CSIRO PUBLISHING

The Rangeland Journal, 2015, **37**, 181–190
http://dx.doi.org/10.1071/RJ14062

Effects of grazing systems on herbage mass and liveweight gain of Tibetan sheep in Eastern Qinghai-Tibetan Plateau, China

Y. Sun[A], *J. P. Angerer*[B] *and F. J. Hou*[A,C]

[A]State Key Laboratory of Grassland Agro-ecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou, 730000, Gansu, China.
[B]Texas A&M AgriLife Research, Blackland Research and Extension Cent, Temple, Texas, 76502-9622, USA.
[C]Corresponding author. Email: cyhoufj@lzu.edu.cn

Abstract. Grazing strategies, consisting of grazing systems and stocking rate adjustments, have evolved from the need to sustain efficient use of the forage resources by livestock, increase animal performance and sustain forage production. A 3-year study was conducted with Tibetan sheep on the Eastern Qinghai-Tibetan Plateau, China to compare: (1) two grazing systems [season-long continuous (SLC; July to December) versus short duration with seasonal rotation (SDSR; July to September in growing-season pasture and October to December in cold-season pasture) with a stocking rate of 24 sheep months ha^{-1}(SM ha^{-1})]; (2) SDSR system with 24, 36 and 48 SM ha^{-1}; and (3) seasonal aspects of stocking rate under the SDSR system by comparing strategies of heavy stocking rate in the growing season and light stocking rate in the cold season (SDSR-HL) versus light stocking rate in the growing season and heavy stocking rate in the cold season (SDSR-LH). No differences were found between grazing systems in liveweight gain per head or per ha and in residual herbage mass. Liveweight gain per head for treatment SDSR24 was greater than for treatments SDSR36 and SDRS48, whereas liveweight gain per ha showed the opposite tendency. No differences were found between the SDSR-HL and SDSR-LH treatments in liveweight gain per head or per ha, whereas the ratio of residual herbage mass at the end of grazing the growing-season pasture to the cold pasture of treatment SDSR-LH was more than twice that of treatment SDSR-HL. Daily liveweight gain of Tibetan sheep decreased linearly with increasing grazing pressure in both growing and cold seasons. It was estimated that, at a grazing pressure index of 310 sheep days t^{-1} DM peak herbage mass, liveweight gain per head and ha appears to be optimised over the whole grazing period. Liveweight loss by Tibetan sheep during the cold season was apparent regardless of grazing pressure indicating that temperature had a stronger influence on sheep performance in the cold season than herbage availability.

Additional keywords: alpine grasslands, domestic animal production, grazing management, rangeland management.

Received 10 May 2014, accepted 16 February 2015, published online 27 March 2015

Introduction

Grazing strategies, consisting mainly of the selection of a grazing system and stocking rate, have evolved from a need to sustain efficient use of the forage resource by livestock and to improve livestock performance and forage production (Briske *et al*. 2008; Hunt *et al*. 2014; O'Reagain *et al*. 2014). Grazing systems originated from nomadism and progressed to more sophisticated rotational systems during the 20th century, and most recently to intensive short-duration systems (Briske *et al*. 2008) but, for forage and livestock production on rangelands, the effects of rotational and continuous grazing are similar (Norton 1998; Teague and Dowhower 2003; Briske *et al*. 2008; O'Reagain *et al*. 2014). In the development of grazing strategies, the optimisation of livestock gains with forage use and productivity are of interest. The relationship between livestock performance and plant productivity received little attention until the 1950s when researchers examined livestock and vegetation responses in relation to economic metrics across stocking rates (Harlan 1958; Klipple and Bement 1961; Riewe 1961). Bement (1969) proposed that the average daily liveweight gain per animal decreased with increasing stocking rate whereas the animal liveweight gain per unit area exhibited an opposite trend. The 'optimum' stocking rate occurred at the 'intersection' of the average daily liveweight gain and the liveweight gain per unit area curves. This model was improved by additional studies that found that liveweight gain per animal remained flat, then decreased linearly after a specific point where grazing pressure exceeded a threshold, and liveweight gain per unit area changed along a parabola with the increasing stocking rate (Manley *et al*. 1997; Hart and Ashby 1998). Furthermore, Hart (1972) described the limitations of other approaches (e.g. Harlan 1958) and suggested the need for a metric to standardise stocking rate. He proposed use of forage allowance, which was defined as forage mass divided by number of animal days per unit area. Hart (1972) also proposed the use of grazing pressure (the inverse of forage allowance) and showed that the relationship between daily liveweight gain per animal and grazing pressure was mathematically linear. Smart *et al.* (2010) suggested that researchers should adopt the use of the grazing pressure index, which can be defined as the 'animal to forage relationship measured in terms of animal units per unit of weight of forage over a period of time' (Bedell 1998). The grazing pressure index would allow stocking rates to be standardised, thus allowing for comparisons across larger geographic areas. In addition, the herbage remaining in pastures, as influenced by stocking rates, is considered to play an important role in keeping rangeland production sustainable and preventing degradation of rangeland (Bement 1969).

On the Qinghai-Tibetan Plateau, grazing of livestock has occurred for thousands of years (Gerald *et al.* 2003; Xin *et al.* 2011; Feng *et al.* 2013) and Tibetan sheep (*Ovies aries*) are one of the major livestock species, with a population of over 50 million animals, providing meat, milk and income for the majority of people living in this region (Harris 2010; Xin *et al.* 2011). However, for centuries, Tibetan sheep have been caught in the vicious cycle of 'alive in summer, strong in autumn, thin in winter and tired in spring' (Dong *et al.* 2003) because of strong abiotic and biotic factors present in the plateau. The seasonal fluctuations in herbage supply, both in quantity and quality, influence the ratio of herbage intake to liveweight gain (Masters *et al.* 1990; Zhao *et al.* 1991; Dong *et al.* 2006; Xin *et al.* 2011). In the spring, pasture growth occurs in May and biomass production increases rapidly (Gerald *et al.* 2003). Forage is generally plentiful and of high nutritive value in the summer (Long *et al.* 1999; Zhao *et al.* 2000). During the autumn and winter (October–May), Tibetan sheep graze standing dormant grasses, and as the long, cold season progresses, they suffer from inadequate feed supply resulting in poor nutrition and health-related problems. During the cold season, Tibetan sheep can lose as much as 20–30% of their liveweight (Ren 2008). These negative biotic effects are exacerbated by poorly planned grazing management on alpine rangeland (Dong *et al.* 2003; Xue *et al.* 2005; Feng *et al.* 2013). Hence, the livestock production and the forage utilisation efficiency of the traditional production system are very low (Zhao *et al.* 1989). Furthermore, to compensate for the low efficiency, producers have increased sheep numbers in order to reach an 'appropriate' herd size to meet their economic needs, which has resulted in continued vegetation and soil degradation of the plateau (Mishra *et al.* 2001; Zhou *et al.* 2002; Shang and Long 2007; Shang *et al.* 2014). This trend has intensified in recent decades (Du *et al.* 2004; Wang *et al.* 2008*a*), causing severe economic and environmental problems for the local people. It has also affected people who live in central and east of China through the changing of the ecological environment at the headwaters area of Yangtze-Yellow River (Shang and Long 2007) and increasing the frequency of dust storms (Fang *et al.* 2004). Given these economic and environmental problems that have been attributed to increasing livestock numbers, no official recommendations of stocking rates exist to ensure sustainable pasture use by producers (Wang *et al.* 2005; Zhang *et al.* 2014) and existing information documenting improvement measures that could be used in management is limited. So, it is of essential importance to develop a grazing strategy that considers both livestock productivity and environmental aspects (Owensby *et al.* 2008).

The objectives of this study were: (1) examine the effects of grazing system and stocking rate on Tibetan sheep performance and alpine rangeland productivity; (2) explore the 'optimal' stocking rate with a seasonal rotational grazing system, (3) examine the seasonal aspects of grazing strategy on Tibetan sheep performance and alpine rangeland productivity under a seasonal rotational grazing system, and (4) investigate the relationship between the daily liveweight gain of Tibetan sheep and grazing pressure index both in growing and cold seasons. To our knowledge, this is the first comparative analysis addressing suitable grazing strategies concerning benefits of livestock and forage productivity in alpine rangeland of the Qinghai-Tibetan Plateau.

Methods

Study site

This study was conducted in Maqu county of Gansu province, China, situated the eastern of the Qing-Tibetan Plateau (N35°58′, E101°53′, 3500 m a.s.l.). The average annual temperature was 2.4°C in the past 13 years, and average warm and cold-season temperatures were 10.3°C and –1.6°C, respectively. Average annual temperatures in 2010, 2011 and 2012 were, respectively, 3.2°C, 2.5°C and 2.5°C. In the growing seasons of 2010, 2011 and 2012, average temperatures were 11.3°C, 10.4°C and 10.4°C, and in the cold season, average temperatures were –0.7°C, –1.4°C and –1.5°C, respectively (Fig. 1). In the past 13 years, precipitation has averaged 616 mm, and average precipitation

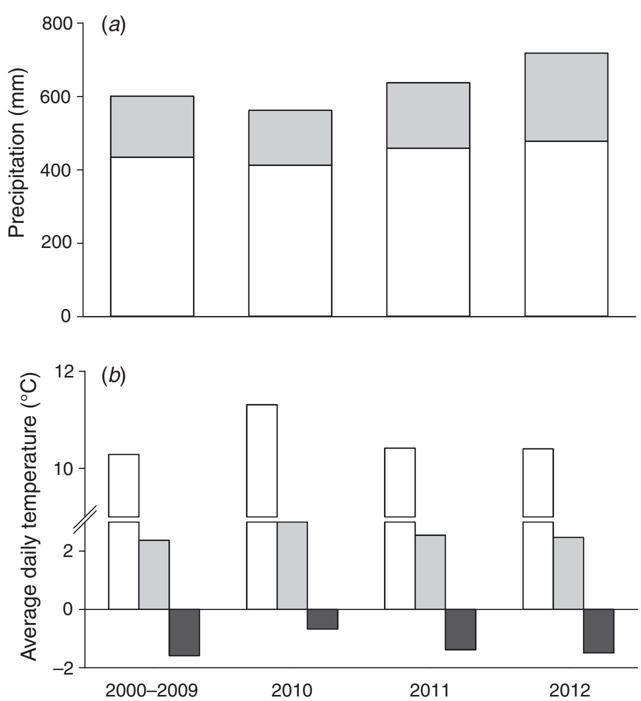

Fig. 1. (*a*) Precipitation and (*b*) average daily temperatures of the latest 13 years at the study site (data from Maqu Weather Station). In (*a*) and (*b*) the no-shaded part of the bar refers to the growing season and the dark-shaded bar refers to the cold season, and in (*b*) the light-shaded bar refers to annual daily average temperature bars.

occurring during the growing and cold seasons was 442 and 173 mm, respectively. In 2010, 2011 and 2012, annual precipitation totalled 580, 637 and 697 mm, respectively; growing season precipitation totals were 423, 459 and 472 mm; and cold-season precipitation totals were 158, 178 and 225 mm, respectively (Fig. 1). The site averages 2580 h of sunshine and more than 270 frost days per year (Ma *et al*. 2013). The soil type at the study site is alpine meadow soil that is primarily Mat-Cryic Cambisols (Gao and Li 1995), which is a common soil in the area surrounding the study site (Wu *et al*. 2010). The plant community type is mainly alpine meadow that is dominated by many monocotyledons species, primarily Poaceae and Cyperaceae. Various dicotyledonous species are also common, such as those belonging to the *Ranunculaceae*, *Polygonaceae*, *Saxifragaceae*, *Asteraceae*, *Scrophulariaceae*, *Gentianaceae* and *Fabaceae* (Ma *et al*. 2010*a*, 2010*b*).

Grazing treatments

In the early spring of 2010, a season-long continuous grazing system (SLC) and short-duration seasonal rotational grazing system (SDSR) were set up with fixed fences, covering 35 ha (24 ha were used for field experiment and remaining areas were supplemental or buffer zones) on a typical alpine rangeland. Prior to the implementation of this experiment, the study site was used by the local government as a yak research institute where continuous grazing had been implemented for the past 30 years. Stocking rates during that period had been kept at moderate to slightly above moderate.

The treatments were: SLC24 – season-long continuous grazing from July to December at 24 sheep months (SM) ha^{-1}, SDSR24 – short-duration seasonal rotational grazing at 24 SM ha^{-1} from July to September in growing-season pasture and October to December in cold-season pasture, SDSR36 – the average response of SDSR-HL and SDSR-LH treatments (see below), SDSR48 – short-duration seasonal rotational grazing at 48 SM ha^{-1} from July to September in growing-season pasture and October to December in cold-season pasture, SDSR-HL – short-duration seasonal rotational grazing at 48 SM ha^{-1} from July to September in growing-season pasture and 24 SM ha^{-1} from October to December in cold-season pasture, and SDSR-LH – short-duration seasonal rotational grazing at 24 SM ha^{-1} from July to September in growing-season pasture and 48 SM ha^{-1} from October to December in cold-season pasture.

For the SLC24 treatment, eight sheep grazed on a 2-ha pasture continuously during the growing and cold seasons (6 months). For the comparison of light stocking rates under two grazing systems, each system had a common stocking rate of 24 SM ha^{-1}. For the SDSR24 treatment, eight sheep grazed in a 1-ha paddock during the growing season (3 months) and were then rotated to a 1-ha cold-season pasture (3 months). For the SR36 treatment, the response of eight sheep grazing on the SDSR-HL and SDSR-LH treatments were averaged. For treatment SDSR48, eight sheep grazed 0.5-ha paddocks sequentially on the growing-season pasture and the cold-season pasture. For the SDSR-HL treatment, eight sheep grazed on 0.5-ha paddocks (48 SM ha^{-1}) on the growing-season pasture and on 1.0-ha paddocks (24 SM ha^{-1}) on the cold-season pasture. For the SDSR-LH treatment, eight sheep grazed on 1.0-ha paddocks (24 SM ha^{-1}) on the growing-season pasture and eight sheep grazed on 0.5-ha paddocks (48 SM ha^{-1}) on the cold-season pasture.

Sheep were moved from the growing-season pastures to the cold-season pastures in late September. Although heavy stocking rates in the cold season would generally not be recommended in this region, heavy stocking does occur in this region when herders concentrate their livestock during very cold winters and when herders are unable to sell livestock before the cold season.

All grazing treatments had three replicates. Within each replicate of the SDSR treatments, growing-season paddocks were subdivided into three sub-paddocks whereas cold-season paddocks were subdivided into two sub-paddocks. In these treatments, sheep were rotated between the sub-paddocks every 10 days during the growing season and every 15 days during the cold season, giving each sub-paddock 20 days of rest during the growing season and 15 days of rest during the cold season. The SLC pasture had no rest/rotation periods and sheep grazed the pasture for 6 months (both growing and cold seasons) during each year of the study.

In order to address the research objectives, the grazing treatment comparisons were as follows: (1) treatments SLC24 versus SDSR24; (2) treatments SDSR24 versus SDSR36 versus SDSR48; and (3) treatments SDSR-HL versus SDSR-LH.

Measurements

Pasture samples were collected in 2010, 2011, and 2012 to determine herbage mass and the residual herbage mass at the end of each grazing period. For this assessment, herbage-mass samples were collected at the beginning and end of each grazing period based on the livestock movement schedule of the SDSR treatments (i.e. 10 days in growing season and 15 days in the cold season). Samples of herbage mass were collected from three randomly placed quadrats (0.5×0.5 m) along a diagonal transect in each grazed sub-paddock. This resulted in nine quadrats for each replicate paddock and each grazing period (30 days) in the growing season and six quadrats for each replicate paddock and grazing period in the cold-season pasture. The SLC paddocks were sampled at the same time as the SDSR treatments with the same number of samples per replicate paddock. The herbage mass of each seasonal grazing period was the average herbage mass (total without litter) of 27 quadrats in the growing season and 18 quadrats in the cold season per replicate. The sampling method for the measurement of residual herbage mass, which included litter, was the same as that used for the measurement of herbage mass for both growing- and cold-season pastures and was conducted at the end of the growing and cold seasons. For the statistical analyses for each scenario, the averages of the residual herbage mass in the growing- and cold-season pastures were used. To assess peak herbage mass during each year of the study, four 1 m $\times$ 1-m cage exclosures were installed in each grazing treatment (growing- and cold-season pastures under SDSR, and pastures under SLC) at the beginning of the growing season during the first year of measurement. At the end of August during each year of the study, a 0.5×0.5-m quadrat was placed inside each cage and herbage mass clipped from the quadrat. After clipping, the cages were placed randomly in another location for the subsequent year's evaluation. All herbage mass samples were oven-dried in at 55°C for 48 h to determine total dry matter (DM) content (AOAC 1980).

For each year of the experiment, 150 5–7-month-old male Tibetan sheep were purchased during the middle of June from local farms near the study area. Of these, 120 were used in the experiment and 30 were kept as replacements in case of sickness or death of the experimental sheep. At the end of each year, the sheep were sold and new ones purchased in the following June. One day after arrival of the sheep, the sheep were ear-tagged, vaccinated, and treated for parasites with Albendazole (Hanzhong Tianyuan Pharmaceutical Co. Ltd, Shanxi, China). Initial liveweights of each sheep were determined as the average of liveweights from two consecutive days (Days 0 and 1) after the sheep had been grazing in the buffer zone for ~2 weeks. The sheep used for the experiment were grouped into 15 groups according to their liveweight to make sure the average original liveweights were similar among the grazing treatments [the average liveweights (kg) at the beginning of the study were 29.1 ± 3.03, 26.6 ± 2.21 and 27.7 ± 2.40 kg in 2010, 2011 and 2012, respectively]. The sheep were marked with paint on their rumps to make it easy to identify the different groups. On Day 0 (1 July in each year of the experiments), the sheep groups were randomly assigned to one of the replicate treatment paddocks for both the SDSR (12 paddocks) and SLC (three paddocks) grazing systems. All the sheep had access to a mineral-mix block, made at a local factory, and fresh water while on pasture for the duration of the study.

Measurements of liveweight were made on two consecutive days at the end of each month to determine liveweight gain.

Data analyses

Repeated-measures ANOVA was used to examine the effects of grazing treatments, sampling year and their interactions on the liveweight gain per head and per ha of Tibetan sheep, residual herbage mass and ratio of the residual herbage mass left in growing-season (G) and cold-season (C) pastures (G/C) for each of the three grazing treatment comparisons described above. Differences among means were considered significant at the $P < 0.05$ level. All statistical tests were performed using the Software Statistical Package for the Social Sciences version 19.0 (SPSS Inc., Chicago, IL, USA).

Liveweight gain per head was determined as the difference between the in- and off-grazing period liveweights following the standardised diet period divided by the number of days. Liveweight gain per ha was determined from sheep numbers on each paddock × daily liveweight gain per head × days on a specific pasture (Schlegel *et al*. 2000). The number of days on a pasture was the actual days that sheep grazed a specific experimental paddock. Sheep that died during the grazing period were replaced with ones from the herd of replacements immediately but the average of the remaining sheep's daily liveweight gain was used as the plot average value. The grazing pressure index (GPI) was determined, according to Smart *et al*. (2010) as follows:

$$\mathrm{GPI} = \mathrm{SR}/\mathrm{PHM} \tag{1}$$

where SR is stocking rate defined as the relationship between the number of animals and the grazing management unit utilised over a specified time period in animal unit days per ha (AUD ha^{-1}) and PHM is peak herbage mass. To derive AUD per ha, we calculated the Animal Unit Equivalent (AUE) for Tibetan sheep as:

$$\mathrm{AUE} = (\mathrm{W_{initial}})^{0.75\cdot}(\mathrm{W_{ref}}^{0.75})^{-1} \tag{2}$$

where $W_{initial}$ is average liveweight of Tibetan sheep during the grazing period in kg, W_{ref}, (kg) is the 454-kg reference liveweight for an Animal Unit (Schlegel *et al*. 2000; Smart *et al*. 2010), and D is the number of days on pasture. ANCOVA was used to test the assumption of homogeneity of regression slopes and intercepts, taking GPI as the covariate.

Results

The treatment-by-year interaction for all the variables was not significant for SLC and SDSR treatments (Table 1). The 3-year means are used, therefore, to describe the differences due to the main effects of the treatments.

Liveweight gain per head and per ha, and residual herbage mass, were not significantly different for the two grazing systems at 24 SM ha^{-1}. Liveweight gain per head under treatment SDSR24 was significantly higher than that of treatments SDSR36 and SDSR48 and the liveweight gain per ha had an opposite trend (Table 2). The residual herbage mass of treatment SDSR24 was higher than that of treatments SDSR36 and SDSR48. However, the ratios of residual herbage mass at the

Table 1. Significance of main effects and interaction of years (Y, 2010, 2011 and 2012) and treatments (T) for liveweight gain (LWG) per head and per hectare, residual herbage mass (RHM, t DM ha^{-1}), ratio of residual herbage mass in growing-season and cold-season pastures (RHM ratio) and grazing pressure index (GPI, AUD t^{-1}) for comparison of grazing system and stocking rates

Scenarios were: (1) GS-a comparison of grazing systems under light stocking rate using season long continuous grazing *v.* short duration seasonal rotation grazing; (2) SR-SDSR, a comparison of stocking rates (light, moderate, and heavy) under short duration seasonal rotation; and (3) SA-SDSR, a comparison of short duration seasonal rotation grazing strategies of heavy stocking rate in growing season and light stocking rate in cold season *v.* Light stocking rate in growing season and heavy stocking rate in cold season

Variables	Source	GS		SR- SDSR		SA-SDSR	
		F	*P*	*F*	*P*	*F*	*P*
LWG (g day^{-1})	Y	1.49	0.265	1.54	0.233	0.17	0.846
	T	0.00	0.985	36.74	0.000	0.25	0.627
	Y×T	0.39	0.684	0.39	0.811	0.39	0.684
LWG (kg ha^{-1})	Y	1.48	0.267	1.98	0.157	0.17	0.845
	T	0.00	0.994	219.19	0.000	0.25	0.630
	Y×T	0.39	0.683	0.84	0.511	0.08	0.927
RHM	Y	1.22	0.320	0.93	0.414	2.56	0.105
(t DM ha^{-1})	T	2.26	0.133	1050.25	0.000	2.37	0.122
	Y×T	0.05	0.995	1.31	0.305	0.33	0.855
RHM ratio	Y	1.94	0.172	0.11	0.897	2.44	0.116
	T	9.59	0.001	0.78	0.470	615.49	0.001
	Y×T	1.132	0.373	0.01	1.000	1.922	0.150
GPI (AUD t^{-1})	Y	3.016	0.087	2.18	0.132	3.422	0.067
	T	2.368	0.115	4711.56	0.001	3.285	0.095
	Y×T	0.620	0.554	0.12	0.973	0.190	0.829

Table 2. Liveweight gain (LWG, kg hd^{-1} and kg ha^{-1}), residual herbage mass (RHM, t DM ha^{-1}), ratio of residual herbage mass at the end of growing and cold seasons (after the natural logarithm transformation), and grazing pressure index (GPI, AUD t^{-1}) (means and standard deviation of the mean) in growing- and cold-season pastures for the stocking rate and grazing system scenarios

Scenarios were: (1) GS, a comparison grazing systems under light stocking rates using season long continuous *v.* short duration seasonal rotation; (2) SR-SDSR, a comparison of stocking rates (light, moderate, and heavy) under short duration seasonal rotation; and (3) SA-SDSR, a comparison of short duration seasonal rotation grazing strategies of heavy stocking rate in growing season and light stocking rate in cold season *v.* light stocking rate in growing season and heavy stocking rate in cold season. Means were averaged across years (2010–2012). Means followed by the same letter are not significantly different ($P < 0.05$)

Scenarios	LWG (kg hd^{-1})	LWG (kg ha^{-1})	RHM (t DM ha^{-1})	RHM ratio	GPI (AUD t^{-1})
			GS		
SDSR-L	11.8 ± 0.38a	47.2 ± 1.52a	2.3 ± 0.03a	1.7 ± 0.07a	23.6 ± 0.21a
SLC	11.8 ± 0.35a	47.2 ± 1.39a	2.2 ± 0.05a	1.6 ± 0.08b	23.8 ± 0.27a
			SR-SDSR		
Light	11.8 ± 0.38a	47.2 ± 1.52a	2.3 ± 0.03a	1.7 ± 0.07a	23.6 ± 0.21c
Moderate	11.0 ± 0.49b	58.7 ± 2.60b	1.9 ± 0.02b	2.1 ± 0.83a	31.3 ± 0.54b
Heavy	9.6 ± 0.63c	77.8 ± 5.01c	1.6 ± 0.03c	2.0 ± 0.11a	46.0 ± 1.11a
			SA-SDSR		
L-H	11.1 ± 0.43a	59.0 ± 2.30a	1.9 ± 0.03a	2.9 ± 0.21a	31.6 ± 0.41a
H-L	10.9 ± 0.56a	58.3 ± 2.97a	1.9± 0.03a	1.3 ± 0.03b	31.1 ± 0.58a

end of the grazing period in the growing-season and cold-season pastures were not significantly different (Table 2).

In describing the relationship between GPI and daily liveweight gain per head (ADG), a linear function was found to be the most appropriate fit. However, the relationship between GPI and liveweight gain per ha was explained by a quadratic function for the whole grazing period (Fig. 2). A theoretical maximum liveweight gain ha^{-1} (LGH) would occur at 71 AUD t^{-1} DM peak herbage mass and the 'optimum' stocking rate would occur at 31 AUD t^{-1} DM peak herbage mass according to the equations: ADG = 86.7 – 0.788 GPI ($R^2 = 0.83$), and LGH = 3.406 GPI – 0.034 GPI^2 – 12.021 ($R^2 = 0.96$).

No significant differences ($P > 0.05$) were found for any of the liveweight gain variables or residual herbage mass between treatments SDSR-HL and SDSR-LH. However, the ratio of residual herbage mass was almost two times higher in treatment SDSR-LH than in treatment SDSR-HL (Table 2).

An assessment was conducted to evaluate effects of GPI on daily liveweight gain per head in the growing and cold seasons for stocking rates under the SLC and SDSR systems. There were linear relationships between GPI and daily liveweight gain per head for each system/stocking rate and season (Fig. 3*a*, *b*; Table 3). In the growing season, there were no significant differences among the slopes of treatments ($P > 0.05$, Table 3) whereas the intercept of daily liveweight gain per head for treatment SDSR48 was larger than that of treatments SDSR24 and SLC24 ($P < 0.01$, Table 3). In the cold season, both the slopes and intercepts of daily liveweight gain per head of all treatments were significantly different ($P < 0.001$, Table 3). As would be expected, the SDSR48 treatment had the greatest change in GPI across months as the cold season progressed. However, sheep on all treatments exhibited comparatively large liveweight losses during the cold season regardless of grazing treatment (Fig. 3*b*).

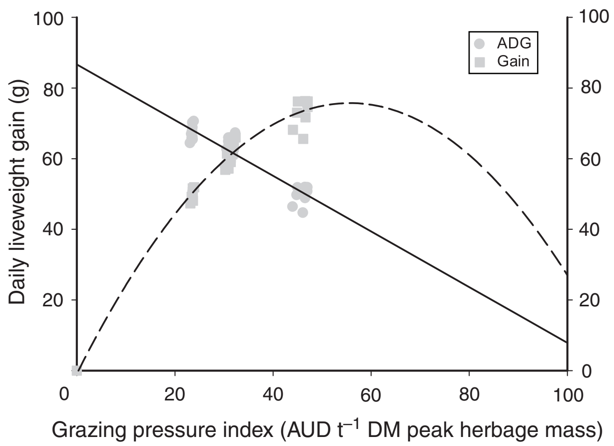

Fig. 2. Relationships between average daily liveweight gain and liveweight gain per ha in the short-duration season rotational grazing system and grazing pressure index of Tibetan sheep (180-day grazing season), based on the data of 2010, 2011 and 2012. Values are means for each stocking rate for each year of the study.

Discussion

Grazing systems

Historically, grazing systems were implemented in an attempt to increase livestock production by allowing key plant species the ability to capture adequate light, water, and nutrients to enhance plant growth and by enabling livestock to more efficiently harvest forage (Briske *et al.* 2008; Hunt *et al.* 2014). In a review of grazing studies that had been conducted during the past 60 years, Briske *et al.* (2008) found that past research indicated that rotational grazing was not superior to continuous grazing on rangelands for many different variables including plant production, liveweight gain per head, and liveweight gain per ha. These findings were

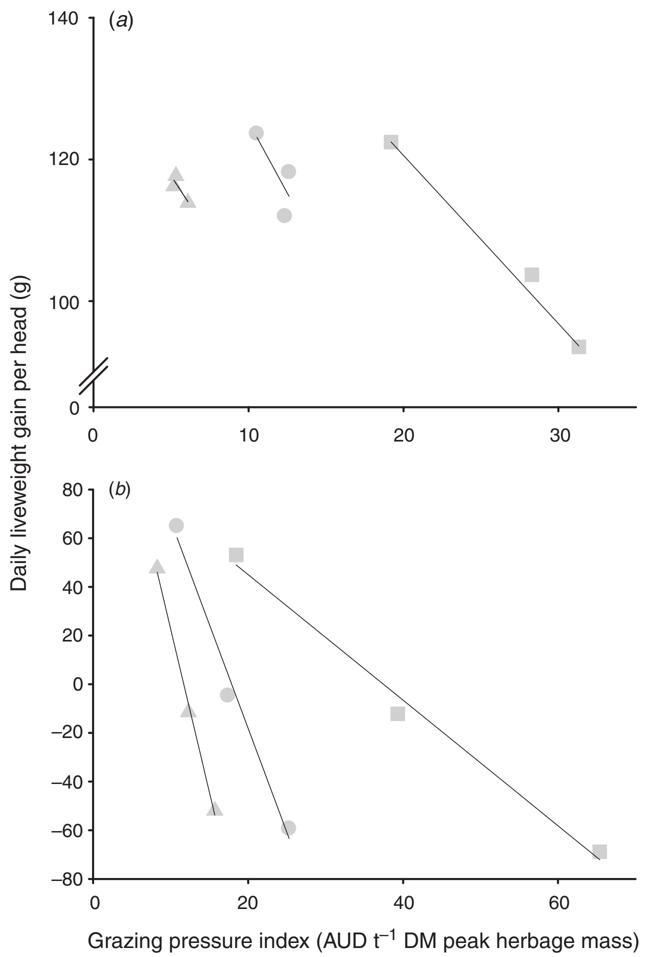

Fig. 3. (*a*) Relationship between grazing pressure index and average daily liveweight gain in (*a*) the growing season and (*b*) the cold season, based on the data of 2010, 2011 and 2012. Values are monthly means averaged across years of the study for treatments SDSR24 (circles), SDSR48 (squares) relating to the short-duration rotational grazing system and treatment SLC (triangles) relating to a continuous grazing system.

true for early grazing experiments comparing continuous and rotational grazing (Sampson 1951; Heady 1961) and in later investigations (Hart *et al*. 1993; Holechek *et al*. 1995; Hunt *et al*. 2014; Manley *et al*. 1997; McCollum *et al*. 1999; Derner and Hart 2007). In this study, we had similar results and did not find any significant differences in the liveweight gain per head and per ha when comparing continuous grazing to rotational grazing at a light stocking rate.

In previous promotions of rotational grazing systems, the benefits of the system were purported to be increased herbage mass production and desirable changes in species composition through rest of key plant species and reduced patch grazing as a result of high grazing pressures minimising selectivity by livestock (Briske *et al*. 2008). However, in our study we did not find significant differences in residual herbage mass between SLC and SDSR systems, which is in agreement with the conclusions of Briske *et al*. (2008) and O'Reagain *et al*. (2014).

Stocking rates

Selecting the appropriate stocking rate is the most important grazing management decision a producer can make as it strongly influences long-term financial returns and environmental outcomes (Holechek *et al*. 1995; O'Reagain *et al*. 2011). Individual livestock performance declines in a linear fashion with increasing stocking rate (Holechek *et al*. 1999; Owensby and Auen 2013) whereas livestock performance per ha responds with a parabolic trend (Bement 1969; Briske *et al*. 2008). The intersection of these two curves is generally considered the 'optimum' stocking rate that ensures economic sustainability. This has been supported by a series of studies (Hart *et al*. 1988; Manley *et al*. 1997; Hart and Ashby 1998). However, few studies exist where optimum stocking rate has been determined for alpine rangelands on the Qinghai-Tibetan Plateau. Generally, the prevailing stocking rate of this region has been based on the local producers' traditional experience (Gerald *et al*. 2003). With global warming (Wang *et al*. 2012) and increased human disturbance in the past several decades (Wang *et al*. 2008*b*) on the Qinghai-Tibetan Plateau, it has become more important to find suitable stocking rates for this region. This has become especially true after the 1980s, when the 'Household Responsibility System' was implemented, which encouraged a semi-sedentary or completely sedentary lifestyle for livestock producers in the Qinghai-Tibetan Plateau (Gerald *et al*. 2003). In this study, the daily liveweight gain per head and the average liveweight gain per ha intersected at 31 AUD t^{-1} DM peak herbage mass (Fig. 2). This stocking rate is similar to the 'constrained flexible stocking rate strategy' described by O'Reagain and Scanlan (2013) and will be useful for livestock producers on the plateau for optimal grazing strategies to benefit the producer's economic returns. However, additional study in this region would be required to evaluate the effects of this optimal stocking rate on environmental and rangeland health indicators. Hart *et al*. (1988) stated that the optimal stocking rate for livestock production could impact on forage production and range condition over the long term. Research examining the production and environmental consequences of adoption of the optimal stocking rate would be useful for shaping policy recommendations for alpine rangelands.

Seasonal aspects

The liveweight gain per head and per ha of Tibetan sheep were influenced by the stocking rate of the whole grazing period rather than some part of the grazing period (Table 1). However, we found that the sheep lost liveweight in the cold season regardless of stocking rate and herbage mass, so temperatures during the cold season appear to have had much stronger effects on livestock production than did stocking rate. Moreover, liveweight losses as the cold season progresses past the end of our study period (December) would likely be even greater (Fig. 3*a, b*), and, therefore, lower stocking rates may play a stronger role in whether sheep survive the cold temperatures, like those used in the SDSR-LH or SLC treatments in this study. Also, we found that the ratio of residual herbage mass in treatment SDSR-HL exhibited a balance between growing-season and cold-season pastures (ratio of G/C was 1.26, Table 2), whereas the ratio of residual herbage mass in treatment SDSR-LH was much

Table 3. Regression equations of monthly grazing pressure (GPI, AUD t^{-1}) and monthly average daily liveweight gain for Tibetan sheep (ADG, g) for the different grazing treatments under continuous (SLC24) and short duration rotational grazing (treatments SDSR24 and SDSR48)

Monthly averages used in the regressions represent means of GPI and ADG across the 3 years of the study for each season and grazing treatment. The levels of significance (*P* values) for the slopes and ADB-intercepts are also given

Season	Treatments	Equation (R^2)	Slopes (*P*)		ADG-intercept (*P*)	
Growing	SDSR24	ADG=165.49–4.0195GPI (0.605)	0.282	0.571	0.002	0.001
	SDSR48	ADG=167.22–2.3144GPI (0.9878)	0.990		0.000	
	SLC24	ADG=134.45–3.3535GPI (0.7463)	0			
Cold	SDSR24	ADG=140.92–7.88GPI (0.9852)	0.000	0.001	0.000	0.001
	SDSR48	ADG=105.90–2.75GPI (0.9890)	0.000		0.000	
	SLC24	ADG=175.73–14.56GPI (0.9965)				

Values of detecting the differences to slopes and ADG-intercepts are 95% confidence limitation of slopes and intercepts.

higher (2.26 times higher than that of SDSR-HL) as the grazing pressure was less during the growing season and more during the cold season. The surplus accumulation of herbage in the growing-season pasture of SDSR-LH may have the potential to reduce productivity (Klein *et al*. 2007) of the whole grazing season. Surplus herbage mass can result in lower total productivity and delay the germination of plant species by changing the solar radiation that is intercepted (Kato *et al*. 2004). Furthermore, the increased amount of dead material relative to vegetative growth creates shading by dead material, and thus reduces photosynthetic capacity (Gerald *et al*. 2003). The negative effects can carry over to plant growth in the following year, which may be exacerbated by the short growing season in the high elevation and low temperatures of the Qinghai-Tibetan Plateau region (Niu *et al*. 2009). In addition, the surplus dead material can reduce the ability of animals to select green in their diet, which may reduce animal productivity before vegetation green-up in the following year (Kahn and Cottle 2014). On the contrary, the very low residual herbage mass in cold-season pasture may result in the degeneration of the rangeland, causing a decrease in livestock production, and environmental problems (e.g. dust storms and erosion) (Yan *et al*. 2000; Shang and Long 2007). At present, the viewpoint held by most people in the region is that overgrazing is the primary cause of rangeland degradation in the Qinghai-Tibetan Plateau (Wang *et al*. 2006; Wang *et al*. 2008*b*) and the low residual herbage mass resulting from overgrazing may be the main contributor. Lower stocking rates in the cold season to reduce grazing pressure may be a sensible choice to reduce overgrazing that can result in degradation.

Liveweight gains and grazing pressure index

Knowledge of relationships between livestock performance and plant productivity can assist in developing livestock management programs that take into account both livestock production and conservation goals (Derner *et al*. 2009). The linear relationship between GPI and liveweight gain per head (Fig. 3*a*, *b*; Table 3) of this study was similar to previous findings (Bement 1969; Hart 1972; Hart *et al*. 1988; Hart and Ashby 1998; Smart *et al*. 2010). In the growing season, the SDSR24, SDSR48 and SLC24 treatments had similar changes in daily liveweight gain for a unit change in GPI ($P > 0.05$) (Fig. 3*a*). The most likely reason for this is the higher quality of the vegetation in the growing season and herbage mass generally does not become limiting. The potential productivity of Tibetan sheep (the intercept of daily liveweight gain per head) of treatments SDSR24 and SDSR48 is higher than that of SLC24 (within the narrow GPI range during the growing season). This suggests that the SLC system had more stable liveweight gains throughout the growing season, which may have resulted from patch grazing (Streeter *et al*. 1974; McNaughton 1984; Coughenour 1991). In the SLC system, the sheep can afford to be more selective because they have more area to graze at any one time. So, they can potentially revisit areas where they have grazed previously and access new regrowth (Briske *et al*. 2008; Lin *et al*. 2012). In the cold season, daily liveweight gain per head in the SLC24 treatment decreased faster than that on the SDSR24 and SDSR48 treatments for a given unit increase in GPI, which may result from herbage quality declining across the pasture caused by sheep patch grazing in the growing season. For the SDSR treatments, the slope on treatment SDSR24 is greater than that on treatment SDSR48. One possible reason for this is that the heavier sheep on treatment SDSR24 had higher herbage intakes than on treatment SDSR48, which may result in a more rapid decrease in the forage quality. However, the low temperatures during the cold season on the Qinghai-Tibetan Plateau play another important role in reducing liveweight gains, which are associated with small increases in GPI. The potential productivity of the SLC system, as indicated by the regression intercepts being larger than that for treatments SDSR24 and SDSR48, may result from the sufficient forage supply (only four sheep ha^{-1}) that carries over into the cold season when plants stop growing. The potential productivity of the SLC system in the cold season is greater than that observed in the growing season. One possible reason for this is that Tibetan sheep may have higher body condition at the beginning of the cold season, and usually, the initial body condition influences the performance of livestock (Launghbaugh 1957; Owensby and Auen 2013). The potential productivity of treatment SDSR24 is greater than that of SDSR48, and the main reason for this would be the greater forage supply over time.

Irrespective of the amount of herbage available or the grazing pressure in the cold season, the daily liveweight gain per head became negative after November and for treatments SLC24, SDSR24 and SDSR48 was highly correlated with average daily temperature in the cold season. This provides an indication that the effects of low temperature may become a dominant factor influencing livestock productivity in the cold season with grazing pressure being less important.

Conclusions

This study provides important information on the grazing management of Qinghai-Tibetan alpine rangeland in north-western China and indicates that grazing system does not affect the Tibetan sheep performance when the stocking rates are set low (e.g. 24 SM ha^{-1}). A grazing pressure of 31 AUD t^{-1} DM peak herbage mass (310 sheep unit days t^{-1} DM peak herbage mass, e.g. 1519 SU-day ha^{-1} for the three study years when the average DM peak herbage mass was 4.9 t) can sustain utilisation under the SDSR system, whereas the theoretical maximum gain ha^{-1} would occur at 71 AUD t^{-1} DM peak herbage mass (710 sheep unit days t^{-1} DM peak herbage mass). It is important for the producer to carefully manage livestock numbers to cope with the severe cold season. This will ensure income while also providing residual herbage to protect the soil from erosion and subsequent degradation.

Acknowledgements

We thank D. Kemp for helpful discussions and S. H. Chang for assistance both in the field and the laboratory. This research was supported by the National Key Project of Scientific and Technical Supporting Programs (2014CB138706), National Natural Science Foundation of China (No. 31172249) and Program for Changjiang Scholars and Innovative Research Team in University (IRT13019).

References

AOAC (1980). 'Official Methods of Analysis.' (AOAC: Washington, DC.)

Bedell, T. E. (1998). 'Glossary of Terms Used in Range Management.' (Society for Range Management: Denver, CO.)

Bement, R. E. (1969). A stocking-rate guide for beef production on blue-grama range. *Journal of Range Management* **22**, 83–86. doi:10.2307/3896186

Briske, D. D., Derner, J. D., Brown, J. R., Fuhlendorf, S. D., Teague, W. R., Havstad, K. M., Gillen, R. L., Ash, A. J., and Willms, W. D. (2008). Rotational grazing on rangelands: reconciliation of perception and experimental evidence. *Rangeland Ecology and Management* **61**, 3–17. doi:10.2111/06-159R.1

Coughenour, M. B. (1991). Spatial components of plant-herbivore interactions in pastoral, ranching and native ungulate ecosystems. *Journal of Range Management* **44**, 530–542. doi:10.2307/4003033

Derner, J. D., and Hart, R. H. (2007). Grazing-induced modifications to peak standing crop in northern mixed-grass prairie. *Rangeland Ecology and Management* **60**, 270–276. doi:10.2111/1551-5028(2007)60[270:GMTPSC]2.0.CO;2

Derner, J. D., Lauenroth, W. K., Stapp, P., and Augustine, D. J. (2009). Livestock as ecosystem engineers for grassland bird habitat in the western Great Plains of North America. *Rangeland Ecology and Management* **62**, 111–118. doi:10.2111/08-008.1

Dong, S. K., Long, R. J., Kang, M. Y., Pu, X. P., and Guo, Y. J. (2003). Effect of urea multi-nutritional molasses block supplementation on live-weight change of yak calves and productive and reproductive performances of yak cows. *Canadian Journal of Animal Science* **83**, 141–145. doi:10.4141/A01-097

Dong, Q. M., Zhao, X. Q., Ma, Y. S., Xu, S. X., and Li, Q. Y. (2006). Live-weight gain, apparent digestibility, and economic benefits of yaks fed different diets during winter on the Tibetan plateau. *Livestock Science* **101**, 199–207. doi:10.1016/j.livprodsci.2005.11.009

Du, M., Kawashima, S., Yonemura, S., Zhang, X., and Chen, S. (2004). Mutual influence between human activities and climate change in the Tibetan Plateau during recent years. *Global and Planetary Change* **41**, 241–249. doi:10.1016/j.gloplacha.2004.01.010

Fang, X., Han, Y., Ma, J., Song, L., Yang, S., and Zhang, X. (2004). Dust storms and loess accumulation on the Tibetan Plateau: a case study of dust event on 4 March 2003 in Lhasa. *Chinese Science Bulletin* **49**, 953–960. doi:10.1007/BF03184018

Feng, B. F., Zhao, X. Q., Dong, Q. M., Xu, S. X., Zhao, L., and Cao, J. H. (2013). The effect of feed supplementing and processing on the live-weight gain of Tibetan sheep during the cold season on the Qinghai-Tibetan Plateau. *Journal of Animal and Veterinary Advances* **12**, 208–211.

Gao, Y. X., and Li, M. S. (1995). Soil regionalization of the Qinghai-Tibetan Plateau. *Mountain Research* **13**, 203–211.

Gerald, W. N., Han, J. L., and Long, R. J. (2003). 'The Yak.' 2nd edn. (RAP Publication: Thailand.)

Harlan, J. R. (1958). Generalized curves for gain per head and gain per acre in rates of grazing studies. *Journal of Range Management* **11**, 140–147. doi:10.2307/3893717

Harris, R. B. (2010). Rangeland degradation on the Qinghai-Tibetan plateau: a review of the evidence of its magnitude and causes. *Journal of Arid Environments* **74**, 1–12. doi:10.1016/j.jaridenv.2009.06.014

Hart, R. (1972). Forage yield, stocking rate, and beef gains on pasture. *Herbage Abstracts* **42**, 345–353.

Hart, R. H., and Ashby, M. M. (1998). Grazing intensities, vegetation, and heifer gains: 55 years on shortgrass. *Journal of Range Management* **51**, 392–398. doi:10.2307/4003323

Hart, R. H., Clapp, S., and Test, P. S. (1993). Grazing strategies, stocking rates, and frequency and intensity of grazing on western wheatgrass and blue Grama. *Journal of Range Management* **46**, 122–126. doi:10.2307/4002267

Hart, R. H., Samuel, M. J., Test, P. S., and Smith, M. A. (1988). Cattle, vegetation, and economic responses to grazing systems and grazing pressure. *Journal of Range Management* **41**, 282–286. doi:10.2307/3899379

Heady, H. F. (1961). Continuous vs. specialized grazing systems: a review and application to the California annual type. *Journal of Range Management* **14**, 182–193. doi:10.2307/3895147

Holechek, J. L., Gomez, H., Molinar, F., and Galt, D. (1999). Grazing studies: what we've learned. *Rangelands* **21**, 12–16.

Holechek, J. L., Pieper, R. D., and Herbel, C. H. (1995). 'Range Management: Principles and Practices.' (Prentice-Hall: New York.)

Hunt, L. P., McIvor, J. G., Grice, A. C., and Bray, S. G. (2014). Principles and guidelines for managing cattle grazing in the grazing lands of northern Australia: stocking rates, pasture resting, prescribed fire, paddock size and water points – a review. *The Rangeland Journal* **36**, 105–119. doi:10.1071/RJ13070

Kahn, L., and Cottle, D. (2014). 'Beef Cattle Production and Trade.' (CSIRO Publishing: Melbourne.)

Kato, T., Tang, Y., Gu, S., Hirota, M., Cui, X., Du, M., Li, Y., Zhao, X., and Oikawa, T. (2004). Seasonal patterns of gross primary production and ecosystem respiration in an alpine meadow ecosystem on the Qinghai-Tibetan Plateau. *Journal of Geophysical Research: Atmospheres* **109**, D12109. doi:10.1029/2003JD003951

Klein, J. A., Harte, J., and Zhao, X.-Q. (2007). Experimental warming, not grazing, decreases rangeland quality on the Tibetan Plateau. *Ecological Applications* **17**, 541–557. doi:10.1890/05-0685

Klipple, G., and Bement, R. (1961). Light grazing: is it economically feasible as a range-improvement practice. *Journal of Range Management* **14**, 57–62. doi:10.2307/3894716

Launghbaugh, J. L. (1957). 'The effect of stocking rate on cattle gains and on native shortgrass vegetation in West-Central Kansas.' Bulletin 394, Kansas Agricultural Experimental Station. (Kansas Agricultural Experimental Station: Manhattan, KS.)

Lin, L. J., Dickhoefer, U., Muller, K., Wang, C. J., Glindemann, T., Hao, J., Wan, H., Schonbach, P., Gierus, M., Taube, F., and Susenbeth, A. (2012). Growth of sheep as affected by grazing system and grazing intensity in the steppe of Inner Mongolia, China. *Livestock Science* **144**, 140–147. doi:10.1016/j.livsci.2011.11.008

Long, R. J., Apori, S. O., Castro, F. B., and Orskov, E. R. (1999). Feed value of native forages of the Tibetan Plateau of China. *Animal Feed Science and Technology* **80**, 101–113. doi:10.1016/S0377-8401(99)00057-7

Ma, M. J., Zhou, X. H., and Du, G. Z. (2010*a*). Role of soil seed bank along a disturbance gradient in an alpine meadow on the Tibet plateau. *Flora* **205**, 128–134. doi:10.1016/j.flora.2009.02.006

Ma, M. J., Zhou, X. H., and Du, G. Z. (2013). Effects of disturbance intensity on seasonal dynamics of alpine meadow soil seed banks on the Tibetan Plateau. *Plant and Soil* **369**, 283–295. doi:10.1007/s11104-012-1560-5

Ma, M. J., Zhou, X. H., Wang, G., Ma, Z., and Du, G. Z. (2010*b*). Seasonal dynamics in alpine meadow seed banks along an altitudinal gradient on the Tibetan Plateau. *Plant and Soil* **336**, 291–302. doi:10.1007/s11104-010-0480-5

Manley, W., Hart, R., Samuel, M., Smith, M., Waggoner, J. Jr, and Manley, J. (1997). Vegetation, cattle, and economic responses to grazing strategies and pressures. *Journal of Range Management* **50**, 638–646. doi:10.2307/4003460

Masters, D., Purser, D., Yu, S., Wang, Z., Yang, R., Liu, N., Wang, X., Lu, D., Wu, L., and Rong, W. (1990). Production from fine wool sheep in three areas in northern China. *Asian-Australasian Journal of Animal Sciences* **3**, 305–312. doi:10.5713/ajas.1990.305

McCollum, F. T. III, Gillen, R. L., Karges, B. R., and Hodges, M. E. (1999). Stocker cattle response to grazing management in tallgrass prairie. *Journal of Range Management* **52**, 120–126. doi:10.2307/4003504

McNaughton, S. (1984). Grazing lawns: animals in herds, plant form, and coevolution. *American Naturalist* **124**, 863–886. doi:10.1086/284321

Mishra, C., Prins, H. H. T., and van Wieren, S. E. (2001). Overstocking in the trans-Himalayan rangelands of India. *Environmental Conservation* **28**, 279–283. doi:10.1017/S0376892901000297

Niu, K. C., Choler, P., Zhao, B. B., and Du, G. Z. (2009). The allometry of reproductive biomass in response to land use in Tibetan alpine grasslands. *Functional Ecology* **23**, 274–283.

Norton, B. (1998). The McClymont Lecture: the application of grazing management to increase sustainable livestock production. *Animal Production in Australia* **22**, 15–26.

O'Reagain, P., Bushell, J., and Holmes, B. (2011). Managing for rainfall variability: long-term profitability of different grazing strategies in a northern Australian tropical savanna. *Animal Production Science* **51**, 210–224. doi:10.1071/AN10106

O'Reagain, P. J., and Scanlan, J. C. (2013). Sustainable management for rangelands in a variable climate: evidence and insights from northern Australia. *Animal* **7**(Suppl. 1), 68–78. doi:10.1017/S175173111100262X

O'Reagain, P., Scanlan, J., Hunt, L., Cowley, R., and Walsh, D. (2014). Sustainable grazing management for temporal and spatial variability in north Australian rangelands – a synthesis of the latest evidence and recommendations. *The Rangeland Journal* **36**, 223–232. doi:10.1071/RJ13110

Owensby, C. E., and Auen, L. M. (2013). Comparison of season-long grazing applied annually and a 2-year rotation of intensive early stocking plus late-season grazing and season-long grazing. *Rangeland Ecology and Management* **66**, 700–705. doi:10.2111/REM-D-13-00014.1

Owensby, C. E., Auen, L. M., Berns, H. F., and Dhuyvetter, K. C. (2008). Grazing systems for yearling cattle on tallgrass prairie. *Rangeland Ecology and Management* **61**, 204–210. doi:10.2111/07-034.1

Ren, J. Z. (2008). 'Ren jizhous' Selected Works.' Vol. 1. (Chinese Agricultural Press: Beijing.) [In Chinese]

Riewe, M. E. (1961). Use of the relationship of stocking rate to gain of cattle in an experimental design for grazing trials. *Agronomy Journal* **53**, 309–313. doi:10.2134/agronj1961.00021962005300050013x

Sampson, A. W. (1951). A symposium on rotation grazing in North America. *Journal of Range Management* **4**, 19–24. doi:10.2307/3894427

Schlegel, M. L., Wachenheim, C. J., Benson, M. E., Black, J. R., Moline, W. J., Ritchie, H. D., Schwab, G. D., and Rust, S. R. (2000). Grazing methods and stocking rates for direct-seeded alfalfa pastures: I. Plant productivity and animal performance. *Journal of Animal Science* **78**, 2192–2201.

Shang, Z. H., Gibb, M. J., Leiber, F., Ismail, M., Ding, L. M., Guo, X. S., and Long, R. J. (2014). The sustainable development of grassland-livestock systems on the Tibetan plateau: problems, strategies and prospects. *The Rangeland Journal* **36**, 267–296. doi:10.1071/RJ14008

Shang, Z. H., and Long, R. J. (2007). Formation causes and recovery of the 'Black Soil Type' degraded alpine grassland in Qinghai-Tibetan Plateau. *Frontiers of Agriculture in China* **1**, 197–202. doi:10.1007/s11703-007-0034-7

Smart, A., Derner, J., Hendrickson, J., Gillen, R., Dunn, B., Mousel, E., Johnson, P., Gates, R., Sedivec, K., and Harmoney, K. (2010). Effects of grazing pressure on efficiency of grazing on North American Great Plains rangelands. *Rangeland Ecology and Management* **63**, 397–406. doi:10.2111/REM-D-09-00046.1

Streeter, C., Rumburg, C., Hall, T., and Siemer, E. (1974). Meadow forage quality, intake and milk production of cows. *Journal of Range Management* **27**, 133–135. doi:10.2307/3896749

Teague, W. R., and Dowhower, S. L. (2003). Patch dynamics under rotational and continuous grazing management in large, heterogeneous paddocks. *Journal of Arid Environments* **53**, 211–229. doi:10.1006/jare.2002.1036

Wang, D. L., Han, G. D., Bai, Y. G., and Da, M. (2005). Interactions between foraging behaviour of herbivores and grassland resources in the eastern Eurasian steppes. *In*: 'Grassland: A Global Resource'. Dublin, Ireland, 26 June–1 July 2005. (Ed. D. A. McGilloway.) pp. 97–110. (Wageningen Academic Publishers: Wageningen, The Netherlands.)

Wang, H., Zhou, X. L., Wan, C. G., Fu, H., Zhang, F., and Ren, J. Z. (2008*b*). Eco-environmental degradation in the northeastern margin of the Qinghai-Tibetan Plateau and comprehensive ecological protection planning. *Environmental Geology* **55**, 1135–1147. doi:10.1007/s00254-007-1061-7

Wang, S., Duan, J., Xu, G., Wang, Y., Zhang, Z., Rui, Y., Luo, C., Xu, B., Zhu, X., and Chang, X. (2012). Effects of warming and grazing on soil N availability, species composition, and ANPP in an alpine meadow. *Ecology* **93**, 2365–2376. doi:10.1890/11-1408.1

Wang, W. Y., Wang, Q. J., and Wang, H. C. (2006). The effect of land management on plant community composition, species diversity, and productivity of alpine Kobersia steppe meadow. *Ecological Research* **21**, 181–187. doi:10.1007/s11284-005-0108-z

Wang, X. H., Zheng, D., and Shen, Y. C. (2008*a*). Land-use change and its driving forces on the Tibetan Plateau during 1990–2000. *Catena* **72**, 56–66. doi:10.1016/j.catena.2007.04.003

Wu, G. L., Liu, Z. H., Zhang, L., Chen, J. M., and Hu, T. M. (2010). Long-term fencing improved soil properties and soil organic carbon storage in an alpine swamp meadow of western China. *Plant and Soil* **332**, 331–337. doi:10.1007/s11104-010-0299-0

Xin, G., Long, R., Guo, X., Irvine, J., Ding, L., Ding, L., and Shang, Z. (2011). Blood mineral status of grazing Tibetan sheep in the North-east of the Qinghai-Tibetan Plateau. *Livestock Science* **136**, 102–107. doi:10.1016/j.livsci.2010.08.007

Xue, B., Zhao, X. Q., and Zhang, Y. S. (2005). Seasonal changes in weight and body composition of yak grazing on alpine-meadow grassland in the Qinghai-Tibetan plateau of China. *Journal of Animal Science* **83**, 1908–1913.

Yan, P., Dong, G., Zhang, X., and Zhang, Y. (2000). Preliminary results of the study on wind erosion in the Qinghai-Tibetan Plateau using ^{137}Cs technique. *Chinese Science Bulletin* **45**, 1019–1025. doi:10.1007/BF02884984

Zhang, Y., Zhang, X., Wang, X., Liu, N., and Kan, H. (2014). Establishing the carrying capacity of the grasslands of China: a review. *The Rangeland Journal* **36**, 1–9. doi:10.1071/RJ13033

Zhao, X., Pi, N., and Feng, J. (1991). A study on the efficiency of energy utilization and requirement for breeding Tibetan sheep. *Alpine Meadow Ecosystem* **3**, 97–102.

Zhao, X., Wang, Q., and Pi, N. (1989). The multifactorial evaluation of optimum grazing plan for alpine meadow pasture in Haibei, Qinghai. *Scientia Agricultura Sinica* **22**, 68–75.

Zhao, X., Zhang, Y., and Zhou, X. (2000). Theory and practice for sustainable development of animal husbandry on the alpine meadow pasture. *Resources Science* **22**, 50–61.

Zhou, H., Zhou, L., Zhao, X., Liu, W., Yan, Z., and Shi, Y. (2002). Degradation process and integrated treatment of 'Black Soil Beach' grassland in the source regions of Yangtze and Yellow Rivers. *Chinese Journal of Ecology* **22**, 51–55.