Plateau pikas (*Ochotona curzoniae*) and plateau zokors (*Myospalax baileyi*) occur naturally in the alpine meadow of the Qinghai–Tibet Plateau (QTP). Their feeding and burrowing activities affect plant composition and soil properties (e.g., soil carbon accumulation and soil nitrogen cycling), but research to study the complex interactions between small mammals, livestock, and habitat is currently lacking. We conducted a sheep grazing trial to determine the effect of grazing management on pika burrow and zokor mound density, and the relationships between sheep production and pika burrow and zokor mound density. The grazing management approaches were warm-season rotational grazing at 24 and 48 sheep months (SM)/ha, cold-season rotational grazing at 24 and 48 SM/ha, seasonal continuous grazing at 24 SM/ha, and whole-year continuous grazing at 48 SM/ha. The results of this study suggested that warm-season rotational grazing at low stocking rate did not significantly change both pika and zokor densities. Cold-season rotational grazing at both high and low stocking rates and seasonal continuous grazing at low stocking rate led to an increase in zokor mound density, but not pika burrow density. Whole-year continuous grazing at high stocking rate increased both pika and zokor densities. The influence of pika and zokor activities on sheep production was complex and differed between grazing management. Sheep liveweight gain peaked at moderate pika burrow and zokor mound density at low stocking rate under both warm- and cold-season rotational grazing. The threshold values of pika density were about 110 and 70 burrows per hectare in warm and cold seasons, respectively. The threshold value of zokor density was about 400 mounds per hectare in the cold season. In contrast, under high stocking rate regardless of management approach, sheep liveweight gain declined significantly as both pika burrow and zokor mound density increased. This paper provides a theoretical understanding and experimental evidence for sustainable grazing management and restoration of degraded grassland by local herders and policymakers.

**Key words:** alpine meadow; burrow density; grazing management; mound density; restoration; Sheep liveweight gain; small mammal management.
rangeland the most extensive terrestrial ecosystem (Bakker et al. 2010, Davidson and Brown 2012). Conflict between livestock and small mammals in grassland ecosystems has existed for millennia (Brown et al. 2006, Davidson et al. 2010, Tchabovsky et al. 2016), yet livestock and small mammals can also exhibit complementary and additive effects, and the ecological relationships between them can be facilitatory, in particular for the grassland on the QTP (Yoshihara et al. 2010, Bock et al. 2011). Better understanding of these interactive roles in the context of human activities is needed, for further advance in grazing management practices on the QTP.

The QTP has been grazed by domesticated yaks (Bos grunniens) and Tibetan sheep (Ovis aries) for ~8000 yr (Qiu 2014, Sun et al. 2015a) and now directly supports ~70% of the local population. Qinghai–Tibet Plateau grassland is home to a large diversity of unique flora and fauna (Zhisheng et al. 2001, Niu et al. 2016). At present, there are about fifteen million yaks and fifty million Tibetan sheep which, together with small mammals (pikas and zokors), are well adapted to the hypoxic environment (Zhao 2013, Sun et al. 2015a, b). Average small mammal population densities are estimated to be ~5 pika/ha and 10 zokor/ha (Fan et al. 1999, Su et al. 2016).

Grazing livestock have an impact on Tibetan population densities of small mammals through causing changes in the physical and chemical properties of the soil (Pech et al. 2007, Jacquot et al. 2013, Liu et al. 2016). These changes, together with a change in availability of foliage, influence population dynamics of small mammals (Jones and Longland 1999, Steen et al. 2005, Zhu et al. 2012). Pika burrow density increased with increasing grazing intensity, by reducing height of dominance plant species (Elymus natans and Puccinellia tenuiflora) on the Tibetan grassland (Harris et al. 2015). In Mediterranean grassland, grazing also reduced food availability of small mammals, and trampling by livestock made the soil less suitable for building burrow systems (Torre et al. 2007).

In the native grassland ecosystem of the QTP, apart from facing the danger of predation by weasels, polecats, foxes, wolves, and eagles (Pech et al. 2007, Davidson and Brown 2012), the activities of plateau pika and zokor exert both destructive and beneficial influences on the alpine meadow ecosystem. Herbage consumption by pika and zokor causes changes in vegetation, such as reduction in vegetation cover and density of forbs and grazing-tolerant grasses, thus promoting bare soil and soil moisture loss (Arthur 2007, Davidson and Lightfoot 2006, Zhang et al. 2016). Small mammals also compete with livestock for herbage and habitat, and thereby, both directly and indirectly, affect livestock production (Arthur et al. 2008, Harris 2010). An adult pika consumes about 77.3 g of fresh grass per day which is about 50% of its body weight. The food intake of 56 adult pikas equals that of one Tibetan sheep (Pi 1973). It has been estimated that small mammals on the QTP consume about 15,000 billion kg of grassland foliage each year (Fan et al. 1999), which is seen by herders and governments to be forage that could have been consumed by sheep. Small mammals also consume insects and the soil macro-biota (Forsyth et al. 2016, Yu et al. 2017) which accelerate soil organic matter turnover. Excavation activities of pika and zokor loosen soil, enhancing the ability of soil to absorb rainfall, contributing to nutrient cycling, and creating microhabitats resulting in increased plant richness (Smith and Foggin 1999). The mounds of zokor also have higher levels of plant-available nitrogen and phosphorus than surrounding soils (Zhang and Liu 2003).

Degradation of QTP grassland is considered to be the result of climate change, and of frequent and persistent grazing by domestic herbivores (Arthur 2007, Li et al. 2010). This degradation has coincided with a widespread increase in Tibetan small mammals’ populations, which has led to the perception that the main cause of grassland degradation is the activity of small mammals. The latter are regarded as pest species because they appear to compete with livestock for scarce food resources. However, Lai and Smith (2003) propose that a critical issue for restoring degraded grassland on the QTP is the need to maintain the important functional role of these keystone burrowing pika and zokor, while simultaneously managing for livestock production. Since the mid-1980s, studies have shifted toward developing a sustainable strategy for managing pika and zokor damage by understanding their ecology and interaction with livestock grazing (Qu et al. 2012). Control programs...
of small mammals have been carried out, but pika and zokor populations continue to increase. The loss in sheep production resulting from small mammals’ consumption of foliage is logically influenced by grazing management (e.g., stocking rate; grazing regime), but until now any estimation or measurement of this has been imprecise.

Though individual elements of the grassland ecosystem on the QTP are well studied, the complex interactions between small mammals, livestock, and habitat are poorly understood. In order to disentangle these interacting roles between livestock and small mammals in the QTP ecosystem, large-scale, long-term experimental studies are required. This study investigates the relationships between pika burrow and zokor mound density and sheep production in alpine meadow, under various grazing management regimes, to test the following hypotheses: (1) Livestock and small mammals indirectly affect each other through their impacts on vegetation and soil; (2) the interactive effects between livestock and small mammals are regulated by grazing management. In testing the above hypotheses, the following aspects were investigated: (1) the relationship between sheep stocking rate and grazing management, and pika burrow and zokor mound density; (2) the relationship between pika burrow and zokor mound density, and sheep liveweight gain; and (3) the implications of the above relationships on best alpine meadow conservation and management practice by government policy and local herders.

**METHODS**

**Study site**

The study was conducted in Maqu County, Gansu Province, eastern of QTP (Fig. 1a). The study site was located at Azi field station (latitude 33°42’1” N, longitude 102°07’02” E, elevation about 3500 m a.s.l.). Vegetation is alpine meadow (Ren et al. 2008), comprised of sedges, grasses, and forbs. Dominant plant species are *Kobresia graminifolia*, *Elymus nutans*, *Agrostis species*, *Poa pratensis*, *Saussurea species*, and *Anemone species*. Soil type is alpine meadow soil, primarily Mat-Cryic Cambisols (Chinese Soil Taxonomy Research Group 1995). Warm season is from June to September, and cold season is from October to May. Mean annual precipitation is 620 mm (Fig. 1b), most occurring as rainfall during the warm-season period. Temperatures range from −21.7°C in cold season to 20.9°C in warm season, with a mean annual temperature of 1.2°C (Fig. 1b). The small mammal species at the site are plateau pika (*Ochotona curzoniae*) and plateau zokor (*Myospalax baileyi*; Fig. 1a).

**Experimental treatments**

The experimental area in the field station comprised 35 ha (24 ha were used for Tibetan grazing trials, and remaining areas were supplemental or buffer zones) on a typical alpine meadow. Sheep grazing trials were set up at the beginning of the study (late April 2010; for full details of sheep management, see Sun et al. 2015a, Du et al. 2017, Wang et al. 2018a). The grazing treatments were as follows: (1) warm-season rotational grazing at two stocking rates of 24 and 48 SM (sheep months)/ha. At each stocking rate treatment, eight sheep grazed from July to September in 1.0-ha and 0.5-ha plots, respectively. There were six replicates for each stocking rate. Each replicate was subdivided into 3 × 10 d breaks. (2) Cold-season rotational grazing at two stocking rates at 24 and 48 SM/ha. At each stocking rate treatment, eight sheep grazed from October to December in 1.0- and 0.5-ha plots, respectively. There were six replicates for each stocking rate. Each replicate was subdivided into 2 × 15 d breaks. Breaks here mean that within each replicate, the warm-season stocked paddocks were subdivided into three sub-paddocks and the cold-season stocked paddocks were subdivided into two sub-paddocks. Sheep were moved between the sub-paddocks every 10 and 15 d in the warm-season rotational grazing and cold-season rotational grazing, respectively. (3) Seasonal continuous grazing at the rate of 24 SM/ha. Eight sheep grazed from July to December in 2.0-ha replicate plot (not subdivided). There were three replicates. (4) Whole-year continuous grazing at the rate of 48 SM/ha was conducted in local herder’s pasture, not in the field station. Four hundred sheep grazed all the year round in 100-ha pasture. Three replicate plots (100 m × 200 m) were pegged out. The distance between any two adjacent plots was 10–20 m. In each replicate plot of each grazing treatment, three widely spaced
25 × 25 m observation zones were pegged out (July 2010) as being representative of the alpine meadow to measure the small mammal activities (counting active entrances and mounds) and collected vegetation data and soil samples.

Counts of pika burrows and zokor mounds
Pika and zokor activities were observed and recorded three times in each trial year (2010 and 2011): early July (beginning of warm season), early October (end of warm and beginning of

Fig. 1. Location of the study site in Maqu County on the Qinghai–Tibet Plateau, bordered by Sichuan and Yunnan provinces in the southeast, and by Gansu and Xinjiang provinces in the northwest. The small mammal species studied: plateau pika and zokor (a); interannual variation and monotonic trends in annual temperature (red) and precipitation (blue) in Maqu County, Qinghai–Tibet Plateau, 1970–2015; lines denote linear fit (b).
cold season), and end of December (middle of cold season). It is difficult to quantify the actual small mammal’s population densities in the field. Generally, active entrance for plateau pika and mound for plateau zokor are usually used to indicate the relative population densities. The higher active burrow entrances and mounds per plot meant the higher disturbance intensity of plateau pika and plateau zokor (Guo et al. 2012). We estimated by counting active pika burrow entrances and zokor mounds as follows: pika: Burrow entrances were plugged with sheets of newspaper, and three days later, the number of plugs cleared by pika was counted (Guo et al. 2012); zokor: All mounds, both beside and covering entrances, and of varying age, were counted.

**Plant, soil, and livestock measurements**

**Plant.**—In each small mammal observation zone (see Experimental treatments), one 0.5 × 0.5 m quadrat was placed, in which all shoots were measured (cm. height) and cut, and the on-ground litter removed and bagged together in August (warm season) and November (cold season) 2010 and 2011. Litter and shoots of each species were separated, oven-dried at 65°C for 48 h, and weighed. The total shoot weight was the sum of individual species.

**Soil properties.**—Surface layer (A horizon) temperature and soil moisture content of each sample were measured at 10 cm depth. The soil was sampled in the middle of each 0.5 × 0.5 m quadrat (as above), with a 10 cm diameter auger, to 10 cm sampling depth. Soil was removed in 10-cm layers, down to a depth of 40 cm, and each layer was separately placed into 2 mm mesh bags. After air-drying for 1 month in a glasshouse, the soil from each layer was divided into root and soil subsamples. Root was then washed free of soil, oven-dried at 115°C for 48 h, and weighed. The soil subsamples were additionally air-dried in the laboratory at room temperature and sieved through a 0.2-mm mesh.

**Sheep liveweight.**—Each sheep was weighed on two consecutive days at the end of each month. Liveweight gain per sheep per day was calculated by dividing the seasonal difference in weight by the number of days in the season. Liveweight gain per hectare was calculated from the numbers of sheep in each paddock times the average liveweight gain per day.

**Statistical analysis**

All data were analyzed using SAS software version 9.3 (SAS Institute, Cary, North Carolina, USA), with significance levels set at \( P < 0.05 \). A goodness-of-fit test (Shapiro-Wilk test) was used to test data distributions and confirm normality. We used a mixed linear model (Proc mixed) to assess differences in plant height, soil moisture, aboveground herbage biomass, density of shrubs, ratio of biomass of sedges to total biomass, ratio of biomass of forbs to total biomass, pika burrow density, and zokor mound density between grazing treatments. In this model, grazing system and stocking rate were used as two fixed factors, and the year was used as a random factor. Least significant difference method \( (P < 0.05) \) was used for testing the significant difference. Prior to linear or nonlinear regressions, the response variables for the samples (observation zone) were averaged and the mean served as the response variable value for each replicate plot. Linear regressions were performed to test the relationships between pika burrow and zokor mound density at the beginning and end of grazing seasons, and the relationships between sheep liveweight gain and pika burrow and zokor mound density. Exponential regressions were computed to test the relationships between plant height, soil moisture, and ratio of biomass of sedges to total biomass with pika burrow density. Quadratic regressions were used to represent the relationships between aboveground biomass and density of shrub with pika burrow density, and the relationship between density of shrub and zokor mound density. Simple linear regressions were performed to test the relationship between plant height, soil moisture, aboveground biomass, ratio of biomass of forbs to total biomass, ratio of biomass of forbs to total biomass with zokor mound density. Pearson’s correlation coefficient was used for testing the above relationships. The significance levels were set at \( P < 0.05 \). All graphs were constructed using SigmaPlot 12.5 for Windows (Systat Software) software and Origin 9.1 (OriginLab, Northampton, Massachusetts, USA).
RESULTS

Grazing management and pika burrow and zokor mound density

These field trials demonstrate that pika burrow density is significantly influenced by grazing system and stocking rate, each independently ($P < 0.01$, $P < 0.01$), and by grazing system and stocking rate in conjunction ($P < 0.01$). Under rotational grazing at 24 SM/ha and 48 SM/ha in both warm (July–October) and cold seasons (October–December) in 2010 and 2011, pika burrow density, as indicated by burrow counts, showed a declining trend (Fig. 2a), with seasonal grazing at 24 SM/ha in both 2010 and 2011 pika burrow density also declined, but increased with whole-year continuous grazing at 48 SM/ha in both 2010 and 2011 (Fig. 2a), and indeed was significantly ($P < 0.01$) higher than under all other grazing management treatments (Fig. 2a).

Zokor mound density was shown to be significantly influenced by grazing system ($P < 0.01$), but not by stocking rate and by grazing system and stocking rate in conjunction ($P = 0.2385$). Zokor mound density, as indicated by mound counts, showed a rising trend at 24 and 48 SM/ha under both seasonal continuous grazing and whole-year continuous grazing in both warm and cold seasons (Fig. 2b), and with rotational grazing in the cold season only (Fig. 2b). Zokor mound density with warm-season rotational grazing was significantly ($P < 0.01$) lower than that with all other grazing management treatments (i.e., cold-season rotational grazing and continuous grazing; Fig. 2b).

Pika burrow and zokor mound densities at the end of each grazing season were closely aligned with their densities at the start of each grazing season (Fig. 3). Under rotational grazing at both stocking rates in warm season, start and end of season pika burrow and zokor mound density both showed significant ($P < 0.05$) positive linear relationships (Fig. 3a, d). Under rotational grazing at both stocking rates in cold season, start and end of season pika burrow density showed a significant ($P < 0.05$) quadratic relationship (Fig. 3b) and zokor mound density showed significant positive linear relationship (Fig. 3e). Under whole-year continuous grazing at 48 SM/ha, pika burrow density increased, but showed no change under seasonal continuous grazing at 24 SM/ha (Fig. 3c). By comparison, zokor mound density increased under both whole-year continuous grazing at 48 SM/ha and seasonal continuous grazing at 24 SM/ha (Fig. 3f).

Relationships between vegetation and soil properties with pika burrow and zokor mound density

There were significant ($P < 0.01$) negative exponential relationships between aboveground biomass, plant height, and ratio of biomass of sedges to total biomass with pika burrow density (Fig. 4a, e). There was a significant ($P < 0.01$) positive exponential relationship between soil moisture and pika burrow density (Fig. 4b). Pika burrow density was the lowest when aboveground biomass was about 4000 kg/ha (Fig. 4c). Pika burrow density increased significantly with increase in density of shrubs and ratio of biomass of forbs to total biomass (Fig. 4d, f).

Zokor mound density significantly decreased as plant height, aboveground biomass, and ratio of biomass of sedges to total biomass increased (Fig. 5a, c, e). There were significant ($P < 0.01$) positive linear relationships between soil moisture and ratio of biomass of forbs to total biomass with zokor mound density (Fig. 5b, e).

Relationships between pika and zokor population densities, and sheep liveweight gain

Sheep liveweight gain and pika burrow density showed significant negative linear relationships at 48 SM/ha under both warm- and cold-season rotational grazing (Fig. 6a, b). Sheep liveweight gain showed significant quadratic relationships with pika burrow density under rotational grazing at 24 SM/ha in both warm and cold seasons (Fig. 6a, b). Under season continuous grazing at 24 SM/ha, sheep liveweight gain increased as pika burrow density increased (Fig. 6c). Under whole-year continuous grazing at 48 SM/ha, sheep liveweight gain decreased as pika burrow density increased (Fig. 6d).

Sheep liveweight gain and zokor mound density showed significant negative linear relationships at both 24 and 48 SM/ha under rotational grazing in warm and at 48 SM/ha in cold season (Fig. 6e, f). Sheep liveweight gain showed significant quadratic relationship with zokor mound density.
density under rotational grazing at 24 SM/ha in cold season (Fig. 6f). With both seasonal continuous grazing at 24 SM/ha and whole-year continuous grazing at 48 SM/ha, sheep liveweight gain decreased as zokor mound density increased (Fig. 6g, h).

**DISCUSSION**

**Effects of grazing management on pika burrow and zokor mound density**

The impact of livestock grazing on pika and zokor has long been recognized (Klemola et al.
2000, Davidson et al. 2010, Yi et al. 2016), but the impact of grazing system and stocking rate on pika burrows and zokor mounds, and the associated underlying mechanisms have not been explored in the context of interactions of sheep, plant, and small mammals (Fig. 7). This study confirms that grazing system and stocking rate both play key roles in influencing the small mammal’s population’s response to livestock grazing (Figs. 2, 3). At the start of this study (July 2010) and prior to applying grazing managements to each trial paddock, there was no significant ($P > 0.05$) difference in small mammal population density between all trial paddocks (Fig. 2). Over the following two trial years, pika burrow and zokor mound density followed different trajectories, depending on the grazing system and stocking rate applied (Fig. 2). Under both rotational grazing and seasonal continuous grazing at 24 SM/ha, pika burrow density

Fig. 3. Relationship between small mammal densities (as indicated by pika burrows/ha and zokor mounds/ha) at the start and end of each grazing season, under rotational grazing in warm and cold seasons, and seasonal and whole-year continuous grazing. Each point is the mean of three (25 × 25 m) observation zones from each rotationally grazed replicate plot and of three observation zones from each continuously grazed replicate plot. Bars are SEs. Solid and dashed lines are regression fits, and dash-and-dot lines show 1:1 relationship.
Fig. 4. Relationship between pika burrow density and plant height (cm), soil moisture (%), aboveground biomass (kg/ha), density of shrubs (Number/ha), ratio of biomass of sedges to total biomass (%), and ratio of biomass of forbs to total biomass (%). Each point is the mean of three (25 × 25 m) observation zones from each rotationally grazed replicate plot and of three observation zones from each continuously grazed replicate plot. Bars are SEs. The lines denote the linear or nonlinear fit.
Fig. 5. Relationship between zokor burrow density and plant height (cm), soil moisture (%), aboveground biomass (kg/ha), density of shrubs (number/ha), ratio of biomass of sedges to total biomass (%), and ratio of biomass of forbs to total biomass (%). Each point is the mean of three (25 × 25 m) observation zones from each rotationally grazed replicate plot and of three observation zones from each continuously grazed replicate plot. Bars are SEs. The lines denote the linear or nonlinear fit.
Fig. 6. Relationship between small mammal densities (as indicated by pika burrows/ha and zokor mounds/ha) and sheep liveweight gain (kg/ha/d), under different grazing managements (rotational grazing in warm and cold seasons at 24 and 48 SM/ha, seasonal continuous grazing at 24 SM/ha, and whole-year continuous grazing at 48 SM/ha). Bars are SEs. Lines are fitted by regression.
dropped significantly \((P < 0.05)\), but with whole-year continuous grazing at 48 SM/ha, pika burrow density increased significantly \((P < 0.05; \text{Fig. 2, 3})\). With warm-season rotational grazing at both 24 and 48 SM/ha, there were no significant \((P > 0.05)\) changes in zokor mound density \((\text{Figs. 2, 3})\), but with cold-season rotational grazing and seasonal and whole-year continuous grazing at 24 and 48 SM/ha, zokor mound density increased significantly \((P < 0.05; \text{Figs. 2, 3})\). Plateau pika prefers open habitats and avoids dense shrub and thick vegetation \((\text{Sun et al. 2015b, Pang and Guo 2018})\). Enclosed trials indicate that pika diet is broad spectrum, consisting mostly of Gramineae, Ranunculaceae, and Asteraceae \((\text{Cairangji et al. 2015})\).

Pika burrow density decreased with increase in plant height \((\text{Fig. 4a})\) and aboveground biomass \((\text{Fig. 4c})\), in particular that of Cyperaceae genera which are dominant in QTP alpine meadow \((\text{Fig. 4f})\). This lends plausible explanation for the decline in pika population density observed when vegetation height and cover were greater under warm-season rotational grazing at both 24 and 48 SM/ha and seasonal continuous grazing at 24 SM/ha \((\text{Fig. 2a})\), than under whole-year continuous grazing at 48 SM/ha \((\text{Tables 1, 2})\). Under cold-season rotational grazing at 24 and 48 SM/ha, following resting of pasture throughout the warm season, a decrease in plant species richness, especially of forbs, coincided with an increase in Cyperaceae biomass \((\text{Wang et al. 2018a, b, Zhang et al. 2018})\). Pikas had apparently moved to inhabit pastures with whole-year continuous grazing dominated by Gramineae and other forbs \((\text{Fig. 4f})\). Density of shrubs was greatest under whole-year continuous grazing at 48 SM/ha stocking rate than other grazing managements \((\text{Tables 1, 2})\). Higher shrub covers enabled pika to both forage and see, and escape to their burrows, from predators \((\text{Blaum et al. 2007, Rosi et al. 2009, Liu et al. 2013})\).

Zokors mainly inhabit moist soil in degraded grassland colonized by forbs with taproots,

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**Fig. 7.** Conceptual model showing the separate and interactive effects of Tibetan sheep and burrowing small mammals (i.e., pika and zokor) on alpine meadow ecosystems. Black arrows indicate effects of sheep, light-gray arrows indicate effects of small mammals, and medium-gray arrows indicate effects of grazing management. Solid arrows represent direct effects; dashed arrows represent indirect effects. The + and – symbols indicate positive and/or negative effects. \((\text{Adopted from Davidson et al. 2010})\).
rhizomes, bulbs, and earthnuts, which are unpalatable to sheep (Zhang et al. 2010, Sun et al. 2015a). Forbs’ roots are nutritionally rich and provide an abundant food source for zokors (Zhang and Liu 2003, Xie et al. 2014). Zokors frequently pull forb stems into their burrows for food or nesting material (Zhang and Liu 2003). Zokor mound density increased with increased soil moisture (Fig. 5b),

Table 1. Statistical summary of the effects ($F$ and $P$ values) of grazing system and stocking rate and their interaction on the different plant and soil characteristics (plant height [cm], soil moisture [%], aboveground herbage biomass [kg/ha], density of shrubs [N/ha], ratio of biomass of sedges to total biomass [%], and ratio of biomass of forbs to total biomass [%]).

| Characteristic                  | Month     | $F$   | $P$   | $F$   | $P$   | $F$   | $P$   |
|--------------------------------|-----------|-------|-------|-------|-------|-------|-------|
| Plant height (cm)              | August    | 5.54  | 0.0073| 16.19 | 0.0002| 18.56 | <0.0001|
|                               | November  | 39.5  | <0.0001| 88.61 | <0.0001| 14.97 | <0.0001|
| Soil moisture (%)              | August    | 6.67  | 0.0031| 3.53  | 0.0672| 7.15  | 0.0021|
|                               | November  | 3.29  | 0.0471| 16.88 | 0.0002| 8.28  | 0.0009|
| Stand herbage biomass (kg/ha)  | August    | 56.2  | <0.0001| 18.61 | <0.0001| 8.04  | 0.0011|
|                               | November  | 47.4  | <0.0001| 19.94 | <0.0001| 10.28 | 0.0002|
| Density of shrubs (N/ha)       | August    | 61.9  | <0.0001| 15.88 | 0.0003| 17.27 | <0.0001|
|                               | November  | 60.8  | <0.0001| 42.22 | <0.0001| 15.74 | <0.0001|
| Ratio of biomass of sedges to total biomass (%) | August    | 7.42  | 0.0001| 4.90  | 0.0323| 4.36  | 0.0191|
|                               | November  | 11.5  | 0.0001| 1.67  | 0.2032| 1.63  | 0.2084|
| Ratio of biomass of forbs to total biomass (%) | August    | 2.22  | 0.1209| 10.78 | 0.0021| 5.2   | 0.0096|
|                               | November  | 3.21  | 0.0504| 6.02  | 0.0184| 2.16  | 0.1275|

Table 2. Effects of different grazing management (rotational grazing in warm and cold seasons at 24 and 48 SM/ha, seasonal continuous grazing at 24 SM/ha, and whole-year continuous grazing at 48 SM/ha) on the different plant and soil characteristics.

| Characteristic                  | Month     | Warm season 24 SM/ha | 48 SM/ha | Cold season 24 SM/ha | 48 SM/ha | Seasonal 24 SM/ha | 48 SM/ha | Whole year 24 SM/ha | 48 SM/ha |
|--------------------------------|-----------|-----------------------|----------|-----------------------|----------|-------------------|----------|-----------------------|----------|
| Plant height (cm)              | August    | 15.16 (2.05)          | 14.56a (1.70) | 12.33a (2.75)          | 14.85a (3.66) | 16.62a (1.27)     | 8.03b (1.02) |
|                               | November  | 10.58a (2.36)         | 7.17b (0.79)  | 5.96c (0.44)           | 5.04c (1.20)  | 11.23a (1.99)     | 4.35c (1.08)  |
| Soil moisture (%)              | August    | 38.76a (8.74)         | 37.91a (4.49) | 44.82a (8.375)         | 41.63a (7.86) | 39.22a (8.58)     | 55.67b (4.51) |
|                               | November  | 43.83b (5.49)         | 32.31c (5.83) | 45.66ab                | 44.96b (7.10) | 35.32c (5.62)     | 53.50a (2.25) |
| Stand herbage biomass (kg/ha)  | August    | 3119.49c (463.72)     | 2895.79c (334.28) | 5023.00a (803.57)      | 4809.27b (60.392) | 4076.95b (229.45) | 2466.74d (699.33) |
|                               | November  | 4683.43a (291.59)     | 2893.10c (801.38) | 2601.87c (684.80)      | 2590.00c (774.29) | 3635.50b (433.48) | 1547.25d (103.87) |
| Density of shrubs (N/ha)       | August    | 1.33c (0.89)          | 1.75c (0.62)  | 2.33c (1.21)           | 1.67c (0.81)  | 3.67b (0.52)      | 8.00a (2.36)  |
|                               | November  | 1.83c (0.72)          | 2.00c (0.85)  | 3.17b (0.41)           | 3.00bc (0.89) | 4.00b (1.79)      | 9.50a (2.43)  |
| Biomass of sedges/total biomass (%) | August    | 47.74a (9.03)         | 48.16a (6.55) | 47.59a (12.52)         | 46.67a (7.57) | 44.96a (13.27)    | 27.02b (5.85) |
|                               | November  | 46.18bc (9.62)        | 50.47a (9.61) | 52.74a (12.69)         | 48.08ab (11.17) | 39.18 cd (12.67)  | 26.76d (5.883) |
| Biomass of forbs/total biomass (%) | August    | 36.79b (9.18)         | 37.17b (8.48) | 34.05b (9.12)          | 40.11b (9.20) | 32.73b (10.50)    | 54.55a (11.19) |
|                               | November  | 37.44b (8.09)         | 36.65b (13.32) | 35.74b (8.28)          | 44.08b (9.40) | 38.02b (9.25)     | 55.21a (8.15)  |

Notes: Values are means of replicates with SEs in parentheses. Weights within a grazing management with different letters are significantly different from each other at the 0.05 level.
density of shrubs (Fig. 5d), and ratio of biomass of forbs to total biomass (Fig. 5f). Cold-season rotational grazing led to an invasion of the shrub Potentilla fruticosa (Table 2), reducing the risk of zokor predation and allowing zokor numbers to increase. This did not occur under warm-season rotational grazing (Vial et al. 2011, Kuiper and Parker 2013). Under whole-year continuous grazing at 48 SM/ha, the dominance of Cyperaceae declined (Tables 1, 2), providing opportunities for colonization by forb species, including those unpalatable to sheep, but also leading to an increase in bare soil (Zhang 2003), thus encouraging the growth of zokor feed species (like Potentilla anserina). Other research indicates possible dietary reasons for fluctuations in small mammal numbers. Development of small mammal populations in alpine meadow is possibly influenced by forage plant quality (e.g., crude protein) and induces secondary compounds (Lindroth and Batzli 1986, Lin et al. 2012). In south Norway, Seldal et al. (1994) found that grazing-induced trypsin inhibitors led to an excessive excretion of enzyme-inhibitory complexes and undigested dietary proteins from the alimentary tract, which can explain the decline phase of cyclic small mammal (Lemming (Lemmus lemmus)) populations. Other studies in the same study site showed that warm-season grazing induced higher secondary compounds in forage (e.g., amino acids, tannins, and total phenols; Feng et al. 2018). The difference in pika burrow density and zokor mound density between trial years can possibly be attributed to differences in weather (Moritz et al. 2008, Savage et al. 2011). Long-term field trials are needed to reveal the effects of climate on pika and zokor populations at Maqu study site.

**Relationships between sheep production, and pika burrow and zokor mound density**

Pika and zokor on the QTP are likely to play as important a role as ecosystem engineers as pocket gophers (Geomys spp.), prairie dogs (Cynomys spp.), and kangaroo rats (Dipodomys spp.) in Northern American grassland (Reichman and Seabloom 2002, Davidson and Lightfoot 2006). They have a profound impact on alpine meadow by consuming vegetation and physically altering the soil (e.g., soil nitrogen), thus maintaining a heterogeneity of soil which may be important to community dynamics, biodiversity, and livestock productivity (Fig. 7; Qu et al. 2012, Pang and Guo 2017).

In this study, two dominant relationships between sheep production and small mammal density were identified as follows: (1) Sheep live-weight gain per hectare reached its maximum at moderate pika burrow and zokor mound density with both rotational and continuous grazing at low stocking rate (Fig. 6); (2) sheep liveweight gain per hectare declined when pika burrow and zokor mound density increased at high stocking rate, under both rotational and continuous grazing (Fig. 6). This study confirms that stocking rate regardless of grazing system influences the relationship between pika burrow and zokor mound density, and sheep liveweight gain per hectare (Fig. 6). At low stocking rate (24 SM/ha), preferential feeding behavior of small mammals controlled the spread of toxic and unpalatable forbs sheep forage, thus maintaining pasture quality, which possibly contributes to the increase in sheep liveweight gain observed at low stocking rate. At high stocking rate (48 SM/ha) and high small mammal population densities, pika and zokor diets overlap extensively with sheep diet. This situation is further compounded by overgrazing leading to an increase in the toxic or unpalatable sheep forage plant species which are the preferred diet of pika and zokor. A shift from herbaceous to woody shrub dominance leads to a reduction in livestock production (Anadóna et al. 2014, Sala and Maestre 2015). In this study, density of shrubs increased significantly with increase in pika burrow and zokor mound density (Figs. 4, 5). In North America, forage grazing by prairie dog (Cynomys spp.) improved forage quality by enhancing plant nitrogen uptake, allowing the forage to be more attractive to bison (Bison bison) and cattle (Bos Taurus; Whicker and Detling 1988, Davidson et al. 2010). This study lacks data on forage quality (e.g., crude protein and digestibility), particularly as influenced by pika and zokor, required to further explore the degree to which small mammals compete with, or alternatively facilitate, livestock production.

**Implications of this research to alpine meadow management practice**

Though nomadic herders have grazed yak, sheep, and horses in coexistence with pika and
zokor on the Tibetan grassland for thousands of years, pika and zokor have long been considered a nuisance to local herders (Goldstein et al. 1990), and central and local government insists that small mammals are a main cause of grassland ecological degradation. Indeed, large-scale poisonings of small mammals are routinely applied by local government. Although rodenticides were initially effective in reducing pika and zokor damage, the benefit was only short term, and small mammals’ populations soon recovered. In addition, in 2010, local herders in Nangchen reported that a large number of avian predators died after feeding on poisoned pikas. The results of this study give sound evidence that rotational grazing at low stocking rate results in a significant drop in pika burrow and zokor mound density, while whole-year continuous grazing at high stocking rate led to an increase in pika burrow and zokor mound density.

As demand for food production continues to grow, unless pasture management practice adapts, the grassland will continue to degrade over the coming decades, and conflicts between plateau small mammals, livestock, and local herders will increase. An important challenge facing local herders is in maintaining the important functional roles of these burrowing small mammals in ways which are compatible with grazing management and increased livestock production. The traditional assumption that the small mammals compete with, and have net negative interactions with, livestock needs to be re-evaluated. In this study, evidence is cited that pika and zokor activities benefit sheep liveweight gain at low stocking rate (24 SM/ha). It is also clear that, at high stocking rate in the alpine meadow ecosystem, pika and zokor cause significant loss of livestock production. At present, whole-year heavy grazing with no rotation is widely adopted by local herders. Thus, appropriate ongoing and sustainable best management practice must achieve an ecological balance between livestock and small mammals, by adjusting grazing strategies, for example by employing rotational grazing at low stocking rate.

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