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Grazing and climate change have site-dependent interactive effects on vegetation in Asian montane rangelands

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Abstract

1. Climate over Asian montane rangelands is changing faster than the global average, posing serious threats to the future of the region's livestock-based economies and cultures. Effects of climate change on rangeland vegetation likely depend on grazing by herbivores but the potential responses of vegetation to such changes in climate and grazing regimes remains unclear.
2. We examined vegetation responses to experimentally simulated climate change (warming, drought and increased rainfall) and grazing (clipping vegetation) between 2015-2018 at two mountain rangeland sites: Spiti valley, in the Indian Trans-Himalaya and Tost, in the Gobi-Altai Mountains in Mongolia.
3. Clipping and climate change manipulations interactively reduced vegetation cover and biomass but did not affect species richness. Treatment effects and their interactions varied between sites. In ungrazed plots, vegetation cover and biomass declined sharply in response to warming (18-35%) and drought (20-50%) at the two sites, and, surprisingly also declined slightly in response to increased rainfall (20%) at Tost. While the effects of climate treatments were largely similar in the grazed and ungrazed plots in Tost, they were larger in the ungrazed plots in Spiti. The decline in vegetation cover was driven by a decline in the cover of both forbs and grasses.
4. In combination, grazing and warming (Tost) or drought (Spiti) had sub-additive effects, i.e., the decrease in vegetation cover in response to grazing and warming/drought was less than the sum of their independent effects but greater than the effect of either manipulation alone. Of the two, warming had a

greater effect than drought at the more arid site (Tost), while drought had a larger effect at the more mesic site (Spiti).

5. *Synthesis and applications.* Our findings show that future changes in climate, including just over 1°C of warming, could undermine the sustainability of pastoral economies and the persistence of wildlife across Asian montane rangelands. Further, grazing by herbivores will play an important role in mediating rangeland responses to climate change; thus, pasture management in concert with local pastoralists will be crucial in mitigating the adverse effects of climate change on rangelands, pastoral livelihoods and wildlife populations.

Keywords

rangeland vegetation, dry steppe, climate change, montane grassland, global warming, pastoral livelihood, trans-Himalayas, Gobi-Altai mountains

Introduction

Rangelands occupy nearly 45% of the Earth's terrestrial surface (Reid et al. 2008). They are vital for global food security and livelihoods of millions of pastoralists, and provide ecosystem services such as soil erosion control, biodiversity maintenance and carbon sequestration. Because rangeland vegetation dynamics and functioning are jointly shaped by climate and grazing by herbivores (Milchunas et al. 1988; Frank et al. 1998; Liang & Gornish 2019), changes in climate and grazing (e.g., due to loss or replacement of native with domestic herbivores, or changes in the size or composition of livestock) could interactively impact the ability of rangelands to provide food, livelihoods and other ecosystem services (Dangal et al. 2016; Eldridge et al. 2016).

Asian montane rangelands are a part of the largest contiguous grassland system in the world, and despite being historically important for pastoralism are still relatively understudied. This rangeland system stretches over central Asia (Kyrgyzstan, Turkmenistan, Uzbekistan, Tajikistan and Kazakhstan), trans-Himalaya (Pakistan, India, Nepal and Bhutan), Tibetan Plateau (China) and steppe and Gobi regions in Mongolia, occupying between 40-65% of land area over this region (Angerer et al. 2008; Gintzburger et al. 2005). The bulk of this region's livestock-based economies and cultures, and a vast majority of this region's mostly rural population, are dependent on these rangelands for nomadic and agro-pastoralism. Further, these rangelands are home to several endangered species of wildlife (e.g., Saiga *Saiga tatarica*, Tibetan antelope *Pantholops hodgsonii*, and snow leopard *Panthera uncia*) (Berger et al. 2013), and comprise a globally important carbon reservoir (e.g., Genxu et al. 2002).

Understandably then, there is concern about the degradation of these rangelands in recent times. This degradation has been linked with rapid changes in livestock grazing regimes arising from ongoing socio-economic changes (Miller 1990; Angerer et al. 2008; Harris 2010; Berger et al. 2013). For example, livestock numbers have increased nearly 9-fold in over a 50-year period in Inner Mongolia (Angerer et al. 2008) and similar rapid increases have been reported from the Gobi region in Mongolia (Berger et al. 2013), Indian trans-Himalayas (Namgail et al. 2007), Qinghai-Tibetan Plateau (Lu et al. 2017), and central Asia (Gintzburger et al. 2005). This intensification of livestock holding and a shift towards smaller bodied livestock has been accompanied by a decline in native herbivores and a large decline in rangeland productivity across the Asian steppes (Angerer et al. 2008; Kerven et al. 2011).

In addition to changes in patterns of grazing, these rangelands are experiencing some of the most rapid climatic changes globally (Christensen et al. 2007). For example, average winter temperature over Qinghai-Tibet Plateau (QTP) has increased by more than 1.5^{o}C in over two decades (Du et al. 2004), and projections suggest a further increase of 2-5^{o}C in the coming decades (Christensen et al. 2007). Similarly, both summer and winter precipitation patterns are changing, although changes in precipitation are harder to project and vary greatly over this region, especially due to local orographic features in mountainous regions (Xu et al. 2008; Christensen et al. 2007). Together with changes in livestock production systems, these climatic changes are likely to influence rangeland vegetation and various aspects of ecosystem functioning, including carbon cycling and storage, hydrological cycles, and forage production. Furthermore, the effects of grazing are likely to be influenced by changes in climate and vice-versa (Klein et al. 2004), making it necessary to study these factors together to better predict future rangeland functioning.

Thus far, most experimental research in these Asian montane rangelands has focused on the effects of warming and has been predominantly conducted on the Tibetan plateau (Klein et al. 2004; Ganjurjav et al. 2015; Lu et al. 2017). However, the effects of changing climatic regimes and grazing systems on rangeland vegetation in other regions of Asia have been less well studied experimentally. Furthermore, most experimental studies manipulate a single climate variable (by imposing either warming or drought) at a single site, making comparisons across different drivers and across sites with different environmental conditions difficult.

To address this gap, we experimentally manipulated growing-season temperature and precipitation, and simulated changes in grazing over 3 years at two sites (Spiti valley, India and Tost, Mongolia) in semi-arid Asian montane rangelands that have a long history of livestock grazing. We examined changes in the cover and composition of the vegetation community in response to these treatments. Previous research from the region suggests that site-level precipitation regimes and micro-site differences in soil moisture influence the direction of vegetation response to warming (Klein et al. 2004; Liancourt et al. 2012; Ganjurav et al. 2016). As our study sites are dry (see Methods: average rainfall in the growing season is <200 mm), and vegetation is typically moisture limited (Bagchi & Ritchie 2011; Liancourt et al. 2013), we expected warming to lower soil moisture and thus lower overall vegetation cover.

Further, we expected that vegetation cover would decline with reduced rainfall and increase with supplemental rain. We also expected vegetation cover and biomass to decline in response to simulated grazing. Finally, we expected that the effects of grazing would be contingent on climate manipulations and vice-versa. Specifically, we expected grazing to exacerbate the effects of warming and drought on vegetation cover because of its negative effects on soil moisture status by increased evaporation (although grazing could also ameliorate soil moisture by reducing transpiration, e.g., see Veron, Paruelo & Oesterheld 2011). We also expected that vegetation decline in response to grazing would be lower in plots with supplemental watering due to a greater capacity for compensatory growth in irrigated plots.

Materials and Methods

Site description

Our two study sites were located in Spiti valley, India and Tost, Mongolia (details follow). Total annual precipitation (rain + snow) between 2013-17 in Spiti varied between 509 and 816 mm whereas in Tost it ranged between 66 and 207 mm (Table S1).

Spiti valley, India

The Spiti valley is a part of the Trans-Himalayan region in the rain-shadow of the Greater Himalayas. It spans an area of roughly 12000 km^2 in the catchment region of the Spiti river and ranges between 3350-6700 m in altitude (Mishra 2001). The climate is arid, with a mean annual precipitation of ~500 mm with most precipitation occurring in the form of winter snow (mean precipitation during the growing season is about ~ 200 mm). Temperature ranges between -30°C during winter and 28°C during summer (Rana 1994). Despite being a low productivity landscape, livestock density is high (Mishra 2001), and the livestock assemblage comprises of yaks, cattle, cattle-yak hybrid (*dzo*), horses, donkeys, sheep and goats. The vegetation is characterized as dry steppe rangeland vegetation comprising a mix of short shrubs (*Caragana versicolor, Lonicera* sp.*, Eurotia* sp.) and forbs and graminoids including several species of *Potentilla, Oxytropis, Poa, Stipa* and *Festuca*. The experimental plots were set up in a representative pasture at an altitude of ~5000 m (32°19'49.12"N, 78° 4'28.70"E). Dominant species in the pasture included sedges like *Carex* sp., *Kobresia* sp., graminoids including *Elymus* sp., *Festuca* sp., and forbs including *Potentilla* sp. Free-ranging domestic yaks graze the area seasonally in addition to native herbivores *bharal* (*Pseudois nayaur*) and wooly hares (*Lepus oistolus*).

Tost mountains, Mongolia

Our study site was situated in the Tost mountains at an elevation of 1450-2550m in Gurvantes soum, South Gobi (43°13'27.7"N, 100° 37'57.1"E), which is part of the south-eastern Altai mountainous landscape. Climate in the region is semi-arid, with low mean annual precipitation (~110 mm at the lower pediments), and high year to year variability. Temperature ranges between -15.4 to 24.4°C. Vegetation, characterized as desert steppe, is dominated by the grass *Stipa glareosa*, and small shrubs and forbs such as *Caragana leucophloea*, *Allium polyrrhizum*, *Ajania* spp., *Artemisia* spp..

According to local statistical information from 2017, Tost *bag* [administrative unit] is home to about 90 herder families who owned 55,229 heads of livestock of which

49,201 were goats, 3461 sheep, 1499 camels, 900 horses and 168 cattle, with 80 to 1200 heads of livestock per family. Except goat and sheep that are herded daily, the rest of the livestock are free ranging (Mijiddorj et al., 2019).

Experimental design

At each site, 5 experimental blocks, each 10 m × 10 m, were established (in 2015 in Spiti, and 2016 in Tost) within 50 m of each other to minimize spatial heterogeneity in soil and vegetation. The blocks were fenced to a height of 2.5 m to exclude large mammals. Within each block, 2 plots each for warming, reduced rainfall and increased rainfall treatments and 2 control plots, each measuring approximately 2 m × 2m and separated by 1-m walkways, were established for a total of 40 plots at each site (Fig. S1 in Supporting Information). Treatments were randomly assigned to plots. We built hexagonal open-top chambers (OTC, dimensions: 170 cm across at the top, 60 cm high) with sides made of transparent acrylic sheets. In a pilot study preceding this experiment, we found that this OTC warmed plots by almost 3^{o}C. Thereafter, we left one side of the hexagon open, and this reduced the warming effect to an average of 1.2^{o}C (±0.25) (P<0.0001, Fig. S2), a degree of warming expected to occur in this region within the next 3 decades (Xu et al. 2017). We deployed temperature loggers (iButton DS1921G by Maxim Integrated) taped to wooden pegs ~10 cm above ground to measure air temperature difference between warmed and control plots at 30-min interval over 85 days between June and August. Ten loggers were deployed in Tost, and 8 in Spiti, distributed over the unmanipulated and warmed plots. We constructed rainout shelters with channels made of clear, transparent polyvinyl assembled on a steel pipe frame such that the shelters intercepted 50% of rainfall (because they covered 50% of the ground area) and diverted it away from the plot. We dug channels around all plots to ensure that runoff from the rainout shelters did not irrigate other plots. Precipitation runoff from additional rainout shelters (dimensions 1 m × 2 m equaling 50% of plot area) was collected in 20L cans and this collected rainwater was uniformly sprinkled on the increased rainfall plots once every two weeks (Fig. S1). Therefore, the increased rainfall treatment plots received ~50% more water. Once or twice over a season in Spiti during a large rain event (but never in Mongolia), the cans were too small to collect all the rain. To examine the effects of intensive biomass removal by grazers, one out of each pair of climate treatment and ambient plots in each block was randomly assigned to a clipping treatment. In these ‘grazed’ plots, aboveground plant biomass was clipped once every two weeks to 2-3 cm above ground using hand-held clippers (Fig. S1). Although we did not weigh clipped biomass to quantify offtake, our clipping treatment simulates a very high intensity of grazing similar to what is prevalent at these sites. In Spiti, for example, pastoralists graze each pasture once or twice every week. Previous studies have estimated that grazers remove nearly 75% of plant production (Bagchi & Ritchie 2010), leading to a five-fold difference in standing plant biomass between intensively and moderately grazed areas (Mishra et al. 2004). Care was taken to remove the clipped biomass from the plots.

Vegetation sampling

At each site, we monitored vegetation in all plots annually at peak biomass (July in Gobi, early August in Spiti), by visually estimating the percent cover of each species rooted within permanent 1 m × 1 m quadrats, and the percent cover of bare ground. The 1 m^2 quadrat was located in the center of each treatment plot, allowing for a buffer area from the plot edges; this also allowed us to avoid sampling any vegetation under the sloping sides of the hexagonal OTCs. Each species was assigned to one of the following plant functional groups: grass, sedge, non-leguminous forb, leguminous forb, or shrub. Data presented here were collected between 2015-2017 (Spiti), and 2016-2018 (Tost).

Live plant biomass

At both sites, we calibrated the relationship between percent cover, height and aboveground biomass for the most common species and by plant functional group. In Spiti, independent calibration measurements were performed in summer 2016. In 178 plots across the site, we estimated the percent cover of species rooted in the plot and subsequently harvested all aboveground biomass. This biomass was then sorted to species, dried and weighed. In Tost, all aboveground biomass inside the 1 m^2 permanent vegetation cover quadrats was harvested in October 2018, sorted by species, dried and weighed. Thus, species cover and biomass could be directly correlated. The details of calibration are provided in a supplement (Tables S2, S3): to summarize, species cover (% cover) was a better predictor of plant biomass than volume (% cover * height). In Spiti, *R*-squared values (correlation) between cover and biomass ranged between 0.75-0.98, and in Tost, from 0.47-0.95. We used these calibrations to estimate the effects of treatments on total plant biomass as well as by plant functional group.

Statistical analysis

For each site separately, we analyzed vegetation cover and peak biomass (August in Spiti, July in Tost), both total and aggregated by plant functional group, in response to climate and grazing treatments. We applied linear mixed-effects models using the lme function in the *nlme* package in R software to analyze our data (Pinheiro et al. 2017). We also analyzed species richness (number of species rooted inside 1 m^2 permanent vegetation quadrats) using generalized linear mixed effects models using the *lme4* package (Bates et al. 2015). We modeled experiment year, climate manipulation and clipping treatments as fixed effects. We included experimental block as a random intercept to account for the spatial variability in the plant community due to factors not examined here such as abiotic drivers of vegetation.

Results

Site characteristics

On average, across the duration of the experiment and all replicate blocks, live vegetation cover was 32.57 (± 5.12)% in Spiti, and 18.02 (± 2.68)% in Tost. Average live biomass in control plots was 135.83 (± 19.38) $g.m^{-2}$ and 22.02 (± 3.30) $g.m^{-2}$ in Spiti and Tost, respectively. On average, there were 6.46 and 5.45 species m^{-2} in Spiti and Tost, respectively.

Effects of climate and grazing manipulations

Where vegetation was not clipped, warming and drought greatly reduced vegetation cover at both sites. The effects of warming were more pronounced than drought at the more arid site (Tost), while the effects of drought were more pronounced at the more mesic site (Spiti). Averaged across treatment years, warming reduced vegetation cover and biomass in the unclipped plots by 17.5% and 26.5% (or 36 $g.m^{-2}$) in Spiti and by 35 and 37% (8.1 $g.m^{-2}$) in Tost (Fig. 2). Reducing rainfall reduced vegetation cover and biomass by 50% and 55% (74 $g.m^{-2}$) in Spiti and by 20 and 23% (1.67 $g.m^{-2}$) in Tost (Fig. 2). Supplemental watering had no impact on total vegetation cover in Spiti but, surprisingly, reduced vegetation cover and biomass by 21 and 26% (5.82 $g.m^{-2}$) in Tost (Figs 1-2; Tables 1, S4-S5). Neither climate manipulations nor grazing treatment affected species richness at either of the two sites (Table 1, Fig. 2) suggesting that the decline in vegetation cover and biomass was not caused by an overall decline in the number of species present but instead due to a decline in their growth.

Simulated grazing reduced vegetation cover and biomass at both sites, but had larger impacts at the more productive site (Spiti). In Spiti, grazing alone (no climate manipulation) reduced vegetation cover by 40% and 47% (64 $g.m^{-2}$) while in Tost, grazing alone reduced vegetation cover and biomass by 25% and 38% (8.32 $g.m^{-2}$, Fig. 2). Grazing and climate treatments together had sub-additive effects on vegetation cover (Tables 1, S4-S5): in Spiti, decline in vegetation cover in plots that were grazed and had reduced rainfall was less than the sum of the independent effects of treatments on vegetation cover. Likewise, in Tost, the combined effect of warming and grazing on vegetation cover was lower than the sum of their independent effects (Table 1, S5; Figs. 1-2). It is worth pointing out that although the combined impacts of grazing and climate manipulations on vegetation cover were sub-additive, they were often greater than the impact of either climate or grazing manipulation alone (Figs. 1, 2, Table 1, S4-S5).

Comparing effect sizes of climate and grazing manipulations on vegetation cover offers further insights. First, the effects of climate manipulations varied by site: e.g., warming effects were more pronounced at the drier site (Tost, Mongolia), whereas reducing rainfall had larger impacts at the relatively wetter site (Spiti, India) (Figs. 3

A, B). Second, grazing had a larger negative impact on vegetation in Spiti than in Tost (Figs. 3 C, D). Third, the interactions between grazing and climate treatments varied between sites: in Spiti, climate manipulations did not significantly impact vegetation cover in grazed plots as shown by effect sizes that were not significantly different from zero (Fig. 3A). In Tost, by contrast, the effects of climate treatments were similar (and negative) across grazed and ungrazed plots (Fig. 3B). At both sites the effects of grazing were largely similar (and negative) across ambient, warmed and watered plots. However, in plots where rainfall was reduced, intensive grazing had no overall impact on vegetation cover (Fig. 3D).

Effects on plant functional types

Dominant plant functional types responded differently to climate treatments and simulated grazing, and the responses varied by site. In Spiti, forbs and grasses declined in response to lowered rainfall (40% and ~75% decline in cover), warming (30-35% decline in cover) and simulated grazing (50% and 70% decline in cover, respectively, Fig. 4, Table S6). When rainfall was reduced, leguminous forbs were completely lost from ungrazed plots, but almost doubled in abundance in grazed plots. Sedges showed a weak decline in response to lowered rainfall although this trend was not statistically significant (Fig. 4, Table S6).

In Tost, forbs and grasses declined in response to warming while shrubs declined in plots where rainfall was reduced. Grasses were not affected significantly by simulated grazing (Fig. 5, Table S7). The decline in forb cover in response to warming depended on the grazing treatment – where plots were grazed, the decline was lower. Shrubs declined in response to grazing and reduced rainfall and there was no significant climate by grazing interaction (Fig. 5, Table S7).

Discussion

Our results indicate that, in Asian montane rangelands, overall vegetation cover and biomass could decline significantly depending on the interaction between warming, drought and grazing. Further, the magnitude of this decline, the relative importance of warming and drought, and their interaction with grazing are likely to be site-specific. The combined effects of grazing and climate manipulations were sub-additive: they never exceeded the sum of their independent effects, but were almost always larger than the effect of either factor alone. Taken together, our findings show that pastoral livelihoods are likely to be undermined by future climatic changes, and the effects of grazing and climate change need to be considered together in the management of these pastures.

Climate & grazing interactively influence vegetation cover & biomass

There has been uncertainty regarding the effects of future warming on vegetation cover and biomass in Asian montane rangelands. Previous studies have reported both a warming induced decline (Klein et al. 2007; Hopping et al. 2018) and increase (Wang et al. 2012; Ganjurjav et al. 2015) in vegetation cover and biomass. Our findings from two sites support the view that future warming will lead to significant declines in vegetation. These divergent findings could be partially explained by precipitation regimes at these sites: our field sites receive less summer precipitation (<200 mm in Tost, 200-300 mm in Spiti) than sites where positive effects of warming on vegetation have been reported (~ 450 mm for sites in Wang et al. 2012, and

Ganjurav et al. 2015). Ganjurjav et al. (2016) found that total plant cover increased with warming at a more moist meadow site but declined with warming at a drier steppe site. Our finding that the drier of the two sites (Tost, Mongolia) experienced a greater warming induced decline in vegetation cover supports the view that the impacts of future warming over this region will vary with prevailing moisture regimes (Liancourt et al. 2012; Ganjurjav et al. 2016).

Considering that soil moisture constrains plant growth in this ecosystem (Bagchi & Ritchie 2011; Liancourt et al. 2012) we expected rain manipulation treatments to significantly influence plant growth. In support of our expectations and corroborating previous findings from Asian highlands (He et al. 2017; Xu et al. 2018) and other global dry steppes (Yahidjan & Sala 2006; Wu et al. 2011), reducing rainfall greatly depressed forb, graminoid and overall vegetation cover at both sites. Contrary to our expectations, however, increasing rain in plots also reduced rather than increased vegetation cover, particularly impacting grasses (both sites) and leguminous forbs (Spiti). Although surprising, previous studies lend support to these findings: He et al. (2017) reported a decline in graminoid biomass in a Tibetan steppe when rain was added to plots while Xu et al. (2018) reported a decline in legumes but an increase in graminoids and forbs. Effects of precipitation manipulation could be affected by topography, ecotype, and biotic interactions (e.g., plant competition), even over small spatial scales, such that water addition may only benefit phenotypes that usually grow in less water stressed areas (Liancourt et al. 2013). In addition to these biological mechanisms, it is also possible that other reasons contributed to these results. For example, although we sprinkled water on our plots as carefully as we could, the rate of water addition was probably much greater than in a typical summer rainfall. As a result, topsoil might have been impacted, and water would also have moved through the soil column much faster than that with less potential for contribution to plant growth. A previous study from a Mongolian grassland lends support to this argument- supplemental watering rapidly influenced community composition when watering interval was low (1 week) but has no effects when the watering interval was high (3 weeks) (Spence et al. 2016). Finally, our water additions were often performed in warm, sunny conditions leading to potentially higher rates of evapotranspiration. The mechanisms underlying the observed decline in vegetation cover upon supplemental watering need to be explored in future work.

Despite differences in site conditions (e.g., soil nutrient status, temperature and precipitation), warming, drought and grazing treatments had qualitatively similar (and negative) impacts on vegetation at our study sites. Differences in the magnitude of climate and grazing induced impacts, and in the responses of plant functional types between the two sites could occur because of differences in history of grazing, edaphic conditions, prevailing climatic regimes and biotic interactions (Milchunas et al. 1993, Liancourt et al. 2013). Perhaps most importantly, precipitation regimes at the two sites are very different: Spiti valley receives more summer (and total annual) precipitation than Tost mountains but Tost experiences higher inter-annual variability in precipitation which could explain why vegetation response to lowered precipitation was lower at this site (Knapp & Smith 2001; Nippert et al. 2006). Similarly, among site differences in climate could have led to the same amount of warming (~1 ^{o}C) producing a greater amplification of the dry conditions in Tost relative to Spiti.

There has been much debate about the role of grazing versus abiotic factors on structure and functioning of rangelands (Milchunas & Lauenroth 1993; Koerner & Collins 2014; Liang & Gornish 2019). Our findings support the view that both grazing and abiotic factors interactively shape rangeland vegetation (Koerner & Collins 2014; Dangal et al. 2016; Lu et al. 2017); thus, prevailing grazing patterns will influence the impact of climate change on rangelands. For example, at the less arid site (Spiti), warming and rainfall manipulations had no or a slightly positive effect on vegetation when plots were grazed compared to when they were not grazed. Further, at both sites the effect of grazing was dampened when rainfall was reduced rather than increased, and conversely the effect of drought was dampened under grazed conditions. This supports findings from a defoliation experiment in Spiti wherein plants compensated aboveground growth (ANPP) for defoliation more in the absence of irrigation (Bagchi & Ritchie 2011). These results suggest that plant community responses to climate and grazing are interlinked, possibly through resource allocation between root and shoot growth. Finally, grazing mediated vegetation compositional changes in response to climate manipulations. Taken together, our results demonstrate that grazing will play a crucial role in mediating the impacts of climate change on Asian montane rangelands, and that the interactive effects of grazing and climate are not easily predicted from their independent effects.

Although temperature and precipitation patterns are changing simultaneously, we could only examine vegetation responses to these drivers independently. Previous studies suggest the combined effects of warming and precipitation changes could be additive (Xu et al. 2018) or interactive (Wu et al. 2011; Ronk et al. 2020). Future work should aim to understand their joint effects on ecosystems. Our experimental rain addition simulates larger but less frequent rain events rather than a regular, small increase in rainfall. While this matches the local inhabitants' perceptions of climate change (Singh et al. 2015; informal accounts of residents of Kibber, Spiti) and observed trends of increasing frequency and magnitude of large storm events (Fu et al. 2013; Goulden et al. 2016), it leaves room to explore how other modes of precipitation increase may impact vegetation. One shortcoming of our study is a lack of soil moisture data; linking changes in soil moisture to changes in vegetation would provide a clearer understanding of mechanisms underlying vegetation responses to climate and grazing.

Conclusions

Pastoralists across the Asian highlands perceive that their rangelands are degrading with changing climate, negatively impacting their livelihoods and influencing their livestock production systems (Lkhagvadorj et al. 2013; Singh et al. 2015). Together with previous findings from the Tibetan plateau (Klein et al. 2007) our study lends support to these concerns. Considering that livestock production accounts for a major portion of monetary income and a source of food and materials (Mishra 2001; Lkhagvadorj et al. 2013), such degradation greatly risks the economic and food security of the region's pastoralists. Although future climate will severely impact rangeland functioning regardless of livestock grazing, based on our findings we suggest that managing pastoral practices will be vital, both to prevent rangeland degradation, and to mediate the impacts of climate change on rangeland functioning and pastoral economies. Examining how different pastoral practices (e.g., rotational grazing, low versus high intensity of grazing, diversification of livestock) influence the responses of vegetation to climate change could help identify best practices.

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Authors' contributions

MK, CM, MS, BB and KS conceived and designed the experiment. MK and TM set up, maintained and collected data. MK analyzed the data with inputs from MS and BB. MK wrote the first draft of the manuscript and all authors contributed substantially to revisions. All authors gave final approval for publication.

Data availability statement

Data used here are available via the Dryad Digital Repository: https://doi.org/10.5061/dryad.g4f4qrfnz

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Table 1. Model summaries describing response of total live vegetation cover, biomass, and species richness to climate and clipping treatments in A) Spiti, India and B) Tost, Mongolia. A random intercept for block was included. Live cover was log-transformed. Generalized linear models were used for species richness with a poisson distribution. Full model summaries are provided in Tables S4-S5.

A)

Source		**Total cover**		**Live biomass**		**Species richness**	
	df	χ^2	*P*	χ^2	*P*	χ^2	*P*
Year	1	**11.829**	**2.7e-03**	0.51	0.47	2.44	0.11
Climate	3	**12.884**	**4.8e-03**	**11.68**	**8.5e-03**	3.26	0.35
Clipping	1	**25.725**	**3.9e-07**	**23.21**	**1.4e-06**	0.01	0.89
Year: Climate	3	0.5472	0.9972	0.21	0.97	0.26	0.96
Year: Clipping	1	**6.6965**	**0.0351**	2.59	0.10	0.11	0.74
Climate: Clipping	3	**19.801**	**1.9e-04**	**21.01**	**0.00**	1.16	0.76
Year: Climate: Clipping	3	1.767	0.9398	1.37	0.72	0.13	0.98

B)

Source		**Total cover**		**Live biomass**		**Species richness**	
	df	χ^2	*P*	χ^2	*P*	χ^2	*P*
Year	1	**183.52**	**<2.2e-16**	**68.02**	**< 2.2e-16**	**22.86**	**1.7e-06**
Climate	3	**45.066**	**8.9e-10**	**14.75**	**2.1e-03**	4.12	0.24
Clipping	1	**11.715**	**6.2e-04**	**21.76**	**3.0e-06**	0.01	0.93
Year: Climate	3	**79.165**	**5.3e-15**	5.82	0.12	5.1	0.16
Year: Clipping	1	**8.4857**	**0.0143**	0.03	0.85	0.1	0.75
Climate: Clipping	3	2.4728	0.4802	6.28	0.10	0.25	0.96
Year: Climate: Clipping	3	**18.329**	**5.4e-03**	4.01	0.26	0.21	0.98

Figure 1. Total live vegetation cover across three years in response to climate treatments in plots where vegetation was not clipped (A,C) and clipped to ~3 cm once every two weeks (B,D) in Spiti (top panels) and Tost (bottom panels). Each point is average (±1 SEM) across blocks at site.

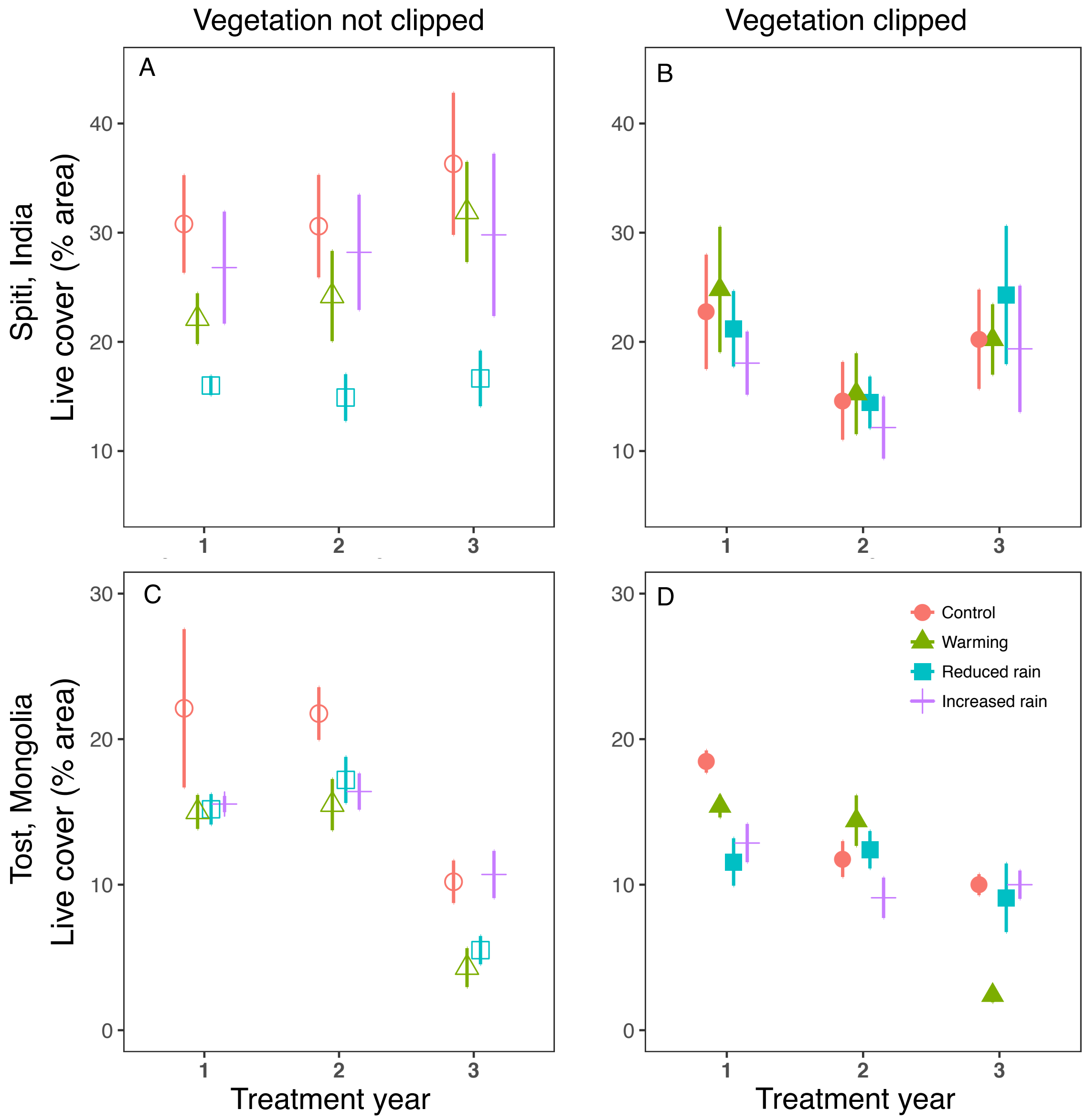

Figure 2. Average species richness (A, B) and live biomass (C, D) in response to simulated climate and grazing treatments in Spiti (A, C) and Mongolia (B, D). Each point is average (±1 SEM) across years (within block), across all blocks at each site.

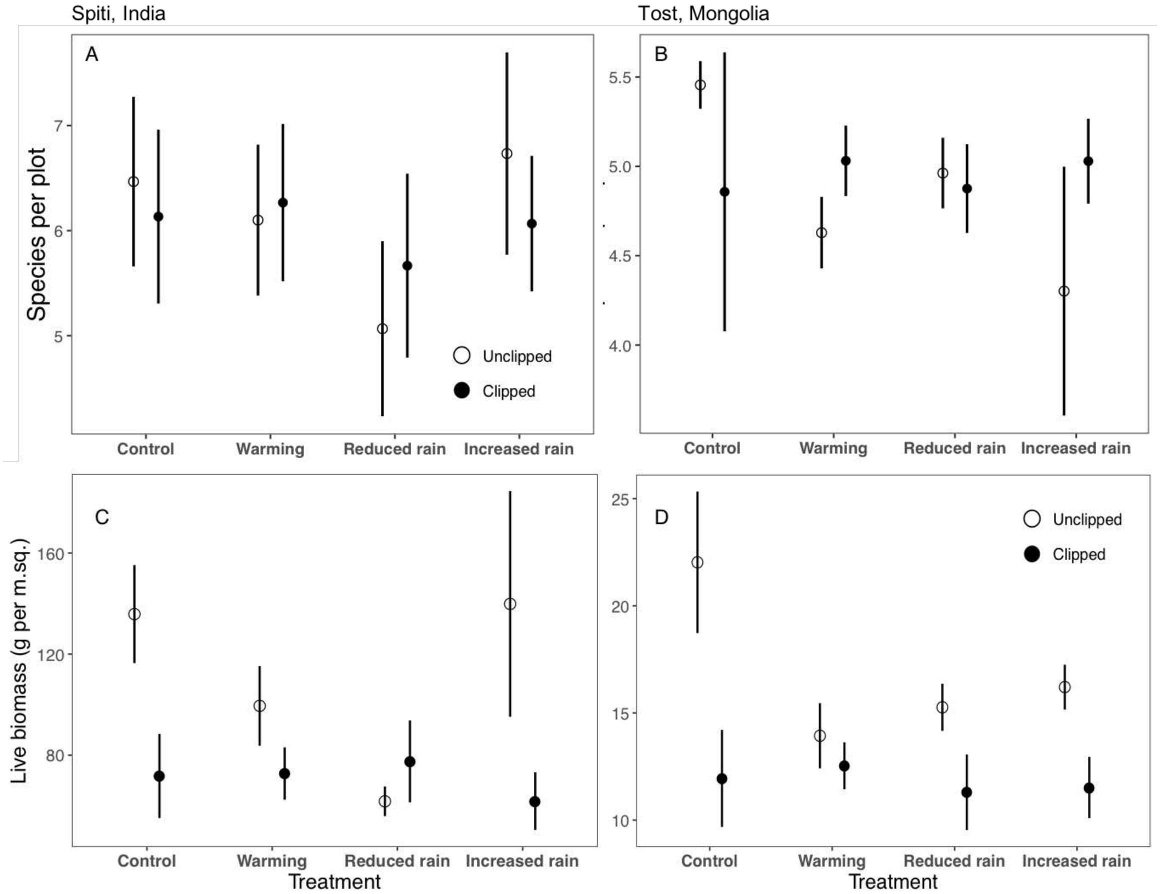

Figure 3. Effect sizes (log ratio of cover in treatment and control plot) of climate (A, B) and grazing (C,D) manipulations. Thus, plots A, B show differences between climate treatment (e.g., warmed) and control plots for both grazed and ungrazed conditions. Plots C, D show differences between grazed and ungrazed plots for each of the different climate manipulations and the control. Each point is mean (±1 SEM) across years in a block, across blocks at a site.

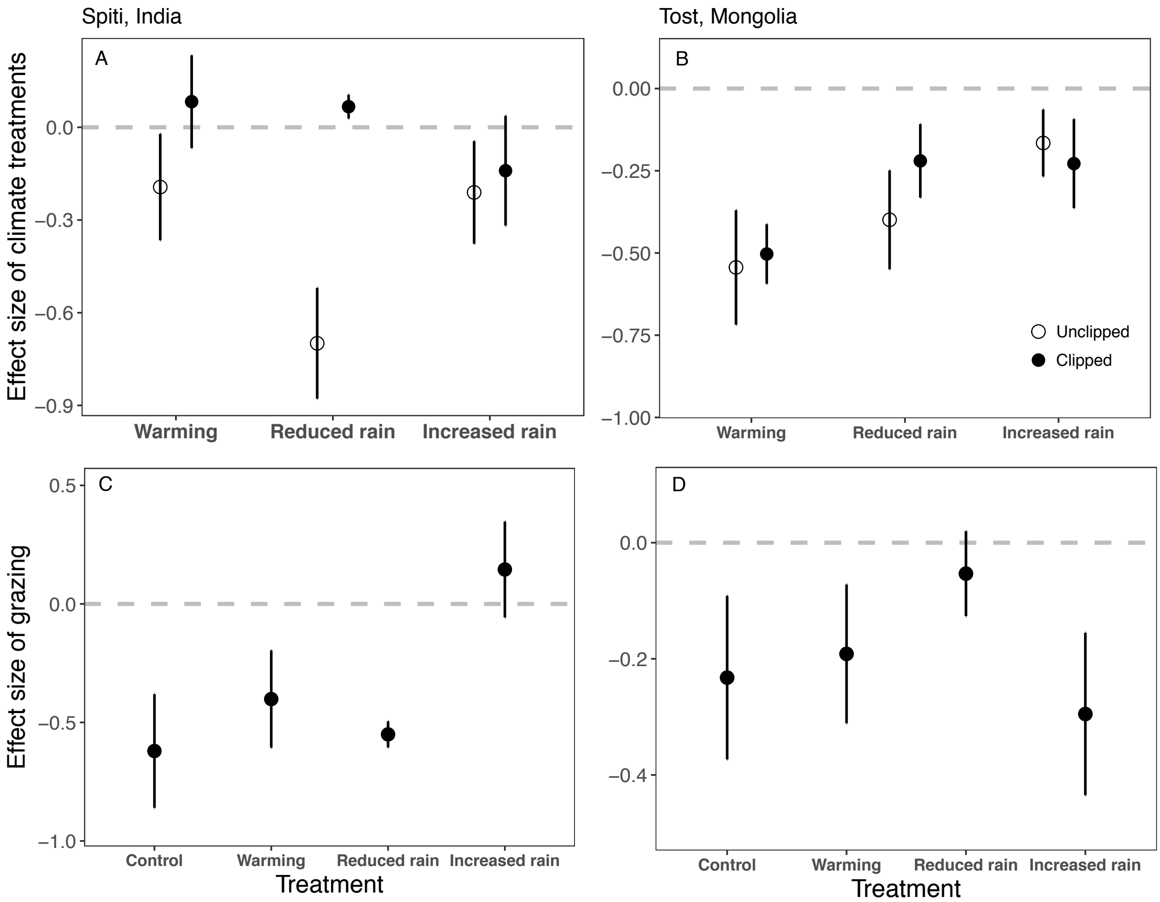

Figure 4. Vegetation cover (% area) of dominant plant functional types in response to climate and clipping treatments at Spiti, India. Each point is average (±1 SEM) across years within block and across all blocks at site.

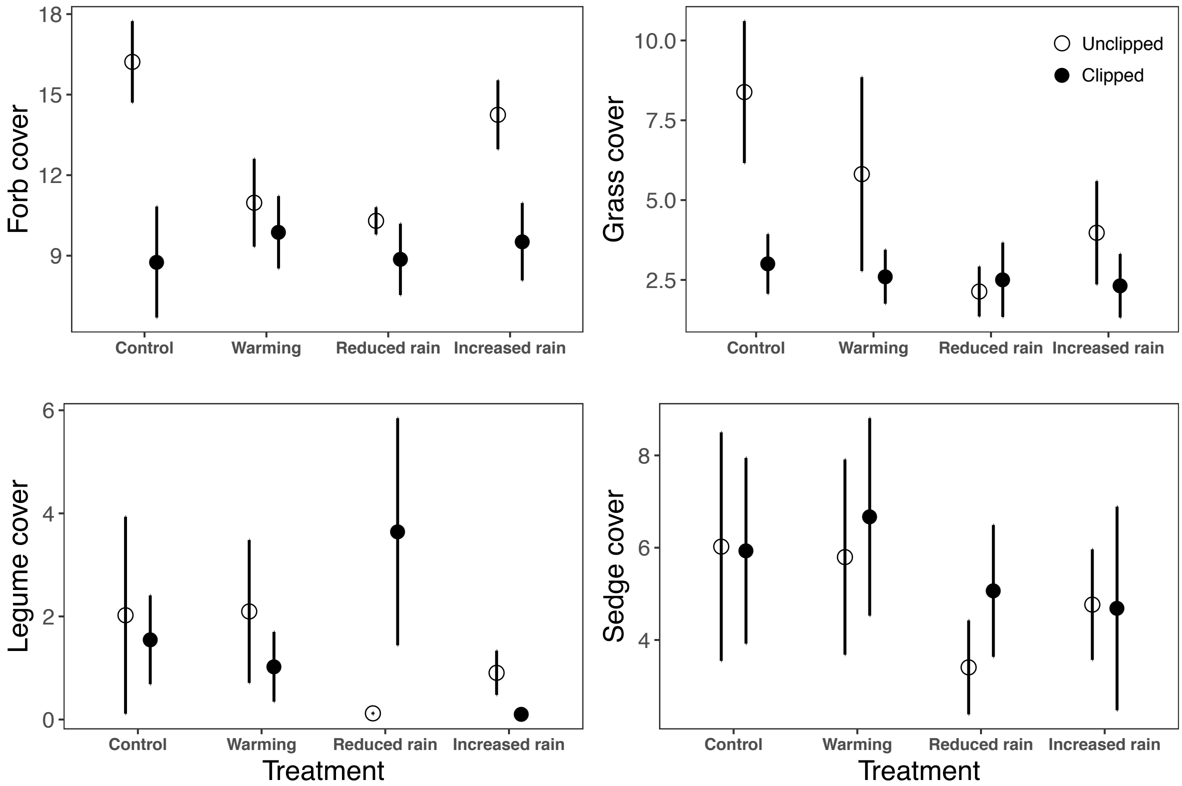

Figure 5. Vegetation cover (% area) of dominant plant functional types in response to climate and clipping treatments at Tost, Mongolia. Each point is average (±1 SEM) across years within block and across all blocks at site.