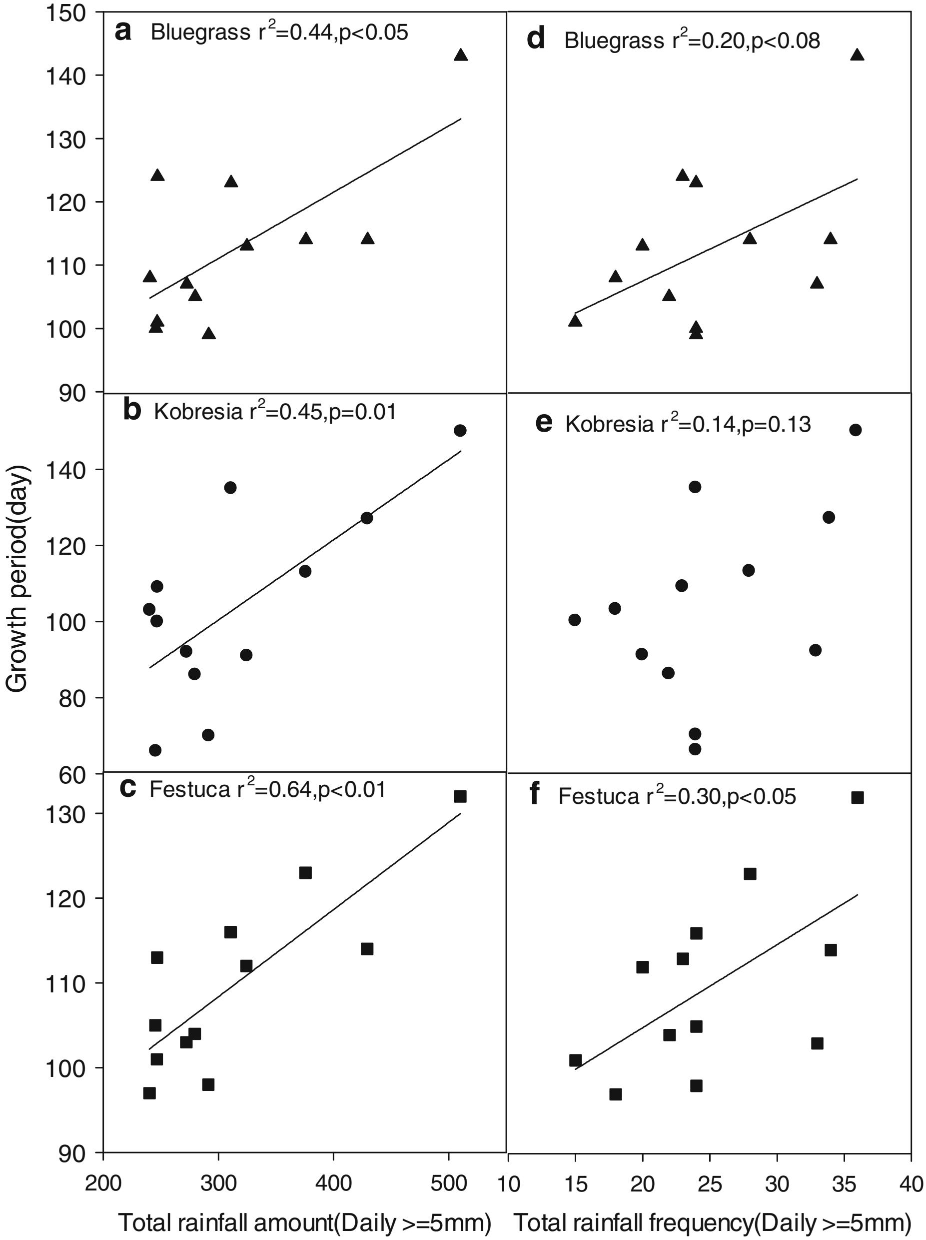

Fig. 3 Relationships of total rainfall and frequency from large events (≥ 5 mm)with growth periods of three dominant forages (Festuca, Kobresia and Bluegrass) from 1994 to 2005

4.1 Effects of rainfall amount and frequency on AGB

Large rainfall events played a pivotal role in promoting leaf development and leaf-level photosynthetic capacity and in maintaining plant activity (Yang et al. 2008). Large rain events not only increased water infiltration in soil but also reduced the proportion of water

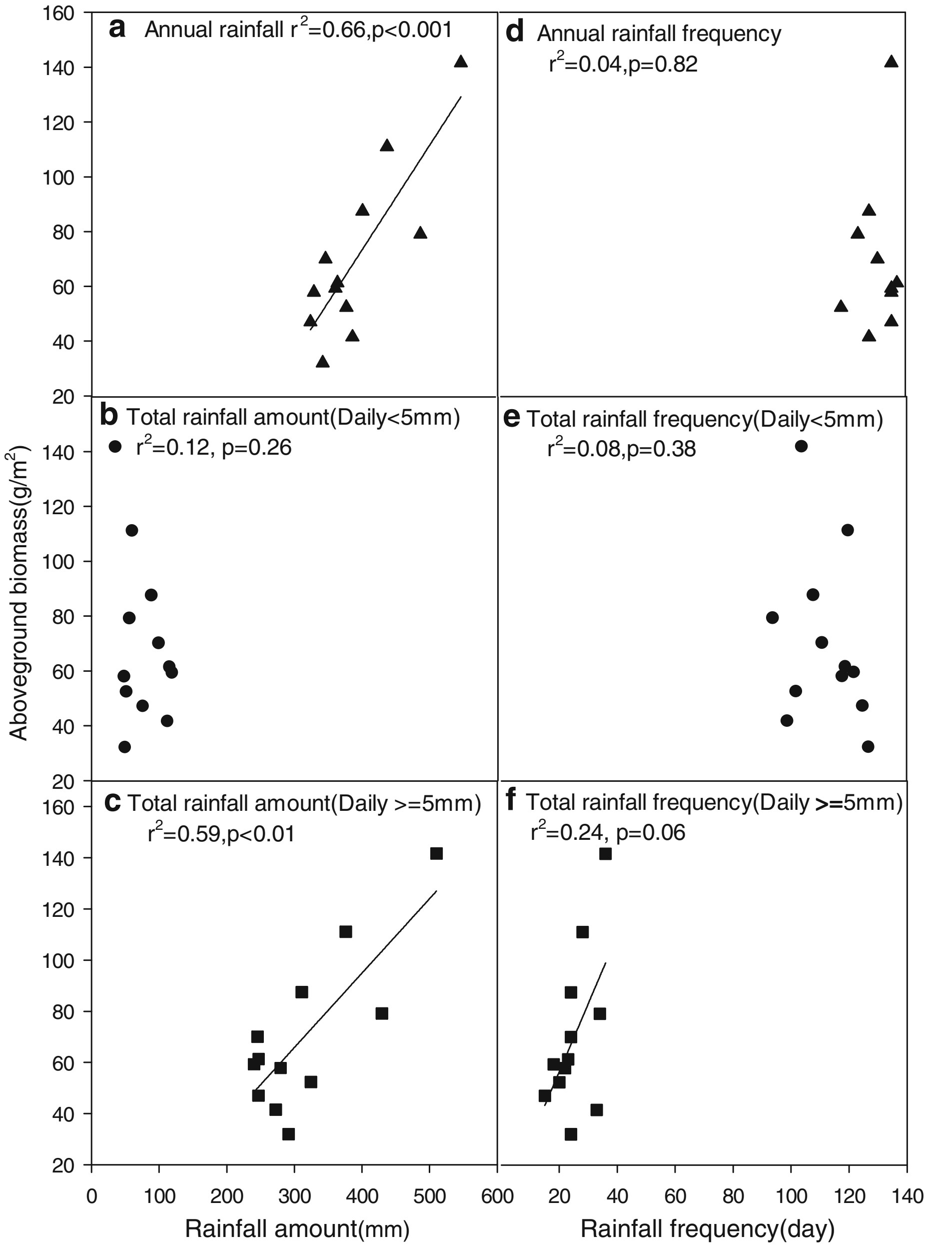

Fig. 4 Relationships of aboveground biomass (AGB) with total rainfall and frequency from annual, small events (< 5 mm), and large events (≥ 5 mm) from 1994 to 2005

loss via evaporation and transpiration (Weltzin et al. 2003). Large rainfall events would thus recharge deeper soil layers more effectively (Knapp et al. 2008). The recharged soil water would become available for plant use above critical thresholds of growth for the long period (Du et al. 2011; Nord and Lynch 2009; Sala and Lauenroth 1982),

Table 2 Correlations of rainfall patterns with AGB and growth period of three dominant forages

	AGB	Festuca	Kobresia	Bluegrass	RA≥5	RA<5	ARA	RF≥5	RF<5	ARF
AGB	1	0.905[a]	0.762[a]	0.789[a]	0.789[a]	−0.351	.830[a]	0.554[b]	−0.278	0.668[b]
Festuca	0.905[a]	1	0.766[a]	0.864[a]	0.824[a]	−0.429	.839[a]	0.604[b]	−0.421	0.675[b]
Kobresia	0.762[a]	0.766[a]	1	0.862[a]	0.707[b]	−0.186	0.801[a]	0.468	−0.381	0.776[a]
Bluegrass	0.789[a]	0.864[a]	0.862[a]	1	0.700[b]	−0.203	0.784[a]	0.519[b]	−0.384	0.841[a]
RA<5	−0.351	−0.429	−0.186	−0.203	-0.684[b]	1	−0.41	−0.265	0.111	−0.108
RA≥5	0.789[a]	0.824[a]	0.707[b]	0.700[b]	1	-0.684[b]	0.946[a]	0.748[a]	−0.518[b]	0.516
ARA	0.830[a]	0.839[a]	0.801[a]	0.784[a]	0.946[a]	−0.41	1	0.817[a]	-0.598[b]	0.597[b]
RF<5	−0.278	−0.421	−0.381	−0.384	−0.518	0.111	−0.598[b]	−0.668[b]	1	−0.224
RF≥5	0.554	0.604[b]	0.468	0.519	0.748[a]	−0.265	0.817[a]	1	−0.668[b]	0.178
ARF	0.069	−0.082	−0.137	−0.102	−0.098	−0.063	−0.15	−0.098	0.806[a]	1

AGB - aboveground biomass; RA<5 - Rainfall Amount (Daily<5 mm); RA≥5 - Rainfall Amount (Daily≥5 mm); ARA - Annual Rainfall Amount; RF<5-Rainfall frequency (Daily<5 mm); RF≥5-Rainfall frequency (Daily ≥5 mm); ARF-Annual Rainfall Frequency

[a] represents significance at the 0.01 level

[b] at the 0.05 level

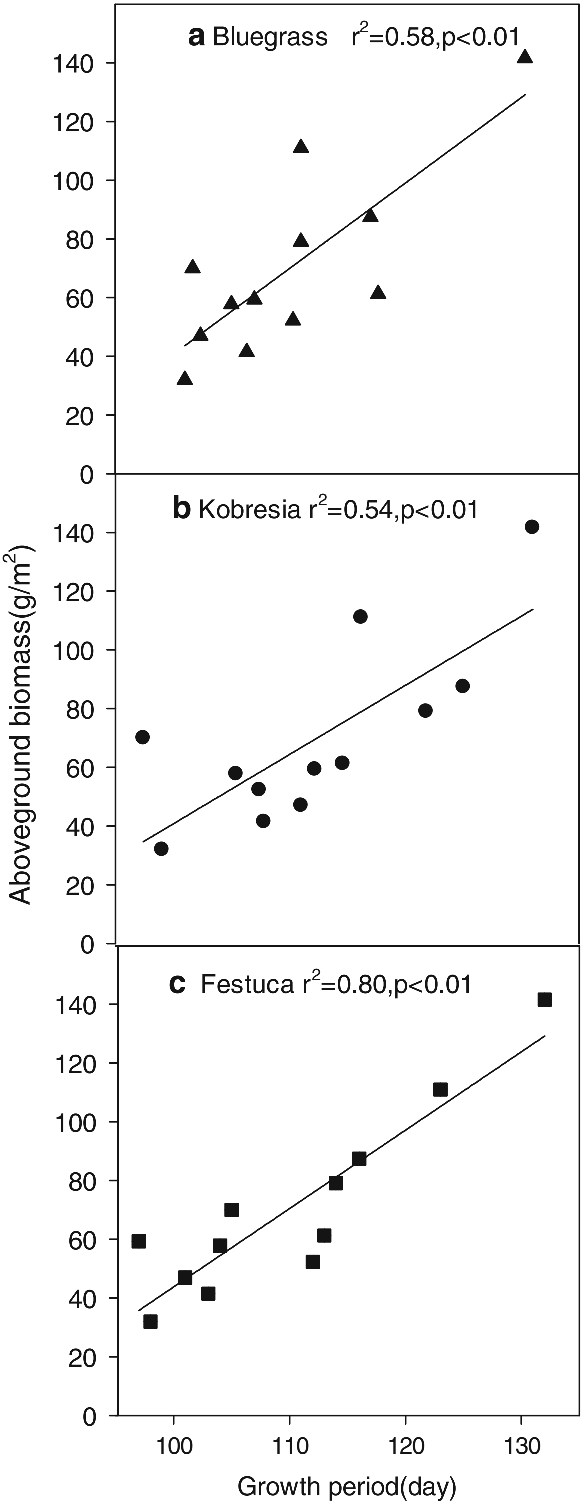

Fig. 5 Relationships between aboveground biomass (AGB) and growth periods of three dominant forage grasses (Festuca, Kobresia and Bluegrass) from 1994 to 2005

Most of large rainfall events in the growing season showed an increasing trend from 1994 to 2005 (especially, in May and Jul). At that time, leaf area is quickly developed with high photosynthetic C uptake to accumulate high biomass (Thomson et al. 1997; Loik 2007; Potts et al. 2006). Rainfall amount and frequency of large events (≥ 5 mm) could thus improve alpine meadow production, which is consistent with previous research (Dougherty et al. 1996; Fay et al. 2008). Large rainfall events (≥ 5 mm) are thus a major part of annual precipitation (80 % total) to promote grassland production (Bai et al. 2008; Fay et al. 2003; Sherry et al. 2008; Yang et al. 2008, 2009, 2010). In the future, the Tibetan alpine meadow may be largely benefited for plant primary production if the increasing trend in large rainfall events continues (Fig. 1).

Alpine meadow production showed a synchronized increase with annual rainfall amount during the study period ($p<0.001$, Fig. 4a). Although some studies found that annual rainfall would have a lag effect on plant production (Milchunas and Lauenroth 2001; Sims and Singh 1978; Sherry et al. 2008; Swemmer et al. 2007) and the linear correlation between previous-year rainfall and ANPP was significant ($p=0.02$) in this study, the results from stepwise regression analysis with current- and two previous-year rainfall showed that the previous-year rainfall could not be included in the model. We thus considered that the effects of previous-year rainfall on plant production were minor compared to the effects of the current-year rainfall. In addition, growth period of the three plants did not present significant correlations with the previous-year rainfall (data not shown).

4.1.1 Effects of rainfall amount and frequency on growth period

Plant life history can be largely affected by the duration, intensity and frequency of rainfall events (Loik 2007; Noy-Meir 1973; Schwinning and Ehleringer 2001). Our results showed that the growth periods of three perennial species increased significantly with rainfall amount and frequency of large events except that of Kobresia with rainfall frequency (Fig. 3a, b, c). This supported previous study that large rainfall could keep higher water availability and pulse leaf sprout during leaf flush than small one (Blum 1996). In earlier spring, plant available water might prompt shoot growth via synthesis of plant hormones, uptake of water and absorption of nutrients (Dieleman et al. 1998), which may result in earlier bud burst. Lack of spring soil moisture may not facilitate turning greenness in annual grassland in California (Zavaleta et al. 2003). In autumn, large rainfall events keep plant vigour (Barr et al. 2007; Jolly and Running 2004) through changing foliar concentrations of nitrogen (Santiago et al. 2005) and altering soil nutrient mineralization (Huxman et al. 2004). The increase in foliar nitrogen content would improve plant vigor (Feng et al. 2009) to delay senescence and increase growth period. In this study, effective rainfall (i.e., large events) increased in April and May after plant flush and in July and August after leaf senescence (Table 1), resulting in the extension of the growing season for the dominant forages (Jolly and Running 2004) and increasing AGB over the study period. However, the growth periods of the three dominant plants responded differently to frequency of large rainfall events (≥ 5 mm). This may result from different ecophysiological environment. Festuca prefers to habit in xerophytes, whereas Bluegrass prefers to habit in mesic environment and Kobresia is not stringent for moisture condition (Zhao 2009).

4.1.2 Relationship between AGB and growth period

With earlier greenness in spring and later senescence in autumn, extension of the growth period indicated that plants would have more time to uptake atmospheric CO_2 and have potential to accumulate primary production (Fay et al. 2003). Our results showed that the growth periods of three dominant species had positive relationships with their respective AGB. Long-term record in the agriculture showed that an increase in the length of growth period significantly stimulated crop yield (Liu et al. 2010; Tao et al. 2006; Wang et al. 2008). The extension of growth period also facilitates the increase in primary production in natural ecosystems (Churkina et al. 2005; Davison et al. 2011).

5 Conclusions

Precipitation is a main controlling factor for plant growth in the low-temperature and high-altitude Tibetan Plateau. The production of the alpine meadow depended on rainfall quantity, frequency, and growth period of the dominant forages, especially large rainfall events (≥5 mm). Our finding not only provides insight for the management of forage grasses in the Qinghai-Tibet Plateau (e.g., conservative grazing), but also demonstrates the necessity to incorporate precipitation patterns and their effects into predictive climatic and ecological models. It is important, therefore, that the frequency, magnitude, and amount of rainfall should be integrated to examine their effects on ecosystem processes in future climate change on the Qinghai-Tibet Plateau.

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