

# Grazing management options for restoration of alpine grasslands on the Qinghai-Tibet Plateau

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**Abstract.** In an attempt to alleviate the problem of grassland degradation on the Qinghai-Tibet Plateau in China, state and local authorities in 2003, initiated the “Retire Livestock and Restore Pastures” ecological engineering program, requiring the use of enclosure fencing to enable grazing exclusion and rotational grazing. A five-year controlled grazing experiment was conducted to determine the effects of this program on (1) sheep live weight gain; and (2a) standing herbage biomass; and (2b) species diversity. Effects of temporal within-year variation in precipitation and temperature on livestock productivity, standing herbage biomass, and species diversity were also investigated. At the end of 5 yr, grazing exclusion showed no significant difference in standing herbage biomass or in species diversity, compared with either continuous grazing or rotational grazing. Rotational grazing at the high stocking rate significantly promoted sheep live weight gain per hectare, but not per sheep; neither standing herbage biomass, nor species diversity, whether under continuous (i.e., traditional) or rotational grazing, showed a significant difference. Under rotational grazing, higher standing herbage biomass and species diversity were required to maintain or increase sheep liveweight, compared with continuous grazing. Temporal distribution of precipitation and temperature had more influence on alpine grassland parameters, than did grazing. Results of this study suggest that herders’ local traditional knowledge and expertise might be useful in modifying Government guidelines to fine tune grazing management with the dynamics of the alpine meadow ecosystem, and that it is important to consider equilibrium and non-equilibrium theory in formulating a policy which benefits both herders and grassland. Traditional continuous grazing at a carefully chosen light stocking rate appears to be the most appropriate way to manage livestock and grassland in this region.

**Key words:** alpine grassland; climate factors; grassland policies; grazing exclusion; plant diversity; rotational grazing; sheep productivity.

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## INTRODUCTION

The Qinghai-Tibet Plateau is called the “Roof of the World” (Qiu 2008, Wang et al. 2008). Besides livestock production, this high plateau also provides a variety of other ecosystem services, including fiber production, carbon sequestration, maintenance of the biodiversity (conservation), and recreation (Niu et al. 2016). Alpine grasslands in the Qinghai Tibet Plateau have however been

regionally degrading. In the 1990s, the degraded grassland area was estimated to be approximately  $4.0 \times 10^7$  to  $6.0 \times 10^7$  ha (Yang 1992), about 33% of the total grassland on the Qinghai-Tibet Plateau (Wu et al. 2009). From 1981 to 2004 in Northern Tibet, some areas of the high plateau experienced particularly high levels of degradation, which resulted in degraded alpine grasslands accounted for 50.8% of the total grassland area, and severely to extremely severely degraded

grasslands accounted for 9.7% of this area (Gao et al. 2010). Tibetan grassland degradation had occurred in the forms of losses in plant species richness (i.e., species diversity), increase in native unpalatable and poisonous plants, and decline in livestock productivity, accelerated soil erosion, and shrub invasion (Akiyama and Kawamura 2010, Wang et al. 2018).

Grassland degradation may be due to a combination of global climate change, rapidly increasing grazing pressure, rodent damage, and other factors (Zou et al. 2002, Christensen et al. 2004). The Chinese government cites overgrazing as a major cause of grassland degradation on the Qinghai-Tibet Plateau (Harris 2010, Shang et al. 2014); however, Harris (2010) clearly questioned those official assumptions about the causes of Tibetan grassland degradation. According to the government Forestry Bureau in 2010, overgrazing rates were estimated as follows: 38% (Tibet), 25% (Qinghai), 37% (Sichuan), and 36% (Gansu; Zhang et al. 2014). Overgrazing may result in significant changes to the composition and structure of the plant community, including significant decreases in the regenerative ability of the grassland biomass, and the amount of nutrients eventually returned to the soil as litter (Yu and Farrell 2013). Under conditions of overgrazing by livestock, degradation of grasslands can become a vicious cycle: Overgrazing causes grassland degradation, which facilitates rodent infestation, which further degrades grasslands (Kang et al. 2007).

In an attempt to alleviate the problem of grassland degradation on the Qinghai-Tibet Plateau, China's state and local authorities initiated the "Retire Livestock and Restore Pastures" ecological engineering program in 2003. Livestock grazed on these high grasslands were moved into fenced areas, and nomadic herders were settled in villages. Seriously degraded grassland was fenced off to prevent grazing, and rotational grazing was implemented where plant species composition and growth were favorable. These strategies are in line with internationally recognized management approaches for restoring vegetation and enhancing the health of overgrazed and degraded rangelands (Blydenstein et al. 1957, Walton et al. 1981, Balmford et al. 2002, Asner et al. 2004). In North America, an eight-year grazing trial showed that rotational grazing

resulted in greater perennial herbaceous basal area and less bare ground on bottom land soils and clay-loam soils, than the continuously grazed control (Teague and Dowhower 2003). Rotational grazing promoted functional groups composed of high forage value species and reduced bare soil, through the accumulation of litter (Jacobo et al. 2006). However, in southeast Australia, a study over 12 yr found that grazing exclusion led to limited changes in vegetation cover, and species composition, because of presumed low site productivity and a high degree of understory degradation (Lunt et al. 2007, Schultz et al. 2011). Grazing exclusion increased water infiltration rates and water retention capacity in the soil (Wu et al. 2011). Enclosures have increased herbaceous cover and decreased bare ground (Witt et al. 2011). Cingolani et al. (2005) used meta-analysis to predict some recovery following grazing exclusion, from a tipping point to a degraded state with low species diversity, suggesting the hypothesis that plant species richness and abundance will increase with protection from grazing.

China's Retire Livestock and Restore Pastures pasture restoration program has been in progress for more than ten years, so it is timely to ask: Is this program successful in the restoration of degraded alpine grasslands on the Qinghai-Tibet Plateau? This question has attracted great attention and inspired a large number of studies to determine the program's success (Shi et al. 2013, Luan et al. 2014, Tang et al. 2015). Resting of pasture in early warm season maintained a desirable grassland species composition and reduced grazing pressure to half the current district stocking rate, delivering improved ecosystem functioning, while improving herder incomes (Wang et al. 2018). Rehabilitation measures may promote above-ground biomass and ground cover, particularly grass biomass in seeded treatments. Such an increase in biomass will increase the region's ability to supply winter forage and provide opportunities to reduce the intensity of grazing of native grassland (Wang et al. 2006). Scientific researchers, however, argued that the new pastoralism forms are not suited to the dynamic characteristics of rangeland ecosystems and are causing rangeland fragmentation and degradation (Yan et al. 2005, Lehnert et al. 2014). After eight years of grazing exclusion, total soil organic

C and N, microbial biomass C and N, acid-extracted carbohydrate C, and soil enzymatic activities of  $\beta$ -glucosidase, urease, and phosphatase in the 0- to 15-cm soil layer were all lower; plant species, root biomass, and soil bulk density were also reduced (Shi et al. 2013). Local Tibetan herders also found that grassland conditions were still very poor after years of policy intervention (Brondizio and Le Tourneau 2016, Yeh et al. 2017).

The policy of grazing exclusion and improving grazing systems was implemented according to the equilibrium concept as a stable sub-climax state of a site where grazing pressure is counterbalanced by the natural regeneration of the vegetation (Vetter 2005). However, the non-equilibrium concept of rangeland ecology was introduced in the 1980s (Ellis and Swift 1988, Jarvel and O'Connor 1999). Ellis and Swift (1988) suggest that in non-equilibrium rangeland ecosystems plant-herbivore interactions are loosely coupled; herbivore populations are controlled by density independent factors; carrying capacity is too dynamic for close animal population tracking; plant biomass is abiotically controlled; and competition among plant species is not an important force in structuring communities. The non-equilibrium concept of rangeland dynamics predicts that the potential for grazing-induced degradation is low in rangelands with relatively variable precipitation (Von Wehrden et al. 2012). For the Tibetan grasslands, there is need for fresh perspectives and information on ecosystem dynamics and pastoral development.

To gain a better understanding of the restoration and management of degraded grasslands on the Qinghai Tibet Plateau, it is important to comprehensively understand potential shifts in vegetation and the underlying processes. Therefore, a five-year (2010–2014) controlled grazing experiment was conducted including continuous grazing at 24 sheep month/ha stocking rate (CG-24), rotational grazing at 48 (RG-48), and 24 (RG-24) sheep month/ha stocking rate and no grazing (NG) was conducted to determine the effect of grazing regimes on (1) the above-ground plant biomass and species diversity; and (2) sheep liveweight gain per head and per hectare. The following questions were addressed: (1) Is grazing, or is grazing exclusion, the best practice to achieve restoration of degraded grassland? (2) If grazing is more appropriate, which grazing

regime produces the best results for both grassland and livestock? Also discussed: the effect of temporal within-year (annual, seasonal, monthly) variation in precipitation and temperature on standing herbage biomass, species diversity, and sheep liveweight gain.

## MATERIALS AND METHODS

### Study site

The study site (latitude 33°42'21" N, longitude 102°07'02" E, elevation about 3500 m a.s.l.) is located on the eastern side of the Qinghai-Tibet Plateau in Maqu County, Gannan Prefecture, Gansu Province, China. Vegetation is Alpine Meadow (Ren et al. 2008); soil type is Alpine Meadow Soil which consists primarily of Mat-Cryic Cambisols (Chinese Soil Taxonomy Research Group 1995). From 2010 to 2014, mean annual temperature was 2.8°C, mean daily temperature was –8.9°C in January and 11.9°C in July (Fig. 1). The warm season is from June to September and the cold season is from October to May, with about 270 frost days per year. Mean annual precipitation is ~610 mm and mostly occurs in July and August. Annual cloud-free solar radiation is ~2580 hr. The vegetation comprises sedges, grasses, and forbs. The dominant species are *Kobresia graminifolia*, *Elymus nutans*, *Agrostis* species, *Poa pratensis*, *Saussurea* species, and *Anemone* species. The study site had been continuously stocked with yaks for 30 yr prior to the establishment of sheep grazing treatments.

### Grazing treatments

For details of each grazing treatment, see Table 1.

Each year of the five-year trial, 150 castrated male Tibetan sheep (5- to 7-month-old) were purchased in June from nearby herders. Of these sheep, 120 were assigned to the study and the remaining 30 sheep were grazed outside the stocking treatment paddocks and used as required to replace animals killed by wolves (*Canis lupus*) or disease. In December, sheep were sold.

On arrival, the young sheep were ear-tagged, vaccinated, and drenched for parasite control with Albendazole (Hanzhong Tianyuan Pharmaceutical, Shanxi, China) and weighed on two consecutive days. The 120 heaviest sheep were divided into 15 groups of 8 sheep, with each

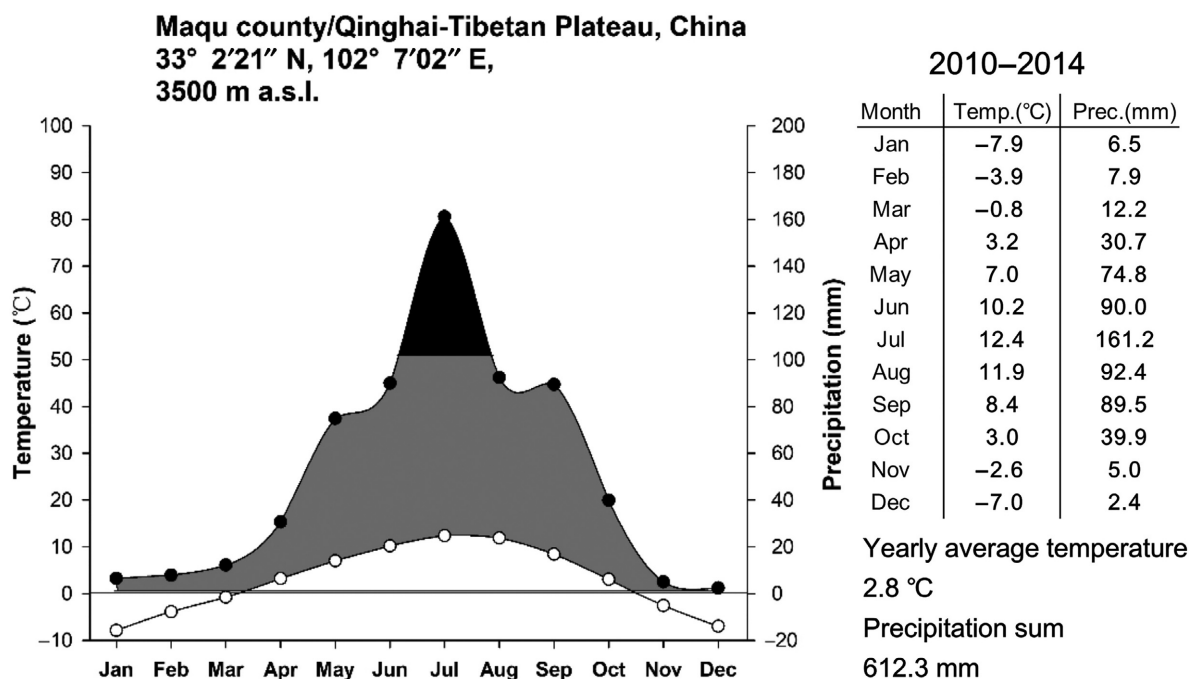


Fig. 1. Combined monthly averages of temperature and precipitation (2013–2014), measured at Maqu County, Gannan Prefecture, Gansu Province, China. This figure uses the ratio of 10°C vs. 20 mm as in the standard Walter-Lieth climate diagrams.

Table 1. Key details of each grazing treatment.

Characteristic	Rotational grazing				Continuous grazing Warm + cold season 2.0 ha
	Warm season		Cold season		
	1.0 ha	0.5 ha	1.0 ha	0.5 ha	
No. of replicates	6	6	6	6	3
“Breaks”	Each of 3 × 10 d	Each of 3 × 10 d	Each of 2 × 15 d	Each of 2 × 15 d	–
No. of sheep	8	8	8	8	8
Stocking rate	8 sheep/ha	16 sheep/ha	8 sheep/ha	16 sheep/ha	4 sheep/ha
SM (sheep months)	24 SM/ha	48 SM/ha	24 SM/ha	48 SM/ha	24 SM/ha

*Notes:* Terminology used here for describing grazing treatments is internationally agreed (Allen et al. 2011). For rotational grazing, the warm season was July through September (3 months) and the cold season was October through December (3 months); paddock sizes were 1.0 and 0.5 ha. For continuous grazing, the warm + cold season was July through December (6 months); paddock size was 2.0 ha. In the no-grazing control, from July through December (6 months), each replicate fenced-off area was 25 m<sup>2</sup>. En dash indicates no “breaks” in the continuous grazing.

group having a similar average live weight. The members of a group were labeled with the same rump markings, and different groups were distinguished by separate markings. The group markings enabled the herder to place the members of each group in their assigned paddocks each day. For an acclimatization period of 1–2 weeks, the sheep grazed pasture outside the treatment paddocks and had access to a locally made mixed-mineral block and fresh water.

After the acclimatization period, the sheep were distributed in their groups to designated paddocks. Each day in the late afternoon, the groups of sheep were individually herded from the paddocks, given access to stream water and more mixed-mineral block, and then held overnight in designated compartments in the yard for protection from wolves and thieves. In the early morning, the sheep were again given access to stream water and returned in their groups to designated paddocks.

### Data collection

*Sheep live weight.*—Individual sheep liveweight was measured at the end of each month on two consecutive days. The gain in live weight per sheep per day was calculated after taking the difference between the live weights at the beginning and at the end of the month. Liveweight gain per hectare was calculated from the number of sheep in each paddock, times the average individual sheep liveweight gain.

*Above-ground herbage biomass.*—Each month, six 0.25-m<sup>2</sup> quadrats were laid down in the middle of each sub-paddock, the above-ground herbage of each quadrat was cut, and the on-ground litter was removed and bagged together with the herbage. Stems, leaves, and litter of each species were separated, bagged, oven dried at 65°C for 48 h, and weighed. Total mass of herbage dry matter (DM) was calculated by summing the herbage DM of each individual species. From the herbage biomass of each species in each quadrat, two indices were derived—plant species diversity ( $H$ ) and plant species evenness ( $E$ ). We used biomass of each species because plant density was too high to accurately identify all individuals of each species.

Plant species diversity index ( $H$ ): The Shannon–Weiner index is a popular diversity index in ecological literature. It is most often calculated as follows:

$$H = - \sum_{i=1}^S P_i \ln P_i$$

where  $H$  is Shannon–Weiner index,  $S$  is the total number of plant species in the quadrat, and  $P_i$  is the proportion of  $S$  made up of the  $i$ th species.

Plant species evenness index ( $E$ ) is the biomass of each species in a quadrat using the formula proposed by Camargo (1993). The Camargo evenness index is calculated independently of plant species richness, is simple to compute (Smith and Wilson 1996), and is defined as:

$$E = 1 - \sum_i^S \sum_{j=i+1}^S \left( \frac{|P_i - P_j|}{S} \right)$$

where  $E$  is Camargo evenness index,  $P_i$  is the proportion of species  $i$  in the sample,  $P_j$  is the proportion of species  $j$  in the sample, and  $S$  is

the total number of plant species in the quadrat. Plant species richness ( $S$ ) is the total number of plant species in each quadrat area.

To determine the relationship of vegetation dynamics with precipitation and temperature, three different scales of temporal variation were investigated: annual, seasonal, and monthly. Seasonal partitioning comprises three periods: early-season (March–June), late-season (July–October), and out-of-season (November–February). Climate data included monthly temperature and precipitation and was provided by Maqu County Meteorological Bureau.

### Statistical analysis

SAS software, Version 9.3 (SAS Institute, Cary, North Carolina, USA) was used for statistical analyses. ANOVA analyses were computed for comparing sheep live-weights, plant above-ground biomass, plant species richness, plant diversity, and plant species evenness between grazing regimes. Least significant difference method was used for testing the significant difference. The level of significance used was  $P < 0.05$ . Correlation analysis tested the relationship between climate factors, sheep live-weight gain, herbage DM, and herbage indices. The level of significance used was  $P < 0.05$ . All graphs were constructed using Sigma Plot 12.5 for windows (Systat Software) software and Origin 9.1 (OriginLab Corporation, Northampton, Massachusetts, USA).

## RESULTS

### Sheep productivity

Sheep live weight gain increased on all grazing days of the continuous grazing treatment. In both rotational grazing treatments however, though sheep live weight increased in the warm season but decreased in the cold season, the rate of liveweight gain decreased in both warm and cold season, throughout the 180 d of trial period (Fig. 2a, b). Sheep live weight began to decrease at one to two months into the cold season (Fig. 2a, b). There was no significant difference in live weight gain per sheep between continuous grazing and rotational grazing treatments at 24 SM/ha stocking rate in the warm season ( $P > 0.05$ ). However, in the cold season of 2013, live weight gain per sheep being continuously

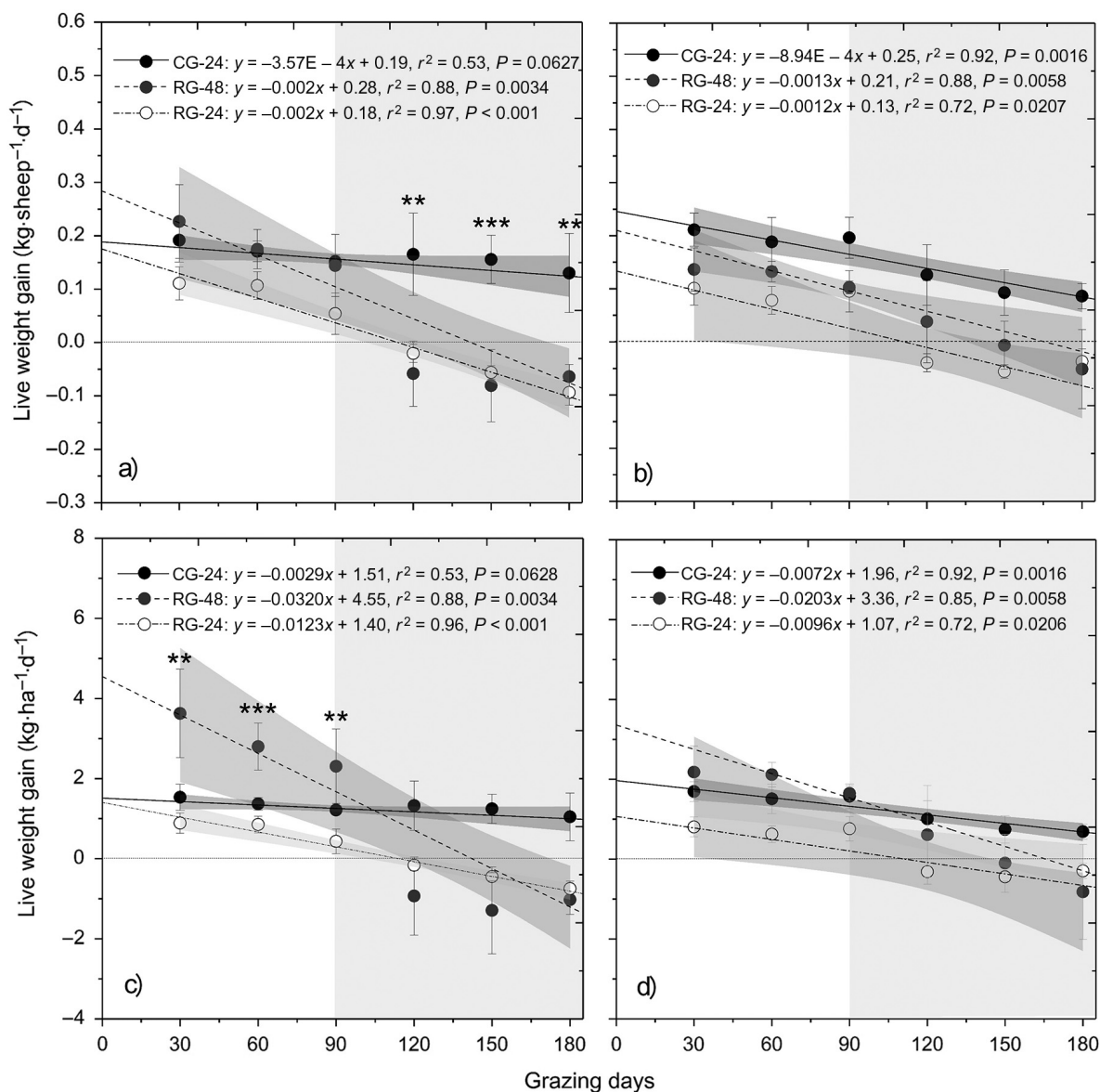


Fig. 2. Effects of continuous grazing at 24 SM/ha (CG-24) and rotational grazing at 24 and 48 SM/ha (RG-24, RG-48) on live weight gain per sheep and per hectare (panels a and c, year 2013; panels b and d, year 2014). The study was conducted in Maqu County, Gannan Prefecture, Gansu Province, China with Tibetan sheep grazed on native grassland. Lines are fitted by regression. Bars are standard errors. Multigroup comparisons of the means were carried out by one-way ANOVA test with post hoc contrasts by Student–Newman–Keuls test. The statistical significance for all tests was set at  $P < 0.05$ . Left half in white represents grazing in warm season; right half in gray represents grazing in cold season.  $*0.01 < P < 0.05$ ;  $**0.001 < P < 0.01$ ;  $***P < 0.001$ ; no symbol, no significant difference.

grazed, increased significantly more than being rotationally grazed ( $P < 0.01$ ; Fig. 2a). Live weight gain per hectare showed no significant difference between rotational and continuous grazing treatments at 24 SM/ha stocking rate in

2013 and 2014 (Fig. 2c, d), but sheep live weight gain per hectare was significantly higher at a stocking rate of 48 SM/ha for rotational grazing ( $P < 0.01$ ) compared to 24 SM/ha in the warm season of 2013 (Fig. 2c).

### Standing herbage biomass

Standing herbage biomass differed between grazing regimes in the warm season only, of both 2013 and 2014 (Fig. 3), being highest in 2013 with rotational grazing at 24 SM/ha (Fig. 3a), but highest in 2014 with no-grazing (Fig. 3b). In the cold season, there was no significant difference in standing herbage biomass between all grazing and no grazing treatments. At 90 d, standing herbage biomass reached a peak with rotational grazing at 24 SM/ha stocking rate. In contrast, standing herbage biomass had a negative relationship with grazing days in the other three grazing regimes. Standing herbage biomass of both continuous grazing and no grazing treatments overlapped in the warm season of 2013 (Fig. 3a).

### Plant species richness

For all treatments, plant species richness decreased steadily throughout the trial period in both 2013 and 2014 (Fig. 4a, b). Species richness under grazing treatments was significantly

higher ( $P < 0.05$ ) than that under no grazing treatment in 2013 (Fig. 4a), with most difference being observed under rotational grazing in 2013 (Fig. 4a), but not in 2014 (Fig. 4b).

### Relationship between live-weight gain and vegetation parameters

Linear regression analysis indicated that standing herbage biomass and species richness strongly correlated with sheep liveweight gain (Fig. 5). Liveweight gain of individual sheep had significant quadratic relationships (CG-24:  $y = 2.04E - 4x^2 + 0.0119x + 0.0025$ ,  $r^2 = 0.61$ ,  $f = 9.68$ ,  $P = 0.0057$ ; RG-24:  $y = -8.66E-4x^2 + 0.05x - 0.55$ ,  $r^2 = 0.28$ ,  $f = 3.13$ ,  $P = 0.0420$ ) with standing herbage biomass at 24 SM/ha stocking rate, with continuous grazing and rotational grazing (Fig. 5a). In contrast, there were positive linear correlations (RG-48:  $y = 0.01x - 0.19$ ,  $r^2 = 0.28$ ,  $f = 59.40$ ,  $P < 0.001$ ) at 48 SM/ha stocking rate with rotational grazing (Fig. 5a). Sheep liveweight began to decrease when standing herbage biomass fell below 3000 kg/ha with rotational grazing. In

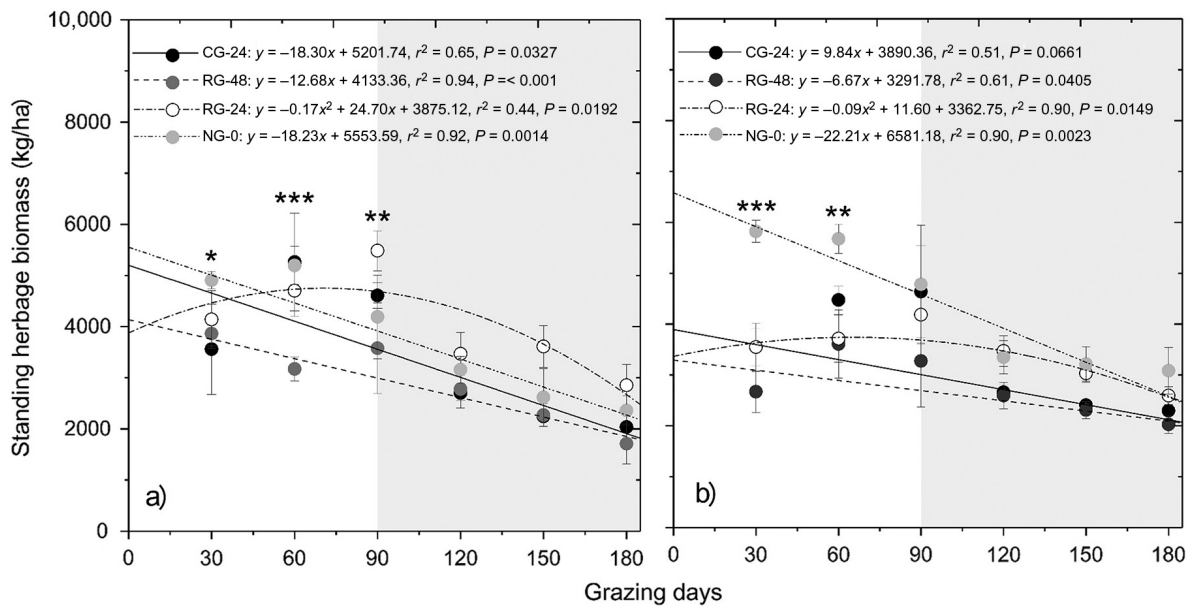


Fig. 3. Effects of continuous grazing at 24 SM/ha (CG-24), rotational grazing at 24 and 48 SM/ha (RG-24, RG-48), and no grazing (NG-0) on standing herbage biomass (a, year 2013; b, year 2014). The study was conducted in Maqu County, Gannan Prefecture, Gansu Province, China with Tibetan sheep grazed on native grassland. Lines are fitted by regression. Bars are standard errors. Multigroup comparisons of the means were carried out by one-way ANOVA test with post hoc contrasts by Student–Newman–Keuls test. The statistical significance for all tests was set at  $P < 0.05$ . Left half in white represents grazing in warm season; right half in gray represents grazing in cold season. \* $0.01 < P < 0.05$ ; \*\* $0.001 < P < 0.01$ ; \*\*\* $P < 0.001$ ; no symbol, no significant difference.

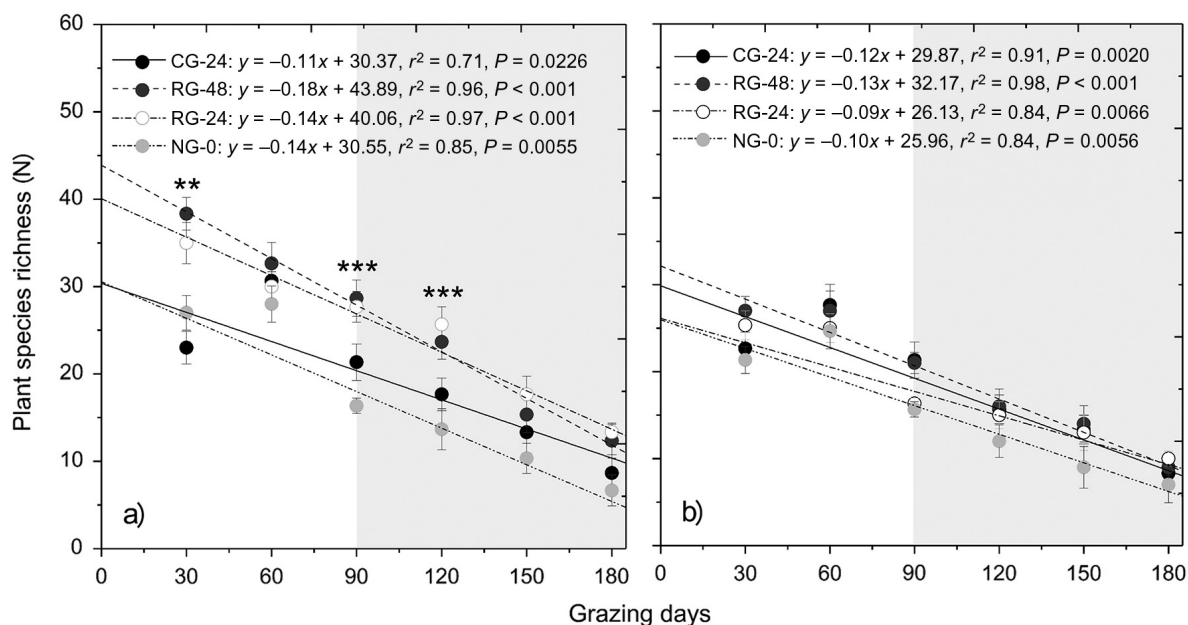


Fig. 4. Effects of continuous grazing at 24 SM/ha (CG-24), rotational grazing at 24 and 48 SM/ha (RG-24, RG-48), and no grazing (NG-0) on plant species richness (a, year 2013; b, year 2014). The study was conducted in Maqu County, Gannan Prefecture, Gansu Province, China with Tibetan sheep grazed on native grassland. Lines are fitted by regression. Bars are standard errors. Multigroup comparisons of the means were carried out by one-way ANOVA test with post hoc contrasts by Student–Newman–Keuls test. The statistical significance for all tests was set at  $P < 0.05$ . Left half in white represents grazing in warm season; right half in gray represents grazing in cold season. \* $0.01 < P < 0.05$ ; \*\* $0.001 < P < 0.01$ ; \*\*\* $P < 0.001$ ; no symbol, no significant difference.

contrast, the threshold for standing herbage biomass with continuous grazing was about 1000 kg/ha (Fig. 5a). Higher standing herbage biomass was required under rotational grazing, compared with continuous grazing, to maintain or increase sheep liveweight. Under rotational grazing, live-weight gain per hectare was significantly more ( $P < 0.05$ ) for each unit increase in standing herbage biomass at the higher stocking rate (Fig. 5c).

Live-weight gain of individual sheep had significant quadratic relationships (CG-24:  $y = -1.56E - 8x^2 + 1.33x - 0.11$ ,  $r^2 = 0.84$ ,  $f = 23.12$ ,  $P < 0.001$ ; RG-24:  $y = -3.34E - 4x^2 + 3.15x - 0.63$ ,  $r^2 = 0.75$ ,  $f = 17.36$ ,  $P < 0.001$ ) with plant species richness at 24 SM/ha stocking rate, with continuous grazing and rotational grazing (Fig. 5b). In contrast, there were positive linear correlations (RG-48:  $y = 4.53E - 5x - 0.14$ ,  $r^2 = 0.50$ ,  $f = 9.85$ ,  $P = 0.01$ ) at 48 SM/ha stocking rate with rotational grazing (Fig. 5b). Sheep live-weight gain peaked when species richness value was 28 and 27 species for CG-24 and RG-24, respectively (Fig. 5b).

Under rotational grazing, sheep liveweight began to decrease when plant species richness fell below 15 plant species per quadrat (Fig. 5).

#### Climate factors

Liveweight gain strongly correlated with average monthly temperature and precipitation through linear regression analysis (Fig. 6). For average monthly temperature,  $r^2$  values were 0.63, 0.67, and 0.67 for CG-24, RG-48, and RG-24, respectively (Fig. 6a). For average monthly precipitation,  $r^2$  values were 0.55, 0.63, and 0.64 for CG-24, RG-48, and RG-24, respectively (Fig. 6b). There was no significant difference in slopes for the three grazing regimes in Fig. 6a, b ( $P > 0.05$ ). In contrast, the slope of RG-48 was significantly different to CG-24 and RG-24 for liveweight gain per hectare ( $P < 0.05$ ). Sheep liveweight began to drop when average monthly temperature fell below  $-1.5^\circ\text{C}$  (Fig. 6a, c), and liveweight gain did not increase when average monthly precipitation was higher than 100 mm (Fig. 6b, d).



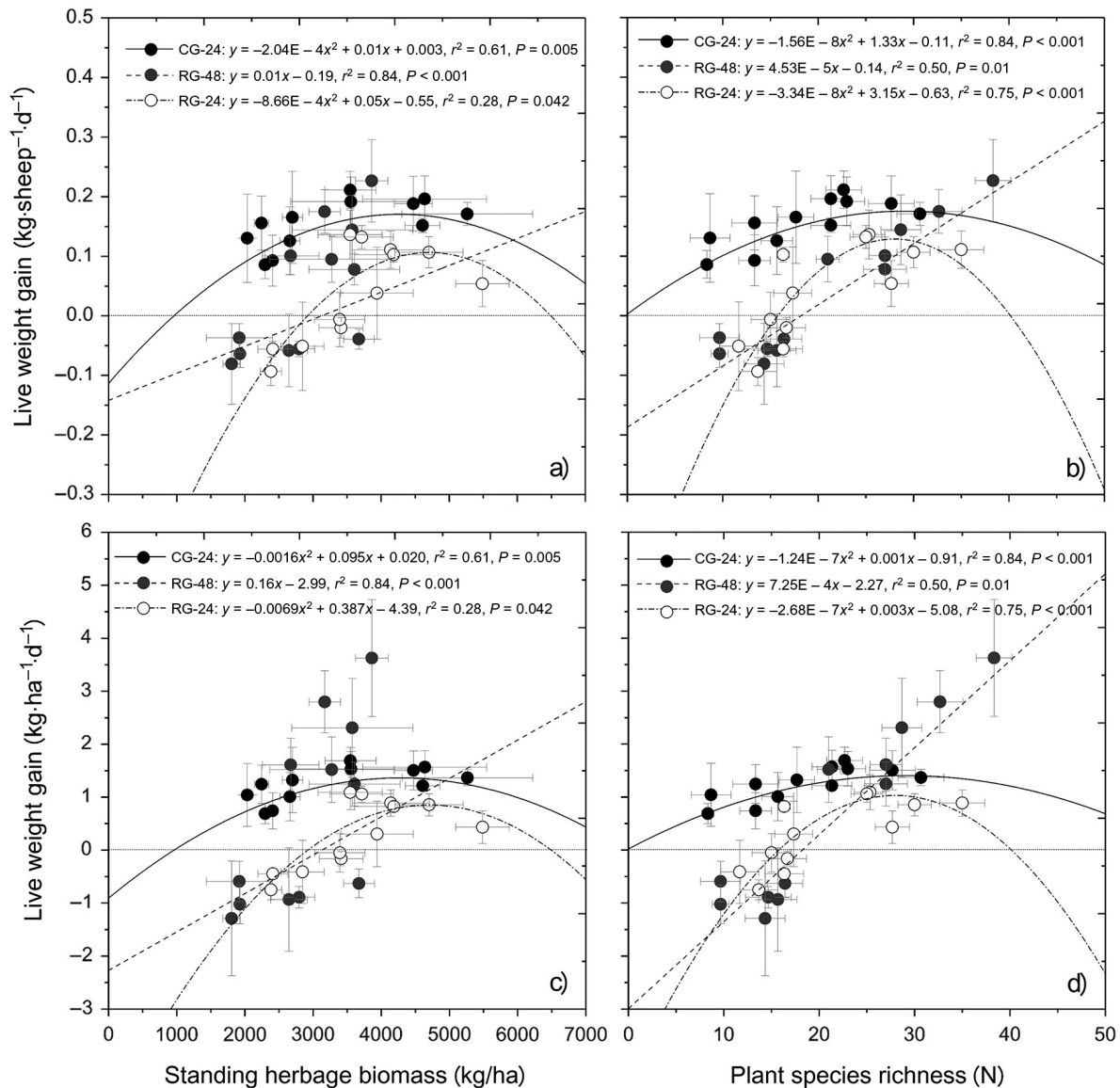


Fig. 5. Relationships between live weight gain (per sheep and per hectare), standing herbage biomass (a, c), and plant species richness (b, d) in continuous grazing at 24 SM/ha (CG-24), rotational grazing at 24 and 48 SM/ha (RG-24, RG-48), and no grazing (NG-0). Lines are fitted by regression. Points are from warm and cold season for each grazing treatment. Bars are standard errors.

Pearson correlation analysis showed that out-of-season (November–February) precipitation and mean temperature had no significant effect on almost all measures of plant biomass and species diversity. The exceptions were standing herbage and sedges which were negatively correlated with out-of-season precipitation. Most of the

plant biomass and all species diversity parameters were correlated with both early-season (March–June) and late-season (July–October) precipitation, and early-season mean temperature, whereas temperature during the late-season (July–October) had only little effect on species dynamics (Table 2).

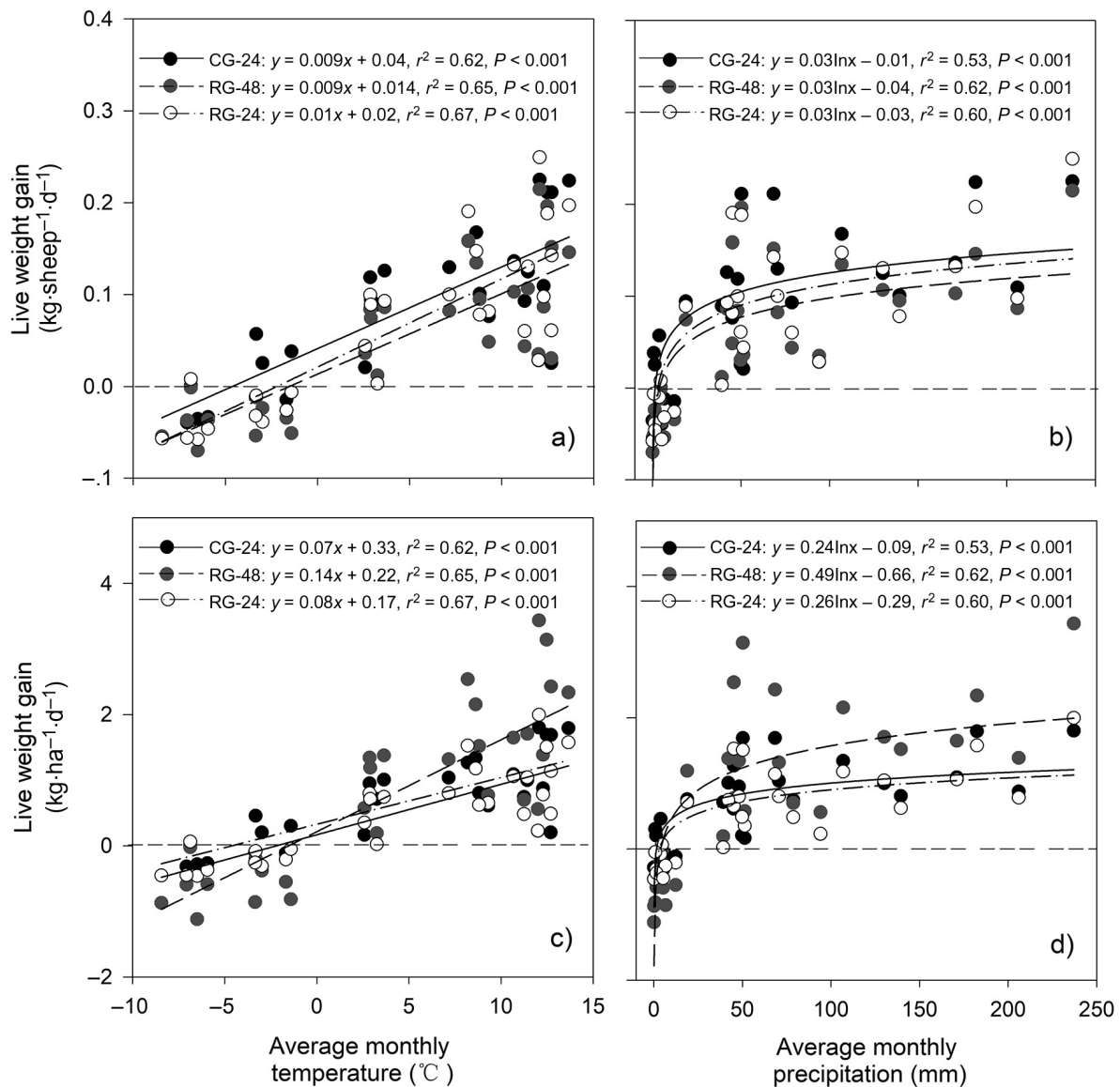


Fig. 6. Relationships between live weight gain (per sheep and per hectare), and average monthly temperature (°C; panels a and c), and average monthly precipitation (mm; panels b and d) in continuous grazing at 24 SM/ha (CG-24), rotational grazing at 24 and 48 SM/ha (RG-24, RG-48), and no grazing (NG-0). Lines are fitted by regression. Points are from warm and cold season for each grazing treatment.

## DISCUSSION

### Comparing the benefits of grazing exclusion vs. grazing on restoration of degraded grassland

Grassland degradation has resulted in a significant increase in the proportion of less-desirable plant species (i.e., *Ligularia virgaurea*), and decreased livestock and grassland productivity

in the region (Li et al. 2013). The exclusion of livestock with mesh fencing to create large enclosures has, in recent decades, become a common grassland management strategy for restoring degraded grasslands on the Qinghai-Tibet Plateau (Wu et al. 2009, Yan and Lu 2015). In this study, five years of grazing exclusion produced some unexpected results, as follows (Figs. 3, 4).

Table 2. Correlation coefficients ( $r$  value) for the relationship between above-ground biomass of standing herbage, sedges, grasses, and forbs, and species diversity indices (species richness, diversity, and evenness) with early, late, and out-of-season average monthly temperature (AMT) ( $^{\circ}\text{C}$ ) and average monthly precipitation (AMP) (mm).

Parameter	Grazing regimes	Early season (Spring)		Late season (Summer)		Out of season (Winter)		Annual	
		AMT	AMP	AMT	AMP	AMT	AMP	AMT	AMP
Standing herbage biomass	CG-24	0.44	0.78	0.56	0.82	0.07	-0.45	0.55	0.79
	RG-48	0.43	0.78	0.48	0.83	0.10	-0.37	0.52	0.81
	RG-24	0.52	0.79	0.49	0.80	0.11	-0.47	0.56	0.83
	NG-0	0.51	0.81	0.45	0.83	0.06	-0.71	0.56	0.83
Sedges biomass	CG-24	0.34	0.57	0.34	0.67	0.16	-0.46	0.15	0.56
	RG-48	0.45	0.58	0.35	0.66	-0.12	-0.57	0.17	0.44
	RG-24	0.28	0.62	0.37	0.68	-0.11	-0.57	0.18	0.46
	NG-0	0.35	0.63	0.31	0.59	0.12	-0.62	0.13	0.49
Grasses biomass	CG-24	0.25	0.55	0.24	0.46	-0.24	-0.12	0.17	0.08
	RG-48	0.23	0.67	0.26	0.47	-0.23	-0.21	0.16	0.10
	RG-24	0.25	0.64	-0.23	0.46	-0.24	-0.13	0.21	0.11
	NG-0	0.26	0.56	-0.30	0.41	-0.33	-0.10	0.19	-0.01
Forbs biomass	CG-24	0.11	0.79	-0.25	0.49	0.22	0.23	0.33	0.46
	RG-48	0.04	0.86	-0.26	0.37	0.24	0.26	0.30	0.36
	RG-24	0.06	0.83	-0.03	0.38	0.24	0.27	0.27	0.37
	NG-0	0.08	0.93	-0.14	0.39	0.25	0.34	0.31	0.52
Species richness	CG-24	0.36	0.54	-0.21	0.32	-0.35	0.19	0.10	0.66
	RG-48	0.27	0.56	-0.24	0.35	-0.35	0.29	0.15	0.70
	RG-24	0.45	0.56	-0.10	0.26	-0.36	0.28	0.16	0.69
	NG-0	0.33	0.53	-0.25	0.24	-0.38	0.24	0.11	0.69
Species diversity	CG-24	0.42	0.42	-0.26	0.47	0.04	-0.37	0.35	0.32
	RG-48	0.44	0.46	-0.31	0.49	0.05	-0.47	0.33	0.43
	RG-24	0.37	0.44	-0.22	0.48	-0.02	-0.36	0.36	0.40
	NG	0.45	0.40	-0.26	0.52	-0.07	-0.48	0.37	0.23
Species evenness	CG-24	0.46	0.38	-0.21	0.47	-0.11	-0.38	0.38	0.22
	RG-48	0.55	0.39	-0.28	0.51	-0.12	-0.44	0.40	0.34
	RG-24	0.49	0.47	-0.19	0.47	-0.10	-0.39	0.44	0.35
	NG-0	0.51	0.45	-0.26	0.50	-0.11	-0.47	0.38	0.28

Notes: CG-24, continuous grazing at 24 SM/ha; NG-0, no grazing; RG-24, rotational grazing at 24 SM/ha; RG-48, rotational grazing at 48 SM/ha. Early-season indicates March–June; Late-season indicates July–October; Out-of-season indicates November–February.

Standing herbage biomass in the warm seasons of 2013 and 2014 was higher following grazing exclusion. In the cold season, there was no significant difference in standing herbage biomass between grazing exclusion and grazing treatments. In both warm and cold seasons of 2013, species richness was lower following grazing exclusion. When grazing is excluded, a rapid reduction in forbs cover occurs due to competition from tall grasses, so species richness decrease. Interestingly, plant diversity was higher following four years of rotational grazing at 48 SM/ha (Fig. 4a). This shows that careful, tactical grazing at suitable stocking rates may be a major tool for rehabilitating grassland. In the

same region, other research showed that enclosure fencing had a positive effect on above-ground vegetation by increasing Graminoid and Sedge species (Wu et al. 2009). The likely reason for this difference is that the stocking rates in this study were controlled and precise, while in the study by Wu et al. 2009 the stocking rates were determined by the distance from pasture to water resource. Moreover, grazing bans also had negative consequences for biodiversity, because this led to a reduction in plant species richness and evenness (Wu et al. 2017). Under grazing bans, dominant grasses with higher competitive ability in grazed pasture are faced with greater competition for canopy resources (i.e., light;

Grime 1979). In Northern Tibet, Cao et al. (2015) found that the levels of both plant species diversity and herbage biomass were higher in areas of a grazing ban, than in communal free grazing land with no grazing ban. In this study, inter-annual variations of standing herbage biomass were mainly determined by local precipitation and temperature (Table 1). This suggested that climatic factors are the main drivers for above-ground productivity (not overgrazing in alpine grassland; Klein et al. 2014). Two main types of factors prevent degraded grassland from recovering without management intervention, that is, biotic interactions and abiotic limitations (Hobbs and Harris 2001). Grazing can have both direct and indirect influences on plant communities: direct through defoliation and trampling affecting plant survival, growth, and reproductive potential, and indirectly by affecting community and habitat interactions (Fuhlendorf and Smeins 2010). Grazing at high stocking rate reduces the competitiveness of less-desirable species through removing leaves and, or physically damaging the plants, especially buds for growth (Zhang et al. 2015). Simply banning grazing will not fix the problem, but possibly lead to rapid population growth of undesirable wild animal species such as rabbits and wild donkeys, which lack sufficient natural predator controls, causing new ecological imbalances (Li and Huntsinger 2011). Human intervention, such as by banning grazing, might promote the recovery of original habitats in the short term, but is not a long-term solution.

#### *Comparing the benefits of continuous vs. rotational grazing on grassland quality and livestock production*

Rotational grazing has been claimed to improve forage yield and quality, and maintain pasture species diversity, because farmer control of grazing frequency and duration, allows beneficial plants to recover without repeated selective grazing of preferred plants (Jacobo et al. 2006, Briske et al. 2011, Sanderman et al. 2015). The results of this study showed that grassland quality and livestock production were not influenced by grazing regime (i.e., by neither rotational nor continuous grazing), but that precipitation, temperature, also stocking rate, are the driving factors.

There was no significant difference in plant species richness and standing herbage biomass between rotational and continuous grazing at 24 SM/ha in both warm and cold season in 2013 and 2014 (Figs. 3, 4). Plant biomass under rotational grazing at 48 SM/ha was significantly lower than that at 24 SM/ha in the warm season of 2013 and 2014 (Fig. 2a, b). Relative to continuous grazing, rotational grazing did not represent a quicker herbaceous recovery in the rest time as reported in North American prairie (Teague and Dowhower 2003, Teague et al. 2004). A feasible explanation for this is that alpine grassland of the Tibetan Plateau has long been adapted to grazing by semi-domesticated yak and Tibetan sheep and is adapted to prevailing summer precipitation (Wang et al. 2018), and the age-old traditional continuous grazing practice encourages compensatory forage growth.

This study demonstrated that sheep liveweight gain per unit sheep in 2013 was significantly higher with rotational grazing at the higher stocking rate in warm season, but in the cold season, continuous grazing-maintained sheep liveweight gain per hectare (Fig. 2a, c). In 2014, sheep liveweight gain per unit sheep, and per hectare, were not increased by rotational grazing (Fig. 2b, d), though sheep production per hectare increased when stocking rate of rationally grazed sheep was doubled (Fig. 2). There is a significant relationship between sheep liveweight gain and sheep feed intake (Kirby and Parman 1986, Wang et al. 2011). Though we did not directly measure diet composition or forage intake, the lack of difference in animal performance between grazing systems leads us to infer that diet composition and forage intake of Tibetan sheep did not differ between systems. In continuous grazing, livestock are not moved from one pasture to another, conserving energy spent on moving between pastures, in rotational grazing, moving livestock too frequently can reduce animal production (weight gains; Du et al. 2017).

This study showed that, for Tibetan sheep to maintain or increase their liveweight, higher plant biomass and species diversity are required under rotational grazing, than with continuous grazing (Fig. 5). Under rotational grazing, Sedges gain dominance. Except in early (spring growth) and late (seed bearing) seasons, these are a less palatable forage, leaving sheep to graze

only the smaller understory forbs. Under continuous grazing, Sedges are less dominant, plant species distribution is more even, and sheep are not confined by a break fence in their selection of forage.

### Climate factors

A correlation between observed 11-yr solar and weather/global temperature cycles has, for the past 150 yr, been a debated issue. With recent advances in satellite instrumentation, this has become more widely understood (Ineson et al. 2011). For this reason, any one year of this five-year field trial is unlikely to be representative of the whole cycle, and a longer-term study would be appropriate. This five-year trial is nevertheless representative of (almost) one half of this cycle.

Livestock performance on the Qinghai-Tibet Plateau has long been associated with seasonal climate variation (Hu et al. 2010, Xu et al. 2010). The results in this experiment showed the influence of mean monthly temperature and precipitation on sheep live weight gain ( $R^2 = 0.63$ – $0.67$  and  $0.53$ – $0.64$ , respectively), indicating a strong link with livestock production. In this trial, Tibetan sheep started to lose their weight in November and December of each year (2013 and 2014; Fig. 2). The key factors to affect sheep live weight were low temperature and heavy snow. When mean temperature fell below  $-2^{\circ}\text{C}$ , sheep began to lose liveweight (Fig. 6). Standing herbage biomass and nutrient content of local pasture decreased sharply during the cold season, when

animals move over larger distances to seek herbage to meet their daily DM requirements (Gregorini et al. 2011). From previous research, Tibetan sheep could lose 12.4–43.7% of their initial live-weights, and domestic yak could lose 25–30% of their initial live-weights during the cold season (Feng et al. 2013). In this study, grazing Tibetan sheep lost 18.7% of their initial live-weights during November and December.

Rainfall (occurring only in the warm season) has previously been shown to affect livestock production through increasing biomass and nutrient content in alpine grassland (Dong et al. 2006). This would contribute to our finding that sheep liveweight gain reached its peak value during the periods of peak precipitation. The influence of both temperature and precipitation on livestock production was the same for all grazing regimes (Fig. 6), so to maximize year-round stock performance, it is appropriate to change the grazing system to suit the season (Fig. 7). It appears that seasonal variation in livestock performance on the Tibetan Plateau is inescapable. To improve livestock performance, we suggest that herders predominantly graze the alpine grasslands only when plants are green and limit winter grazing. This can only be achieved with Government support for the design, modification, building, and management of sheds and supplementary (winter) forage.

The results in this study highlight the importance of temporal distribution patterns of precipitation and temperature on vegetation dynamics

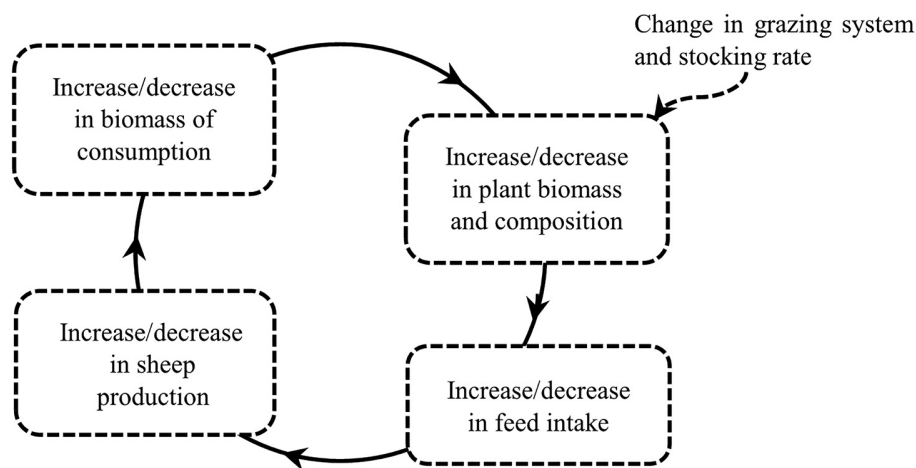


Fig. 7. Feedback mechanism between sheep production, and plant biomass and composition.

(Table 2). Most of the variation in species composition and diversity was determined by early season precipitation and mean temperature (March–June; Table 2), whereas only a small proportion of the variance in the investigated vegetation parameters could be explained by either annual or late-season precipitation and mean temperature (July–October; Table 2). In the first three years of this research study, vegetation dynamics were predominantly determined by inter-annual differences (temperature and precipitation), and to a lesser extent by grazing intensity (Sun et al. 2015). In the final two years of this study, we also found that temporal distribution of precipitation and temperature, particularly during the early-season (from March to June), determined the variation in vegetation dynamics significantly more than annual rates of precipitation or temperature. In the medium term (5 yr), species diversity and forage biomass were more closely linked to early-season precipitation and temperature, than to grazing.

For Tibetan alpine grasslands, therefore, traditional measures for pasture condition and carrying capacity may not be effective gauges for management. New perspectives regarding non-equilibrium ecosystem dynamics and concepts about plant succession processes in semi-arid ecosystems (Fernandez-Gimenez and Allen Diaz 1999) provide interesting frameworks for analyzing Tibetan grassland. Current grazing policy needs to be adjusted taking into account the modern ecological understanding of the non-equilibrium of ecosystems. Therefore, it is essential to better understand whether alpine grassland is an equilibrium or non-equilibrium ecosystem in the future.

## CONCLUSION

In conclusion, our results provided insight into the Government recommendations and policies regarding management of the alpine grasslands of the Qinghai-Tibet Plateau, and restoration of the degraded grassland using such practices as grazing bans and rotational grazing. Non-grazed paddocks (simulating grazing ban) did not show in a significant increase in standing herbage biomass and plant diversity indices, compared with all grazed paddocks during the same 5 yr. Sheep liveweight gain per hectare was significantly

higher under continuous grazing, compared to rotational grazing at the same stocking rate. This liveweight gain per hectare was exceeded under rotational grazing at the higher stocking rate (48 SM/ha).

Temporal distribution of precipitation and temperature, particularly during the early-season (from March to June) and late-season (from July to October), had more influence on herbage biomass and plant diversity indices than grazing. The study found that sheep liveweight increased during the warm season and declined in the cold season from November onwards when forage is often covered with snow.

This study suggests that herders' local traditional knowledge and expertise might be useful in modifying Government guidelines to fine tune grazing management with the dynamics of the alpine meadow ecosystem. Traditional continuous grazing at a carefully chosen light stocking rate appears to be the most appropriate way to manage livestock and grassland in this region. This study also suggests that it is important to consider equilibrium and non-equilibrium theory in formulating a policy which benefits both herders and grassland.

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