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Plateau pika burrowing and yak grazing jointly determine ecosystem greenhouse gas emissions of alpine meadow

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Abstract

Domestic yak (*Bos grunniens*) have coexisted with plateau pika (*Ochotona curzoniae*) for thousands of and they play irreplaceable roles in shaping the structure and function of alpine meadow ecosystem. However, the mechanisms whereby the greenhouse gas (GHG) emissions change in response to the interactive effects between yak grazing and plateau pika burrowing remain unclear. In this study, we examined the response of ecosystem GHG emissions (CO_2, CH_4, and N_2O flux) to yak grazing and pika burrowing in alpine meadow in Zoige County, China. The GHG emissions was measured with a static opaque chamber method. Our results revealed that CO_2, CH_4, N_2O flux and CO_2-eq were significantly influenced by yak grazing and pika burrowing independently, and in conjunction. Crucially, the relative importance of pika burrowing was higher than yak grazing on a pastoral scale. Specifically, high pika burrowing led to an increase of 440.29%, and 110.72% for CO_2-eq relative to low pika burrowing under moderate and heavy yak grazing situations, respectively. The value of CO_2-eq with low pika burrowing was negative, especially under light yak grazing conditions. Furthermore, we found that GHG emissions were sensitive to plant species richness, soil temperature, soil moisture, soil organic carbon, and soil microbial factors. Structural equation modeling indicated that pika burrowing can affect CO_2-eq though altering soil temperature and belowground biomass under heavy yak grazing conditions and changing soil moisture and soil microbe under light yak grazing. The results of this study enrich our understanding of the role of small burrowing mammals in the carbon sequestration of alpine meadow. In the context of the carbon neutrality of alpine grassland ecosystem, small mammals' activities and their interactions with domestic livestock-induced changes in microtopography on GHG emissions should not be neglected.

KEYWORDS
driving mechanism, GHG emissions, plateau pika, soil properties, yak grazing

1 | INTRODUCTION

As the largest group of mammals, small mammals play irreplaceable roles in regulating ecological processes and functions of alpine grassland together with livestock (Davidson et al., 2012; Wang et al., 2020). Compared to the existed conflicts between small mammals and livestock, the mutualistic relationship due to their complementary effects is usually neglected (Martínez-Estévez et al., 2013;

Smith et al., 2019; Tchabovsky et al., 2016). Indeed, plateau pika (*Ochotona curzoniae*) and domestic yak (*Bos grunniens*), Tibetan sheep and Hequ horse are well adapted to the hypoxic environment, and they have synergistic effect on plant and soil properties (e.g., plant composition, soil carbon accumulation, and soil nitrogen cycling) of alpine grassland (Li et al., 2019; Pech et al., 2007).

Plateau pika is a small diurnal and non-hibernating lagomorph, which live in subterranean, and its burrowing activity is seen to affect soil nutrient recycling in alpine grassland (Pang et al., 2021; Yu et al., 2017). At present, the ecological relationship between plateau pika and livestock has been further recognized (Li et al., 2019; Su et al., 2016; Wang et al., 2020). The plateau pika has a competitive relationship with livestock for food resources when they are both at high population densities (Badingqiuying et al., 2016; Pang et al., 2021). The physiological traits of plateau pika were altered by resource fluctuations, ultimately leading to population changes (Feijó et al., 2020). In contrast, plateau pika at low to moderate density has beneficial effects on livestock by increasing forage quality and productivity (Arthur et al., 2008). For example, the liveweight gain of sheep peaked at about 110 and 70 burrows/ha of pika density in warm and cold seasons, respectively (Wang et al., 2020). Furthermore, plateau pika can exploit yak feces to supplement their food intake and survive severe winter, which was demonstrated by the identification of yak DNA in pika stomach contents (Speakman et al., 2021). Many studies have examined the individual and distinctive effects of pika and livestock activities on grassland structure and function (Sun et al., 2015; Zhang et al., 2020). In alpine meadows, clipping and burrowing behaviour of plateau pika decreased aboveground biomass and plant height (Zhang et al., 2020), but significantly increased plant diversity, soil organic carbon, and soil nutrients (Pang et al., 2020; Yu et al., 2017). The changes in plant and soil properties can further affect the coupling and linkages between above and belowground of ecosystems (Wang et al., 2022). In the central grasslands of North America, the strong influences of domestic cattle (*Bos taurus*) and prairie dogs (*Cynomys* spp.) on structure and function of grassland were, where they co-occurred, compared to where each appeared alone (Davidson et al., 2010). However, such research to study the synthetic effects of domestic yak and plateau pika on the plant–soil feedbacks, especially their interactions on greenhouse gases (GHG) emissions of alpine meadow are currently lacking.

A variety of biotic and abiotic processes directly lead to GHG emissions in alpine meadows (Cai et al., 2017; Zhu et al., 2015). Specifically, soil respiration contained soil microbial, soil fauna and root respiration are the main sources of CO_2 emissions; CH_4 and N_2O are emitted through the combination of microbial processes (e.g., methanogenesis, nitrifier-denitrification and denitrification) in soil (Luo et al., 2020). In the meantime, these emission processes are also driven by change in environmental factors due to climate change (Eskander & Fankhauser, 2021; Luo et al., 2020), grazing management (You et al., 2021) and land degradation (Abdalla et al., 2018). To the best of our knowledge, most of the field trials on GHG emissions of Tibetan grassland were conducted in controlled small plots where livestock and small mammals were both excluded (Wang et al., 2019). Crucially, livestock and small mammals always have both independent and interactive impacts on ecosystem GHG emissions through their foraging, burrowing behaviours, and excrement (Qin et al., 2015; Tang et al., 2021). For example, the contents of soil organic carbon and nitrogen were increased by excreta decomposition of livestock, then led to more CH_4 emissions by stimulating microbial activities such as methanogens (Cai et al., 2017; Maljanen et al., 2007). Likewise, Plateau pika can enhance GHG emissions by triggering a decline in plant photosynthetic tissue, and loss in soil nutrients with burrowing activities (Liu et al., 2013; Peng et al., 2015; Qin et al., 2020). Furthermore, plateau pika activities could offset the positive effects of warming on soil organic carbon pool (Yuan et al., 2021). Contrarily, the positive impacts of plateau pika disturbance on soil carbon stock were also observed in few studies in alpine grassland (Yu et al., 2017; Zhao et al., 2019). Yet, there is still considerable debate on the ecosystem-level effects of plateau pika burrowing on GHG emissions in alpine meadows, especially, no direct measurements of CO_2, CH_4, and N_2O emissions related to soil carbon stock responding to the combined disturbance of pika and yak.

Hence, we established an experiment with two conditions/situations/'treatments' (pika burrowing and yak grazing) in an alpine meadow of Zoige County on the east QZP. In this study, we aim to investigate the effects of plateau pika and yak grazing on GHG emissions in the pasture for grazing in the warm season. In detail, we address that: (1) What are the distinctive and synthesize effects of pika burrowing and yak grazing on GHG emissions? (2) What are the driving mechanisms regulating these effects? We hypothesize that: () GHG emissions will be higher in the plot with heavy yak grazing intensity and high pika burrow density; (ii) On a pastoral scale, GHG emissions probably are governed by pika burrowing more than yak grazing; and (iii) Pika burrowing and yak grazing directly or indirectly affect GHG emissions through their synergistic impacts on plant, soil properties, and soil microbe diversity (Figure 1). The results of this study

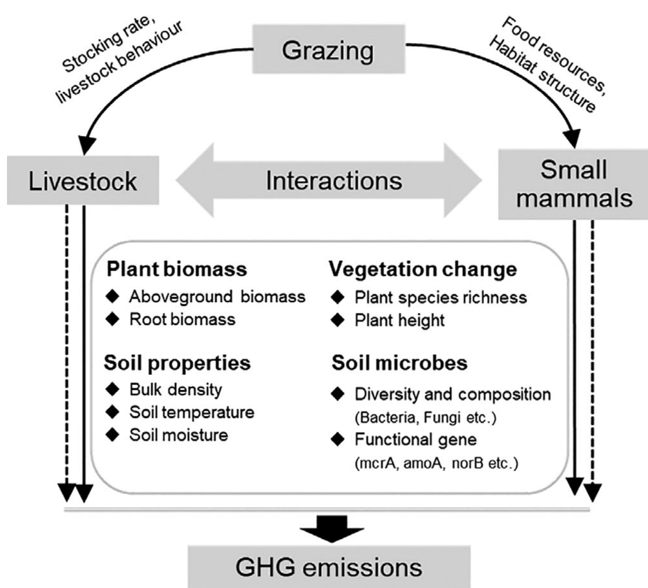

FIGURE 1 Conceptual framework of the mechanistic pathways of combination of livestock and small mammals on GHG emissions

enrich our understanding of the role of small burrowing mammals in the carbon sink of the alpine meadows.

2 | MATERIALS AND METHODS

2.1 | Site description

The field experiment was conducted in a typical warm-season yak grazing farm pasture (latitude 33°40′11″N, longitude 102°56′51″E, elevation ca. 3490 m) located 20 km northern of Zoige County (Figure S1A). The mean annual precipitation (MAP) is 640 mm, and mainly occurs in warm season (from May to September). The mean annual temperature (MAT) is 0.9°C. The minimum temperature is −9.6°C in January and the maximum temperature is 11.1°C in July (Liu et al., 2022). During the sampling period (in August 2018 and 2019), the monthly total precipitation was 99.41 and 130.57 mm, and the monthly mean temperature was 12.28 and 10.55°C. Vegetation type is alpine meadow, dominated by *Kobresia humilis*, *Elymus nutans*, *Saussurea* spp. and *Anemone* spp. The soil is classified as Mat-Cryic Cambisols (Chinese Soil Taxonomy Research Group, 1995). Prior to carrying out the experiment, the study area was freely grazed with yak during warm season each year.

2.2 | Experimental design

In early July 2018, two sampling areas (2-hectare each) were established 0–100 m and 900–1000 m from the entrance to the pasture where yak were released and subsequently dispersed over the pasture (Figure S1B). Since yak tends to concentrate close to the entrance of pasture to forage, rest, ruminate, drink, and excrete (Du et al., 2017), the distance away from the entrance to pasture was deemed to represent a surrogate for grazing intensity. In general, grazing intensity near the herder's house was higher, and herbage utilization gradually diminished with a greater distance away from the entrance to pasture (Guo et al., 2020). To evaluate the grazing intensity, we recorded the number of yaks in each sampling area every hour between 08:00 am and 18:00 pm each day in July 2018 and 2019. The grazing intensity was calculated with a published evaluation method (see Zhang et al., 2015). The grazing intensity was estimated as 9.10 and 0.80 yaks/ha respectively, corresponding to the abovementioned distances from the entrance. Hence, the two yak grazing conditions in this study were heavy stocking at 9.10 yak ha^{-1} and light stocking at 0.80 yaks/ha.

In each sampling area (grazing conditions), three plots were randomly confined for light and heavy disturbance by plateau pika, respectively, for a total of 12 plots (Figure S1B). The size of each plot was 25 m × 25 m, which is about the mean home range of plateau pika (Pang et al., 2020; Smith, 2008). In this study, the total pika burrows per plot (pika burrowing density) was used to represent the disturbance of plateau pika. We investigated pika burrows per plot by using aerial photography with light unmanned aerial vehicles (Qin et al., 2020) to gain two pika burrowing situations (low/high pika burrowing and heavy/light yak grazing). The density of light and high pika burrowing conditions were about 600 and 1800 burrow/ha, respectively. In addition, within each plot, we randomly set 4 quadrats (0.5 m × 0.5 m) to obtain the GHG emissions, plant and soil samples (Figure S1B). Also, the pika burrow density of each quadrat was investigated.

For detailed main parameters of each yak grazing condtons and pika burrowing condtons, see Table S1. The terminology used in the paper is the internationally accepted standard terms for grazing lands (Allen et al., 2011).

2.3 | Field sampling and analyzing

2.3.1 | GHG emissions measurement

GHG emissions (CO_2, CH_4, and N_2O flux) was measured with a static opaque chamber and the gas analyzer method following the guideline in the previous research (Wei et al., 2020). In each aforementioned quadrat, the air samples were collected in each chamber at four-time intervals for each sampling event (0, 10, 20, and 30 min) from 09:00 to 11:00 am, and from 15:00 to 17:00 pm to represent daily average flux. Gas samples were collected on six consecutive days each year (13th to 18th August in 2018, 15th to 20th August in 2019). Gas samples were drawn through a three-way stopcock, using a 60 ml syringe, and then transferred for storage into 500 ml aluminum foil gas-collecting bags (Luo et al., 2020). In the laboratory, a CH_4/CO_2 analyzer with syringe injection (DLT-100, Model No. 908–0011-0001) was used for simultaneous CH_4 and CO_2 analysis, and an N_2O/CO analyzer (Model No. 908–0015-0000) was used for simultaneous N_2O analysis. The fluxes were calculated based on the equation with modifications made for QTP conditions (Liu et al., 2017) as follows:

$$F=\rho\cdot\frac{V}{A}\cdot\frac{P_s}{P_0}\cdot\frac{T_0}{T}\cdot\frac{dC_t}{D_t}$$

Where: F is GHG flux (mg m^{-2} hr^{-1}), ρ is gas density under standard conditions (1.977 and 0.717 kg m^{-3} for CO_2 and CH_4, respectively), V is chamber volume (m^3), A is the base area of the chamber (m^2), Ps is the atmospheric pressure (KPa) of the sampling sites, P_0 is the atmospheric pressure under standard conditions (101.325 kPa), T_0 is the temperature under standard conditions (273.15 K), T is the temperature inside the chamber (K), and dCt/dt is the average rate of concentration change with time.

2.3.2 | CO_2 equivalents (CO_2-eq.)

N_2O and CH_4 have global warming potentials that are 310- and 25-times higher than CO_2 (Sperow, 2020). The CO_2-eq was calculated as

$$CO_2-eq=CO_2\,flux+25\times N_2O\,flux+310\times CH_4\,flux$$

2.3.3 | Plant and soil properties determination

After GHG emissions measurements in each quadrat, we measured plant surveys and collected soil samples. In the 0.5 m × 0.5 m quadrat under each chamber, plant height and total number of plant species (SR) were measured. All on-ground plants were harvested and bagged to bring back the indoor. The dry weight after oven-dried at 65°C for 48 hr represented the aboveground biomass (AGB).

Soil moisture (SM) and soil temperature (ST) were measured at depth of 0–10 cm during gas sample collection using Field-Scout TDR-100. Soil bulk density (SBD) was measured with the cutting ring method. Soil was sampled at depth of 0–10 cm using an auger with 9 cm diameter, then root and soil fractions were separated. The root fractions were washed and weighed as belowground biomass (BGB) after drying. The soil fractions were sieved through a 0.2 mm mesh, then take sufficient samples for refrigerated storage (−80°C) for the determination of soil microorganisms. The remaining samples were stored in a refrigerator at 4°C for soil properties analysis. Soil total nitrogen (STN) was obtained from colorimetric method with the Element analyzer (Eelementar vario EL cube Germany) and soil organic carbon (SOC) was measured with the traditional potassium dichromate oxidation method. The soil microbial community was analyzed by Illumina MiSeq sequencing analysis (Liang et al., 2021).

2.4 | Statistical analysis

Firstly, the distributions and normality were inspected by a goodness-of-fit test (Shapiro–Wilk test). We used a mixed linear model to assess the effects of yak grazing and pika burrowing and their interaction on GHG emissions, plant and soil properties. In this model, yak grazing and pika burrowing were used as two fixed factors, and the year was used as a random factor. The level of significance test set at $p < 0.05$. A Tukey's HSD test with the "*agricolae*" package was performed to evaluate differences in GHG emissions, plant and soil properties, and microbe diversity between two pika burrowing conditions, or between two yak grazing conditions, with significance at $p < 0.05$. Next, we conducted principal component analysis (PCA) through "*FactoMineR*", "*factoextra*" and "*corrplot*" packages in R software based on data of plant characteristics and soil properties to reveal the explanatory

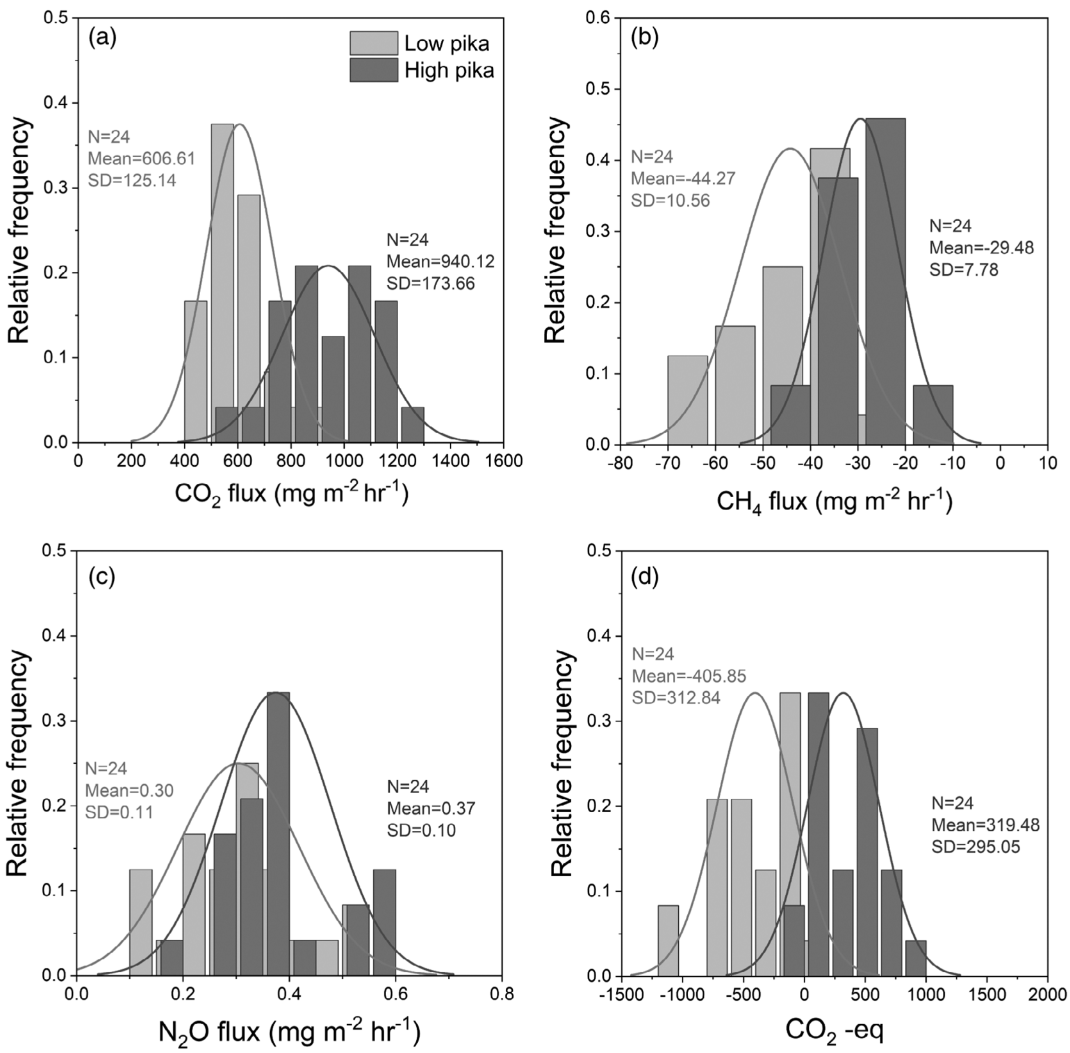

FIGURE 2 Relative frequency of CO_2 flux (a), CH_4 flux (b), N_2O flux (c) and CO_2-equation (d) under low and high pika burrowing conditions

powers of variance in different condtons. Several principles should be taken into account: (a) The sampling adequacy of individual and set variables by the Kaiser–Meyer–Olkin measure (KMO value >0.50) and Bartlett's test of sphericity ($p < 0.05$); (b) Removal of variables with communality values <0.5 and (c) The selection of main components by the latent root criterion (eigenvalues >1.0). The relationships between GHG emissions with plant and soil properties and microbe diversity were explored with the "*corrplot*" package. Finally, structural equation modelling (SEM) with "*sem*" package was used to evaluate the direct and indirect effect of pika burrowing on CO_2-eq via changes in plant properties, soil properties, and microbe under light grazing and heavy grazing conditions. Prior to SEM analyses, the main components (PC1) of each plant, soil, and microbe properties group were selected via the PCA approach. Correlations among PC1 of each plant, soil, and microbe properties group with AGB, BGB, SR, SBD, STN, and soil bacteria diversity under light grazing and heavy grazing conditions were explored in "*corrplot*" package. Path coefficients and their significance were estimated with the maximum likelihood method. The model fitting degree was expressed by *p* values of χ^2 test >0.05, root mean square error of approximation (RMSEA) < 0.05, standardized root mean square residual (SRMSR) < 0.08, comparative fit index (CFI) > 0.90, Tucker-Lewis iIndex (TLI) > 0.90. All statistical analyses were performed in R version 4.1.2 (R Core Team, 2021) and all figures were drawn using ORIGIN 2021b software.

3 | RESULTS

3.1 | Response of GHG emissions to pika burrowing and yak grazing

For the mean values, CO_2 flux, CH_4 flux, N_2O flux and CO_2-eq ranged from 606.61 to 940.12 mg m^{-2} hr^{-1} (Figure 2a), −44.27 to −29.48 mg m^{-2} hr^{-1} (Figure 2b), 0.30 to 0.37 mg m^{-2} hr^{-1} (Figure 2c)

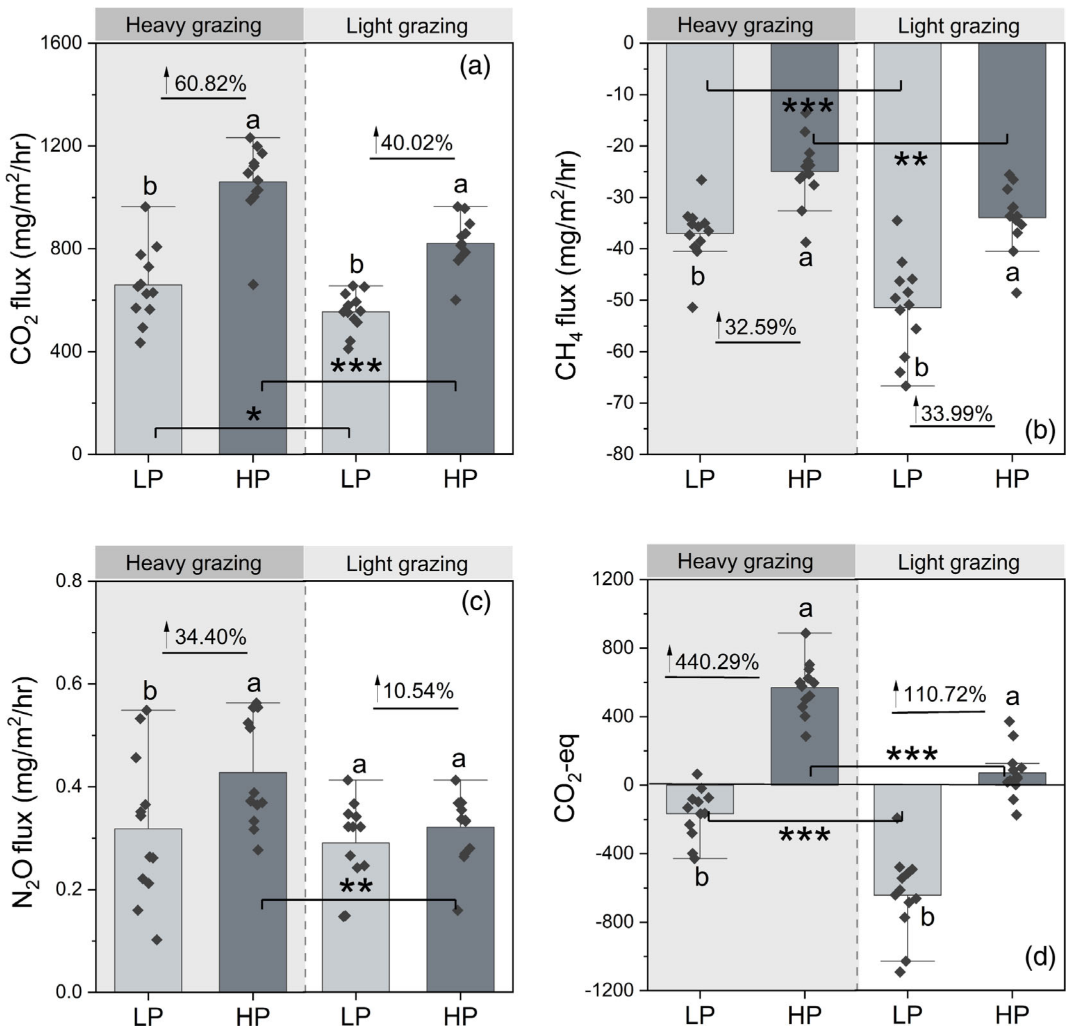

FIGURE 3 Response of GHG emissions (CO_2 flux (a), CH_4 flux (b) and N_2O flux(c)) and CO_2-equation (d) to yak grazing and pika burrowing conditions. Significant differences ($p < 0.05$) between pika burrowing conditions under the same yak grazing conditions are indicated by different lower-case letters; significant differences between yak grazing conditions under same pika burrowing conditions are expressed by asterisk; *$0.01 < p < 0.05$, **$0.001 < p < 0.01$, ***$p < 0.001$; left half in grey represents heavy yak grazing, right half in white represents light yak grazing, HP, high pika burrowing; LP, low pika burrowing [Colour figure can be viewed at wileyonlinelibrary.com]

and −405.85 to 319.48 mg m^{-2} hr^{-1} (Figure 2d) under low and high pika burrowing conditions, respectively.

The mixed linear model analysis demonstrated that GHG emissions were significantly influenced by yak grazing ($p < 0.05$) and high pika burrowing ($p < 0.05$), each independently, and by yak grazing and pika burrowing ($p < 0.05$) in conjunction (Table S1). CO_2 flux, CH_4 flux, and CO_2-eq under pika burrowing condtons were significantly ($p < 0.05$) higher than that under low pika burrowing condtons regardless of yak grazing treatments (Figure 3a,b,d). Under heavy yak grazing condtons, high pika burrowing led to increases by 60.82%, 32.59%, 34.40%, and 440.29% for CO_2 flux, CH_4 flux, N_2O flux and CO_2-eq (Figure 3). Meanwhile, under light yak grazing condtons, high pika burrowing led to an increase of 40.02%, 33.99%, 10.54%, and 110.72% relative to low pika burrowing for CO_2 flux, CH_4 flux, N_2O flux and CO_2-eq, respectively (Figure 3).

3.2 | Response of plant, soil properties to pika burrowing and yak grazing

The PCA analysis demonstrated that 59% of the total variance for the plant and soil properties was explained by the first two axis (Figure 4). In detail, PC1 was more closely to SM, BGB, SOC and STN; PC2 was more closely to AGB and SR (Figure 4). SR, SM, SOC and STN under high pika burrowing conditions were significantly ($p < 0.05$) lower than that under low pika burrowing conditions regardless yak grazing conditions (Figure 5c,e,g,h). With heavy yak grazing, ST was significantly ($p < 0.05$) greater under high pika burrowing conditions than that under low pika burrowing conditions (Figure 5d). There was no significant difference ($p > 0.05$) in soil microbial diversity between heavy and low pika burrowing conditions in both two yak grazing situations (Figure 5i–k).

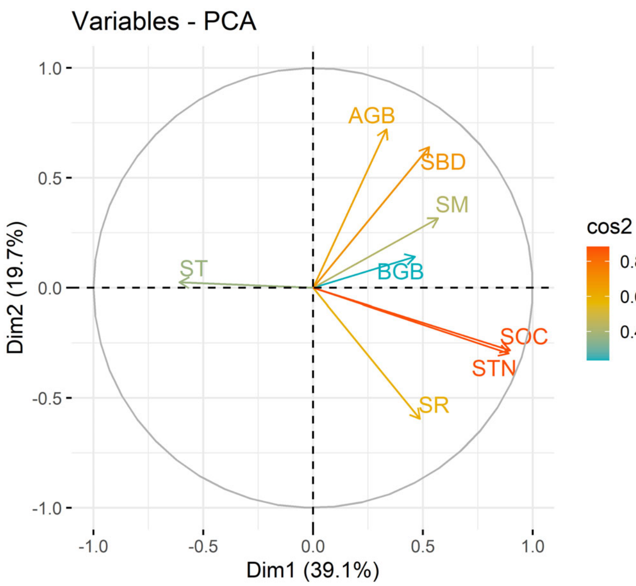

FIGURE 4 Principal component analyses of plant and soil properties. AGB, aboveground biomass; BGB, belowground biomass; SR, plant species richness; ST, soil temperature; SM, soil moisture; SBD, soil bulk density; SOC, soil organic carbon; STN, soil total nitrogen [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | SEM mining the GHG emissions links to environmental factors induced by pika activities, and yak grazing

The CO_2 flux, CH_4 flux and CO_2-eq were negative closely associated with SR, SBD, SOC, and STN ($p < 0.05$; Figure 6a) under heavy yak grazing conditions. Similarly, Shannon-Winner index of soil microbe, STN, and SOC were the dominant factors that correlated with GHG emissions (i.e., CO_2 and CH_4 flux), followed by SBD and SR (Figure 6b) under light yak grazing conditions. Furthermore, significant positive relationships were found between the GHG emission with the ST ($p < 0.05$) as well as pika burrow density ($p < 0.05$; Figure 6b).

SEM was used to further reveal the driving mechanisms that affectthe GHG emissions by pika burrowing under two yak grazing conditions (Figure 7). Under heavy yak grazing, the SEM analysis demonstrated that pika burrowing had significant negative influences on plant and soil properties with the effect coefficients of −0.52 and −0.44, respectively (Figure 7a). Contrarily, pika burrowing exerted significant positive effects on ST with the effect coefficient of 0.78 (Figure 7a). CO_2-eq was determined by ST, soil properties, and soil microbe with standard total effect values of 0.06, −0.33, and − 0.22, respectively (Figure 7b). Under light yak grazing, pika burrow density had significant negative effects on plant, soil properties and SM with the effect coefficients of −0.68, −0.59, and − 0.58, respectively (Figure 7c). There were significant positive effects of SM, and plant properties on CO_2-eq (standard total effect values are 0.16 and 0.26, respectively; Figure 7d). Nevertheless, soil microbe, and soil properties had significant negative effects on CO_2-eq with effect coefficients of −0.36 and −0.10, respectively (Figure 7d).

4 | DISCUSSION

4.1 | Responses of GHG emissions to pika burrowing and yak grazing

Response of GHG emissions to grazing regimes has been well known on the QZP (Liu et al., 2017; Luo et al., 2020), but the activities of small mammals (e.g., pika burrowing and zokor digging) on GHG emissions remains controversial and how yak grazing and pika burrowing jointly shape GHG emissions are still unclear. Our results of field trials emphasized that CO_2, CH_4, N_2O flux, and CO_2-eq were significantly influenced by pika burrowing and yak grazing (Table S2; Figure 3). GHG emissions were the highest in the site which disturbed heavily by yak and pika simultaneity (Figure 3). Crucially, our results found that the relative importance of pika burrowing was greater than yak grazing on a pastoral scale (Table S2). Generally, compared to plateau pika activities, domestic livestock have broader landscape-scale

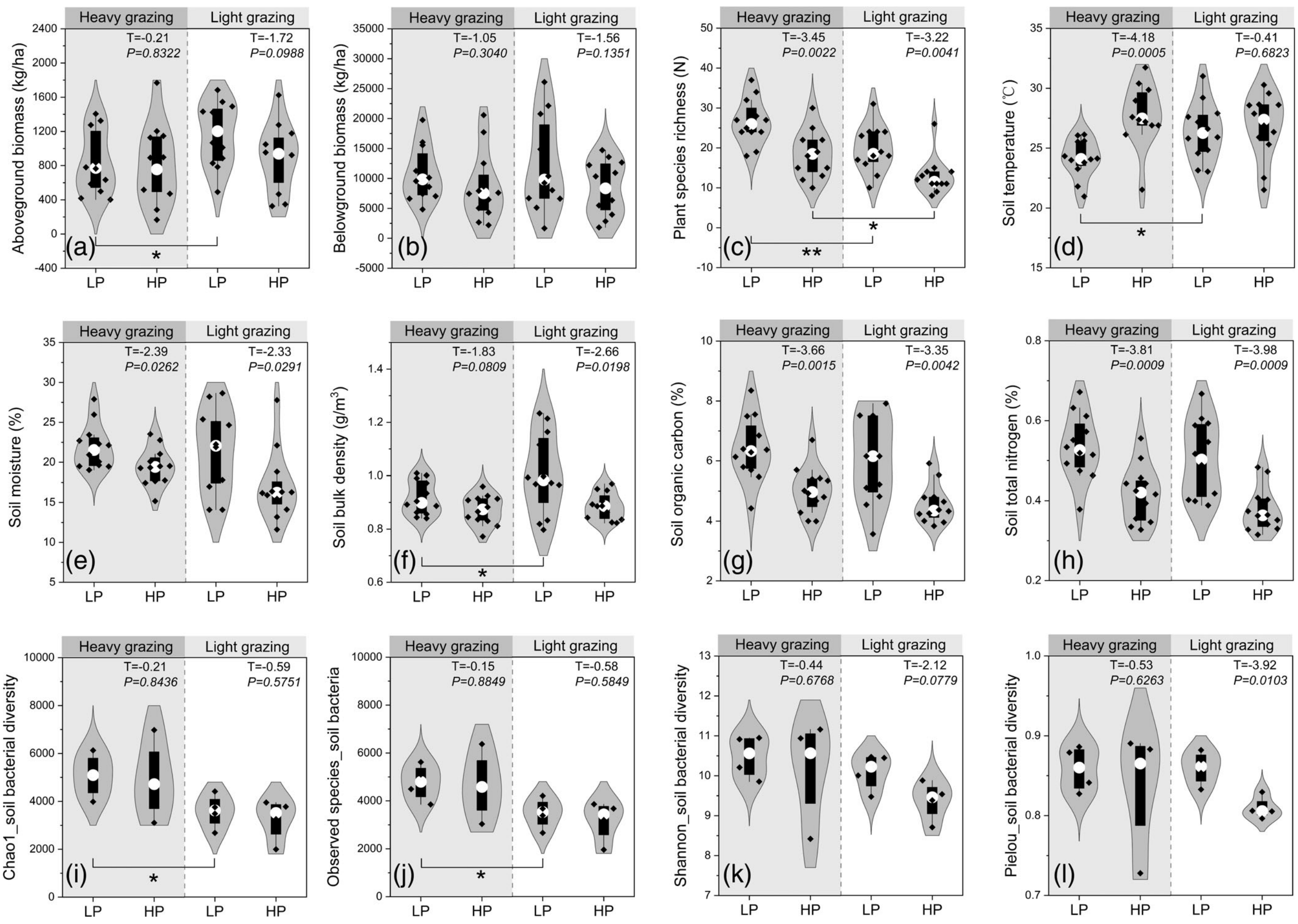

FIGURE 5 Response of aboveground biomass (a), belowground biomass (b), plant species richness (c), soil temperature (d), soil moisture (e), soil bulk density (f), soil organic carbon (g), soil total nitrogen (h), and soil bacterial diversity Chao1 index (i), observed species (j), Shannon-Wiener diversity index (k), Pielou evenness index (l) to yak grazing and pika burrowing conditions. Significant differences (p < 0.05) between pika burrowing conditions under same yak grazing conditions are indicated by p values of t-test; significant differences between yak grazing conditions under same pika burrowing conditions are expressed by asterisk; *0.01 < p < 0.05, **0.001 < p < 0.01, ***p < 0.001; left half in gry represents heavy yak grazing, right half in white represents light yak grazing; HP, high pika burrowing; LP, low pika burrowing

effects, while plateau pika have more intensive, localized impacts due to their sedentary behaviour and burrowing activities (Wang et al., 2019). Grazing events (foraging, trampling and excrements) could change soil water content, soil temperature, and the substrates supply from plant part to soil biota and microorganism that mediate the progress of GHG emissions production (Dowhower et al., 2020). Recent studies also showed that GHG emissions were affected by stocking rate rather than grazing system in grassland ecosystem (Ma et al., 2021; Wang et al., 2019). For example, increased yak excrement decomposition under high stocking rate may promote CO_2 emission by microbes through stimulating soil organic matter mineralization (Tang et al., 2021). In comparing to suitable stocking rate, high stocking rates lead to progressive reductions in plant biomass, which eventually result in reducing soil carbon stock (Chen et al., 2011). In agreement with other studies (Liu et al., 2013; Zhou et al., 2020), our study also demonstrated the important roles of plateau pika on GHG emissions (Figure 3). Specifically, high pika burrowing led to an increase of 440.29% and 110.72% for CO_2-eq under heavy and light yak grazing conditions, respectively (Figure 3). GHG emissions are closely related to plant cover, soil attributes, and microbial activity (Cai et al., 2017) which are regulated by pika through their foraging and burrowing activities (Yuan et al., 2021). For example, soil attributes (e.g., SBD, SOC, and soil texture) can change water holding capacity, then affect gas diffusivity of soils and relevant microbial activities, thereby modifying GHG emissions (Cai et al., 2017; Zhao et al., 2019). More potential mechanisms GHG emission from the interactive effects of pika burrowing and yak grazing need further to be explored.

4.2 | The driving mechanisms regulating mutual effects between pika burrowing and yak grazing on GHG emissions

Livestock and small mammals produce CO_2 flux themselves directly and affect CO_2 flux indirectly through changing substrate availability

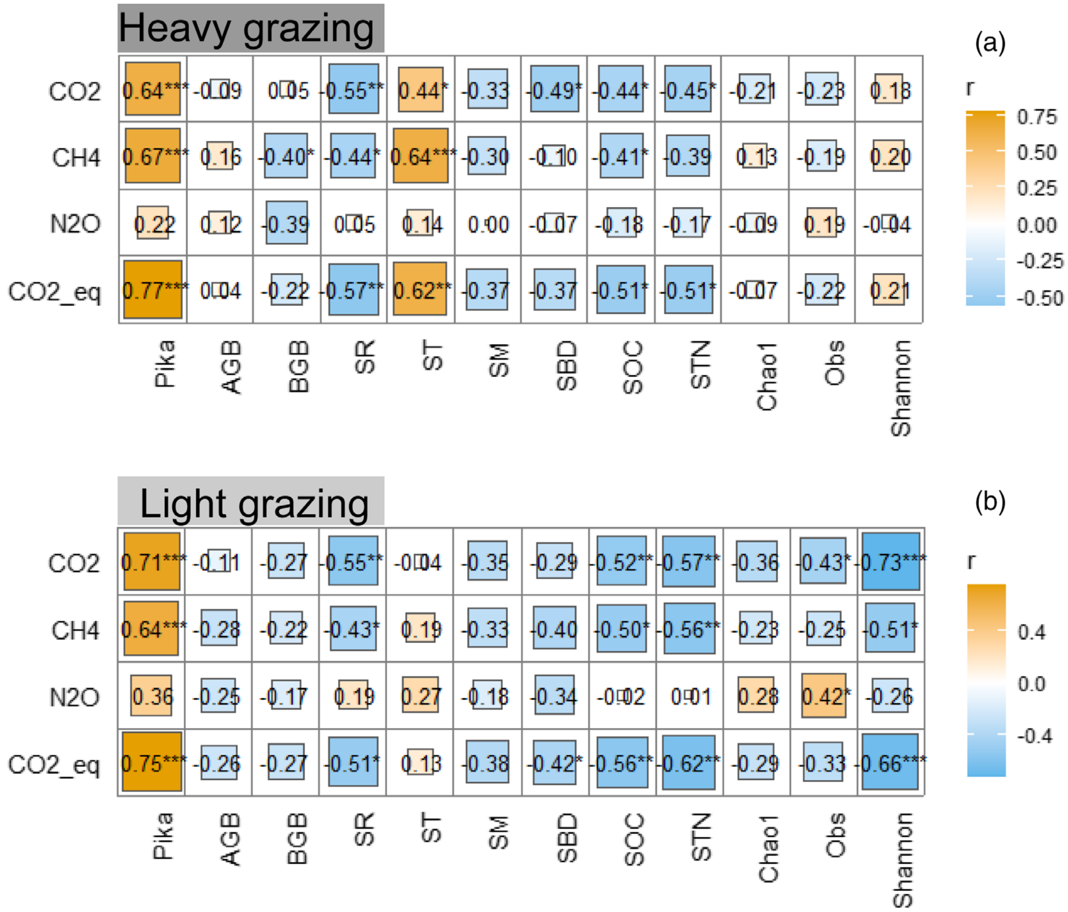

FIGURE 6 Relevance among variables of plant, soil properties, and microbe diversity with GHG emissions under heavy (a) and light (b) yak grazing conditions. The value within the square represents the value of the correlation coefficient. *, ** and *** show the significant correlations at 0.05, 0.01 and 0.001 levels. AGB, aboveground biomass; BGB, belowground biomass; Chao1, Chao1 diversity index of soil bacteria; Obs, observed species of soil bacteria; SR, plant species richness; ST, soil temperature; SM, soil moisture; SBD, soil bulk density; SOC, soil organic carbon; STN, soil total nitrogen; Shannon, Shannon-Wiener diversity index of soil bacteria [Colour figure can be viewed at wileyonlinelibrary.com]

and soil physico-chemical characteristics (Han & Zhu, 2020; Li et al., 2019; Pelster et al., 2016). The CO_2 flux measured in this study consisted of root and soil respiration. The major factor determining the root respiration rate is root biomass (Lubbers et al., 2013). In this study, foraging and consumption of plants by pika reduced the biomass of root, especially under light yak grazing conditions (Figure 5b), then decreased carbon fixation via promoting root respiration (Girkina et al., 2018). Soil respiration is mainly determined by soil properties and microbial activities (Jian et al., 2018). Under heavy yak grazing, CO_2 flux was significantly positively related to ST and negatively correlated with SR, , and STN (Figure 6a). High pika burrowing may increase CO_2 flux by promoting ST and reducing SR, SOC and STN (Figure 5d,e,g,h). Pika burrowing can promote ST due to creating tunnel and turn deep soil to the surface and expose to the air (Qin et al., 2015). Meanwhile, loosening the surface soil led to more oxygen in soil, then made more soil carbon releases, which may decrease the soil's organic carbon stock (Zhang et al., 2015; Zhou et al., 2020). In the sampling plot which was heavily disturbed by pika and yak , the possible reason for higher CO_2 emissions was competition among microorganisms induces the microbes to use more C energy for cell integrity and maintenance and led to higher soil respiration (Jacotot et al., 2018).

CH_4 flux is affected by many factors such as soil water content and soil temperature (Pelster et al., 2016), These factors influence CH_4 emission by altering the quantity and activity of methane-oxidizing bacteria and methanogens (Aghdam et al., 2017; Cai et al., 2017). CH_4 flux in this study showed good consistency with soil temperature and negative relations with soil moisture (Figure 6a). Soil temperature under high pika burrowing conditions was significantly higher than that under low pika burrowing conditions (Figure 5d). Soil temperature was increased with more fresh soil was exposed to the sunlight due to pika burrowing contained excavating, cleaning, and maintaining the underground cavern (Chen et al., 2017; Qin et al., 2021). Some studies showed that CH_4 flux in grassland is closely related to microbial composition, abundance, and function of methanotrophs (e.g., *Proteobacteria* and *Verrucomicrobia*) and methanogens (Görres et al., 2013; Zhang et al., 2015). Our results also found that the alpha diversity of soil bacteria has a significant negative correlation with CH_4 flux, particularly under light yak grazing conditions (Figure 6b). And that, the alpha diversity of soil bacteria under heavy

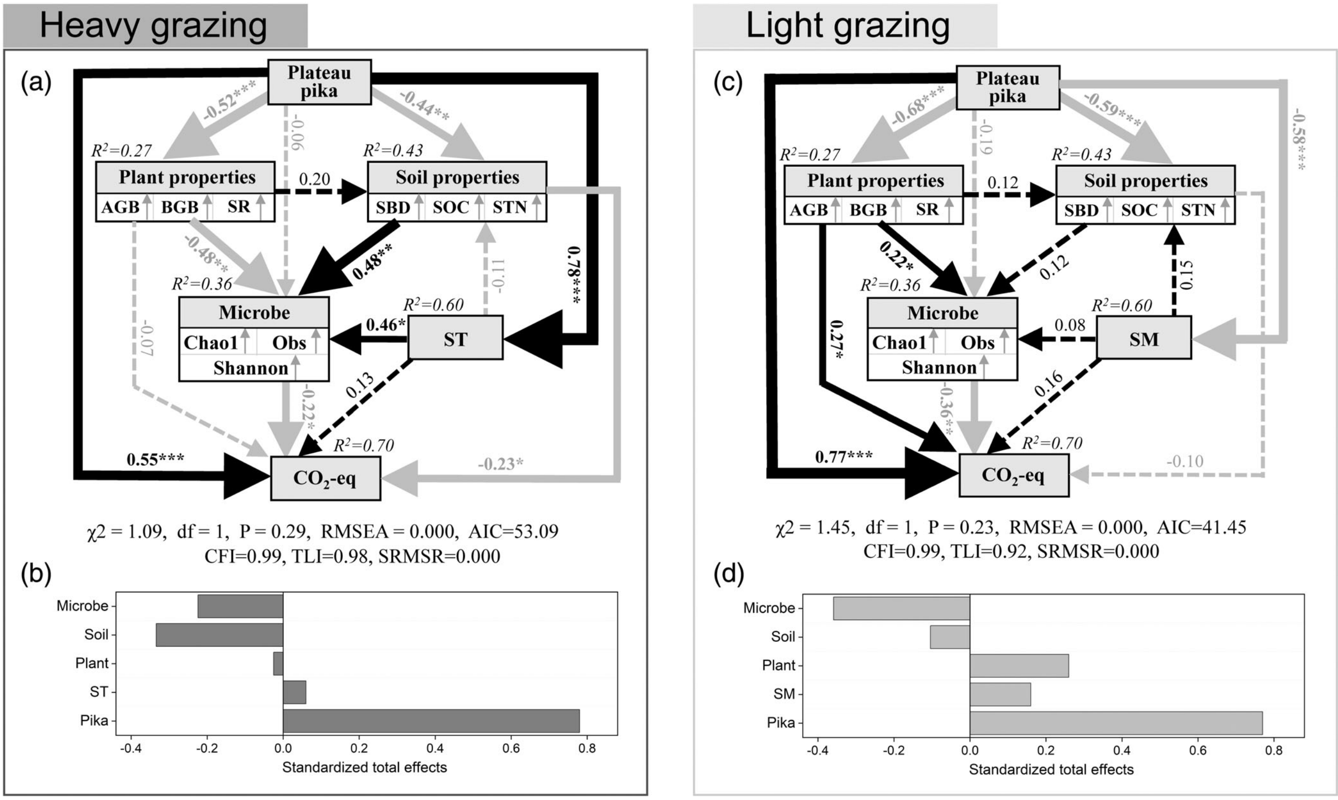

FIGURE 7 Structural equation model (SEM) fitted to linking pika burrow density to plant, soil properties, ST, SM, and soil microbial factors to GHG emissions under heavy (a) and light (c) yak grazing conditions. Significant paths are expressed by black and gry arrows. The thickness of the solid arrows reflects the magnitude of the standardized SEM coefficients. Standardized coefficients are listed beside each significant path."-"values respect negative effects. Standardized total effects bar graph (direct plus indirect effects) derived from the SEM depicted above (B and D). AGB, aboveground biomass; BGB, belowground biomass; Chao1, Chao1 diversity index of soil bacteria; Obs, observed species of soil bacteria; SR, plant species richness; ST, soil temperature; SM, soil moisture; SBD, soil bulk density; SOC, soil organic carbon; STN, soil total nitrogen; Shannon, Shannon-Wiener diversity index of soil bacteria

yak grazing was significantly higher than that under light yak grazing (Figure 5k,m). These differences in soil microbes probably provide an explanation for CH_4 flux was increased with heavyigh grazing intensities. Besides, high-intensity fecal addition of yak could stimulate CH_4 release. Anaerobic conditions formed by wetting of urine deposition can stimulate methanogenic activity (Cai et al., 2017). Also, the decrease of redox potential and increase of soil pH caused by urea hydrolysis are beneficial to methanogenic activity (Wang et al., 2021).

N_2O flux is mainly dependent on soil nitrification, denitrification, and mineralization processes, which could offer the substrates for N_2O production (Xu et al., 2008). Indeed, soil mineralization, nitrification, and denitrification rate are all sensitive to soil temperature, soil moisture, and contents of soil organic matter (Thilakarathna & Hernandez-Ramirez, 2021). Under heavy yak grazing conditions, N_2O emissions from high pika burrowed area was up to 1.3times higher than from low pika burrowed areas (Figure 3c). The promotion of soil aeration and permeability due to plateau pika digging enhanced the microbial nitrification, which possibly was the main process (reduction of NO_3^- to NO_2^-, then to N_2O) of N_2O emission (Wang et al., 2021). Meanwhile, more yak dung deposition by heavy grazing pressure would enhance the abundance of ammonia-oxidizing bacteria (AOB), which are functionally more important in nitrification in soil (Cai et al., 2017). Additionally, changes in oxidation–reduction condition of soil through reducing soil moisture and organic matter in mixed subsoil with topsoil (Yu et al., 2017) might be another explanation for N_2O emission.

Overall, our results indicated that through the driver of pika burrowing, SEM indicated soil microbe, and soil properties demonstrated significant negative effects on CO_2-eq under two grazing conditions (Figure 7). Whereas plant properties showed different effects on CO_2-eq. Pika burrowing can affect CO_2-eq though altering ST in the site near to entrance and changing SM in the site far from entrance (Figure 7). The lack of plant insulation is associated with greater temperature in bare soil due to heavy yak grazing (Liu et al., 2017; Qin et al., 2020), which can lead to more soil organic carbon being mineralized (Pang et al., 2021; Yu et al., 2017). In addition, higher water infiltration generated more dissolved organic carbon to leach into deep soil, thus resulting in carbon loss of topsoil (Pang et al., 2020). These different driving mechanisms further verify pika burrowing and yak grazing may interact synergistically to facilitate carbon loss. However, much remains to be explored about how these linkages between domestic yak and plateau pika and their context dependencies translate into synthetic effects on GHG emissions of alpine meadows.

4.3 | Limitations of this study

Most of the regions in the alpine meadow are undergoing carbon loss due to degradation (Zhang et al., 2014). Increasing efforts have been carried out to research the internal mechanism and consequences of carbon budget induced by small mammals (Tang et al., 2021; Zhao et al., 2019). Our study has two main aspects distinguish from other few studies in the past on this subject. First, we comprehensively consider the impacts of pika burrowing, yak grazing and their reciprocal actions on GHG emissions. Second, our results indicated that GHG emissions governed by pika burrowing more than yak grazing on a pastoral scale. Given that our experiment was carried out in the summer pasture, the seasonal variation in GHG emissions was not considered. Moreover, we indicated grazing intensity as the distance to the entrance of the pasture. This could limit our ability to make the quantitative evaluation of the effects of yak grazing on GHG emissions because of the lack of GHG emissions from rumination of yak (Lin et al., 2009). To get a better understanding of the responses of GHG emissions to pika burrowing and yak grazing, further research is needed to: (1) quantify the combined effects of plateau pika and domestic yak on seasonal variation of GHG emissions, especially in cold seasons; (2) large-scale, long-term experiments are essential to be established in other areas of QZP.

5 | CONCLUSIONS

In the context of carbon neutrality of QZP, it is vitally important to explore the effects of small mammals and their interactions with livestock on GHG emissions. Our findings indicated that CO_2, CH_4, N_2O flux, and CO_2-eq were significantly influenced by pika burrowing and yak grazing independently, and in conjunction. Crucially, the relative importance of pika burrowing was higher than yak grazing on a pastoral scale. A notable observation in this study was that the value of CO_2-eq with low pika burrowing was negative, especially under light yak grazing conditions. CO_2-eq was more sensitive to community structure, soil properties, and soil microbial factors. Furthermore, our results suggest that pika burrowing can affect CO_2-eq though altering ST and BGB in the site with heavy yak grazing and changing SM and soil microbe in the site with light yak grazing. In the context of carbon neutrality of grassland ecosystem of QZP, pika's activities and their interactions with livestock-induced changes in microtopography on GHG emissions should not be neglected. Moreover, as the climate crisis is getting serious, natural-based solutions (NbS) offer a no-regret route for tackling climate change and reducing carbon loss. Our study demonstrates that appropriate pika populations are beneficial for soil carbon sequestration in alpine meadow. Hence, policymakers and scientists should re-examine the plateau pika poisoning programmes that have the objective of eradicating populations in future.

AUTHOR CONTRIBUTIONS

Yingxin Wang and Fujiang Hou conceived the ideas and designed the methodology; Yingxin Wang, Shuaijun Hou, Yuhui Tian, and Zhaofeng Wang collected the data; Yingxin Wang, Jian Sun, Shenghua Chang, and Junhe Chen analyzed the data; Yingxin Wang, Yongqiang Qian, Jianmin Chu, and Fujiang Hou wrote the manuscript. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

No conflict of interest exists in the submission of this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Abdalla, K., Mutema, M., Chivenge, P., Everson, C., & Chaplot, V. (2018). Grassland degradation significantly enhances soil CO_2 emission. *Catena*, *167*, 284–292. https://doi.org/10.1016/j.catena.2018.05.010

Aghdam, E. F., Scheutz, C., & Kjeldsen, P. (2017). Assessment of methane production from shredder waste in landfills: The influence of temperature, moisture and metals. *Waste Management*, *63*, 226–237. https://doi.org/10.1016/j.wasman.2016.11.023

Allen, V. G., Batello, C., Berretta, E. J., Hodgson, J., Kothmann, M., Li, X. L., & Sanderson, M. (2011). An international terminology for grazing lands and grazing animals. *Grass and Forage Science*, *66*, 2–28. https://doi.org/10.1111/j.1365-2494.2010.00780.x

Arthur, A. D., Pech, R. P., Davey, C., Yanming, Z., & Hui, L. (2008). Livestock grazing, plateau pikas and the conservation of avian biodiversity on the Tibetan Plateau. *Biological Conservation*, *141*(8), 1972–1981. https://doi.org/10.1016/j.biocon.2008.05.010

Badingqiuying, S. A. T., Senko, J., & Siladan, M. U. (2016). Plateau pika *Ochotona curzoniae* poisoning campaign reduces carnivore abundance in southern Qinghai, China. *Mammal Study*, *41*(1), 1–8. https://doi.org/10.3106/041.041.0102

Cai, Y. J., Chang, S. X., & Cheng, Y. (2017). Greenhouse gas emissions from excreta patches of grazing animals and their mitigation strategies. *Earth-Science Reviews*, *171*, 44–57. https://doi.org/10.1016/j.earscirev.2017.05.013

Chen, W., Wolf, B., Zheng, X. H., Yao, Z. S., Butterbach-bahl, K., Brueggemann, N., Liu, C. Y., Han, S. H., & Han, X. (2011). Annual methane uptake by temperate semiarid steppes as regulated by stocking rates, aboveground plant biomass and topsoil air permeability. *Global Change Biology*, *17*(9), 2803–2816. https://doi.org/10.1111/j.1365-2486.2011.02444.x

Chen, J. J., Yi, S. H., & Qin, Y. (2017). The contribution of plateau pika disturbance and erosion on patchy alpine grassland soil on the Qinghai-Tibetan Plateau: Implications for grassland restoration. *Geoderma*, *297*, 1–9. https://doi.org/10.1016/j.geoderma.2017.03.001

Chinese Soil Taxonomy Research Group. (1995). *Chinese soil taxonomy* (pp. 58–147). Beijing, PRC: Science Press.

Davidson, A. D., Detling, J. K., & Brown, J. H. (2012). Ecological roles and conservation challenges of social, burrowing, herbivorous mammals in the world's grasslands. *Frontiers in Ecology and the Environment*, *10*(9), 477–486. https://doi.org/10.1890/110054

Davidson, A. D., Ponce, E., Lightfoot, D. C., Fredrichson, E. L., Brown, J. H., Cruzado, J., Brantley, S. L., Sierra-Corona, R., List, R., Toledo, D., & Ceballos, G. (2010). Rapid response of a grassland ecosystem to an experimental manipulation of a keystone rodent and domestic livestock. *Ecology*, *91*, 3189–3200. https://doi.org/10.1890/09-1277.1

Dowhower, S. L., Teague, W. R., Casey, K. D., & Daniel, R. (2020). Soil greenhouse gas emissions as impacted by soil moisture and temperature under continuous and holistic planned grazing in native tallgrass prairie. *Agriculture, Ecosystems & Environment*, *287*, 106647. https://doi.org/10.1016/j.agee.2019.106647

Du, W. C., Yan, T., Chang, S. H., Wang, Z. F., & Hou, F. J. (2017). Seasonal hogget grazing as a potential alternative grazing system for the Qinghai-Tibetan plateau: Weight gain and animal behaviour under continuous or rotational grazing at high or low stocking rates. *The Rangeland Journal*, *39*, 329–339.https://doi.org/10.1071/RJ16119

Eskander, S. M., & Fankhauser, S. (2021). Reduction in greenhouse gas emissions from national climate legislation. *Nature Climate Change*, *10*(8), 750–756. https://doi.org/10.1038/s41558-020-0831-z

Feijó, A., Ge, D., Wen, Z., Xia, L., & Yang, Q. (2020). Divergent adaptations in resource-use traits explain how pikas thrive on the roof of the world. *Functional Ecology*, *34*(9), 1826–1838. https://doi.org/10.1111/1365-2435.13609

Girkina, N. T., Turnerb, B. L., Ostlec, N., & Sjögerstena, S. (2018). Composition and concentration of root exudate analogues regulate greenhouse gas fluxes from tropical peat. *Soil Biology and Biochemistry*, *127*, 280–285. https://doi.org/10.1016/j.soilbio.2018.09.033

Görres, C. M., Conrad, R., & Petersen, S. O. (2013). Effect of soil properties and hydrology on archaeal community composition in three temperate grasslands on peat. *FEMS Microbiology Ecology*, *85*(2), 227–240. https://doi.org/10.1111/1574-6941.12115

Guo, Y. R., He, X. Z., Hou, F. J., & Ren, J. Z. (2020). Stocking rate affects plant community structure and reproductive strategies of a desirable and an undesirable grass species in an alpine steppe, Qilian Mountains, China. *The Rangeland Journal*, *42*, 63–69. https://doi.org/10.1071/RJ19080

Han, M. G., & Zhu, B. (2020). Changes in soil greenhouse gas fluxes by land use change from primary forest. *Global Change Biology*, *26*(4), 2656–2667. https://doi.org/10.1111/gcb.14993

Jacotot, A., Marchand, C., & Allenbach, M. (2018). Biofilm and temperature controls on greenhouse gas (CO_2 and CH_4) emissions from a rhizophora mangrove soil (New Caledonia). *Science of the Total Environment*, *650*, 1019–1028. https://doi.org/10.1016/j.scitotenv.2018.09.093

Jian, J., Steele, M. K., Thomas, Q., Day, S. D., & Hodges, S. C. (2018). Constraining estimates of global soil respiration by quantifying sources of variability. *Global Change Biology*, *24*, 4143–4159. https://doi.org/10.1111/gcb.14301

Li, X. C., Wang, Z. N., Wang, D. L., Wang, L., Pan, D. F., Li, J., De, K. J., & Seastelt, T. R. (2019). Livestock grazing impacts on plateau pika (*Ochotona curzoniae*) vary by species identity. *Agriculture Ecosystems & Environment*, *275*, 23–31. https://doi.org/10.1016/j.agee.2019.01.007

Liang, D., Guo, J., Hou, F., & Bowatte, S. (2021). High level of conservation and diversity among the endophytic seed bacteriome in eight alpine grassland species growing at the Qinghai Tibetan plateau. *FEMS Microbiology Ecology*, *97*(6), fiab060. https://doi.org/10.1093/femsec/fiab060

Lin, X., Wang, S., Ma, X., Xu, G., Luo, C., Li, Y., Jiang, G., & Xie, Z. (2009). Fluxes of CO_2, CH_4, and N_2O in an alpine meadow affected by yak excreta on the Qinghai-Tibetan Plateau during summer grazing periods. *Soil Biology & Biochemistry*, *41*(4), 718–725. https://doi.org/10.1016/j.soilbio.2009.01.007

Liu, Y. S., Fan, J. W., Harris, W., Shao, Q. Q., Zhou, Y. C., Wang, N., & Li, Y. Z. (2013). Effects of plateau pika (*Ochotona curzoniae*) on net ecosystem carbon exchange of grassland in the three rivers headwaters region, Qinghai-Tibet, China. *Plant and Soil*, *366*(1), 491–504. https://doi.org/10.1007/s11104-012-1442-x

Liu, M., He, W., Zhang, Z. C., Sun, J., Cong, N., Nie, X. W., Wang, Y. F., Zhang, L., Yang, B., Chen, Y. C., Zhou, H. K., Shao, X. Q., & Wang, Y. X. (2022). Mutual feedback between above- and below-ground controls the restoration of alpine ecosystem multifunctionality in long-term grazing exclusion. *Journal of Cleaner Production*, *333*, 130184. https://doi.org/10.1016/j.jclepro.2021.130184

Liu, Y., Yan, C. Y., Matthew, C., Wood, B., & Hou, F. J. (2017). Key sources and seasonal dynamics of greenhouse gas fluxes from yak grazing systems on the Qinghai-Tibetan Plateau. *Scientific Reports*, *7*, 40857. https://doi.org/10.1038/srep40857

Lubbers, I. M., Van Groenigen, K. J., Fonte, S. J., Six, J., Brussaard, L., & Van Groenigen, J. W. (2013). Greenhouse-gas emissions from soils increased by earthworms. *Nature Climate Change*, *3*(3), 187–194. https://doi.org/10.1038/NCLIMATE1692

Luo, C. Y., Wang, S. P., Zhang, L. R., Wilkes, A., Zhao, L., Xu, S. X., & Xu, B. (2020). CO_2, CH_4 and N_2O fluxes in an alpine meadow on the Tibetan Plateau as affected by N-addition and grazing exclusion. *Nutrient Cycling in Agroecosystems*, *117*, 29–42. https://doi.org/10.1007/s10705-020-10062-0

Ma, Z., Shrestha, B. M., Bork, E. W., Chang, S. X., Carlyle, C. N., Döbert, T. F., Sobrinhoa, L. S., & Boyce, M. S. (2021). Soil greenhouse gas emissions and grazing management in northern temperate grasslands. *Science of the Total Environment*, *796*, 148975. https://doi.org/10.1016/j.scitotenv.2021.148975

Maljanen, M., Martikkala, M., Koponen, H. T., Virkajärvi, P., & Martikainen, & P. J. (2007). Fluxes of nitrous oxide and nitric oxide from experimental excreta patches in Boreal agricultural soil. *Soil Biology and Biochemistry*, *39*(4), 914–920. https://doi.org/10.1016/j.soilbio.2006.11.001

Martínez-Estévez, L., Balvanera, P., Pacheco, J., & Ceballos, G. (2013). Prairie dog decline reduces the supply of ecosystem services and leads to desertification of semiarid grasslands. *PLoS One*, *8*(10), e75229. https://doi.org/10.1371/journal.pone.0075229

Pang, X. P., Wang, Q., Zhang, J., Xu, H. P., & Guo, Z. G. (2020). Responses of soil inorganic and organic carbon stocks of alpine meadows to the disturbance by plateau pikas. *European Journal of Soil Science*, *71*(4), 706–715. https://doi.org/10.1111/ejss.12895

Pang, X. P., Yang, H., Wei, X. X., & Guo, Z. G. (2021). Effect of plateau pika (*Ochotona curzoniae*) bioturbation on soil C:N:P stoichiometry in alpine meadows. *Geoderma*, *397*, 115098. https://doi.org/10.1016/j.geoderma.2021.115098

Pech, R. P., Arthur, A. D., Zhang, Y. M., & Lin, H. (2007). Population dynamics and responses to management of plateau pikas *Ochotona curzoniae*. *Journal of Applied Ecology*, *44*, 615–624. https://doi.org/10.1111/j.1365-2664.2007.01287.x

Pelster, D. E., Gisore, B., Goopy, J., Korir, D., Koske, J. K., Rufino, M. C., & Butterbach-Bahl, K. (2016). Methane and nitrous oxide emissions from cattle excreta on an East African grassland. *Journal of Environmental Quality*, *45*(5), 1531–1539. https://doi.org/10.2134/jeq2016.02.0050

Peng, F., You, Q., Xue, X., Guo, J., & Wang, T. (2015). Effects of rodent-induced land degradation on ecosystem carbon fluxes in alpine meadow in the Qinghai-Tibet Plateau, China. *Solid Earth*, *6*(1), 303–310. https://doi.org/10.5194/se-6-303-2015

Qin, Y., Chen, J., & Yi, S. (2015). Plateau pikas burrowing activity accelerates ecosystem carbon emission from alpine grassland on the Qinghai-Tibetan plateau. *Ecological Engineering*, *84*, 287–291. https://doi.org/10.1016/j.ecoleng.2015.09.012

Qin, Y., Huang, B., Zhang, W., Yu, Y., Yi, S., & Sun, Y. (2021). Pikas burrowing activity promotes vegetation species diversity in alpine grasslands on the Qinghai-Tibetan Plateau. *Global Ecology and Conservation*, *31*, e01806. https://doi.org/10.1016/j.gecco.2021.e01806

Qin, Y., Sun, Y., Zhang, W., Qin, Y., Chen, J. J., Wang, Z. W., & Zhou, Z. H. (2020). Species monitoring using unmanned aerial vehicle to reveal the ecological role of plateau pika in maintaining vegetation diversity on the northeastern Qinghai-Tibetan plateau. *Remote Sensing*, *12*, 2480. https://doi.org/10.3390/rs12152480

Smith, A. T. (2008). The world of pikas. In P. C. Alves, N. Ferrand, & K. Hackländer (Eds.), *Lagomorph biology: Evolution, ecology, and conservation* (pp. 89–102). Berlin, Heidelberg: Springer Verlag.

Smith, A. T., Badingqiuying, W.,. M. C., & Hogan, B. W. (2019). Functional-trait ecology of the plateau pika *Ochotona curzoniae* in the Qinghai-Tibetan Plateau ecosystem. *Integrative Zoology*, *14*(1), 87–103. https://doi.org/10.1111/1749-4877.12300

Speakman, J. R., Chi, Q., Ołdakowski, Ł., Fu, H., Fletcher, Q. E., Hambly, C., Togo, J., Liu, X., Piertney, S. B., Wang, X., Zhang, L., Redman, P., Wang, L., Tang, G., Li, L., Cui, J., Thomson, P. J., Wang, Z., Glover, P., … Wang, D. (2021). Surviving winter on the Qinghai-Tibetan Plateau: Pikas suppress energy demands and exploit yak feces to survive winter. *Proceedings of the National Academy of Sciences*, *118*(30), e2100707118. https://doi.org/10.1073/pnas.2100707118

Sperow, M. (2020). Updated potential soil carbon sequestration rates on US agricultural land based on the 2019 IPCC guidelines. *Soil and Tillage Research*, *204*, 104719. https://doi.org/10.1016/j.still.2020.104719

Su, J. H., Nan, Z. B., & Ji, W. H. (2016). Effects of livestock grazing on rodents in grassland ecosystems. *Acta Prataculturae Sinica*, *25*, 136–148 (In Chinese). https://doi.org/10.11686/cyxb2015587

Sun, Y., Angerer, J. P., & Hou, F. J. (2015). Effects of grazing systems on herbage mass and liveweight gain of Tibetan sheep in eastern Qinghai-Tibetan Plateau, China. *Rangeland Journal*, *37*, 181–190. https://doi.org/10.1071/RJ14062

Tang, R., Du, Z., Zhu, G., Fang, Y., El-Naggar, A., Singh, B. P., Cai, Y. J., & Chang, S. X. (2021). Yak dung pat fragmentation decreases yield-scaled growing-season nitrous oxide emissions in an alpine steppe on the Qinghai-Tibetan Plateau. *Biology and Fertility of Soils*, *57*(8), 1103–1115. https://doi.org/10.1007/s00374-021-01601-0

Tchabovsky, A. V., Savinetskaya, L. E., Surkova, E. N., Ovchinnikova, N. L., & Kshnyasev, I. A. (2016). Delayed threshold response of a rodent population to human-induced landscape change. *Oecologia*, *182*(4), 1075–1082. https://doi.org/10.1007/s00442-016-3736-9

Thilakarathna, S. K., & Hernandez-Ramirez, G. (2021). Primings of soil organic matter and denitrification mediate the effects of moisture on nitrous oxide production. *Soil Biology and Biochemistry*, *155*, 108166. https://doi.org/10.1016/j.soilbio.2021.108166

Wang, L., Ma, J. G., Bowatte, S. M., Hoogendoorn, C., & Hou, F. J. (2021). Evidence of differences in nitrous oxide emissions and biological nitrification inhibition among elymus grass species. *Biology and Fertility of Soils*, *334*, 1–9. https://doi.org/10.1007/s00374-021-01592-y

Wang, Q., Pang, X. P., & Guo, Z. G. (2022). Small semi-fossorial herbivores affect the allocation of above-and below-ground plant biomass in alpine meadows. *Frontiers in Plant Science*, *13*, 830856. https://doi.org/10.3389/fpls.2022.830856

Wang, Y. X., Yuan, H., Zhang, X. L., Sun, Y., & Hou, F. J. (2019). Tibetan sheep grazing modifies rodent density and their interactions effect on GHG emissions of alpine meadow. *Scientific Reports*, *9*(1), 17066. https://doi.org/10.1038/s41598-019-53480-z

Wang, Y. X., Zhang, X. L., Chang, S. H., Wang, Z. F., & Sun, Y. (2020). Pika burrow and *zokor* mound density and their relationship with grazing management and sheep production in alpine meadow. *Ecosphere*, *11*(5), e03088. https://doi.org/10.1002/ecs2.3088

Wei, J., Chen, C. H., Wang, J. Y., & Wen, X. F. (2020). Theory, hypothesis, and application advance in chamber-based technology and methods for flux measurement. *Chinese Journal of Plant Ecology*, *44*, 318–329. https://doi.org/10.17521/cjpe.2019.0201

Xu, Y., Wan, S., Cheng, W., & Li, L. (2008). Impacts of grazing intensity on denitrification and N_2O production in a semi-arid grassland ecosystem. *Biogeochemistry*, *88*(2), 103–115. https://doi.org/10.1007/s10533-008-9197-4

You, Y., Ren, J., Wu, J., Ma, Z., Gu, Y., Wang, Y., & Hou, F. (2021). Forage taste agents modifying yak grazing decrease soil microbial diversity in alpine meadow. *Applied Soil Ecology*, *168*, 104160. https://doi.org/10.1016/j.apsoil.2021.104160

Yu, C., Zhang, J., Pang, X. P., Wang, Q., Zhou, Y. P., & Guo, Z. G. (2017). Soil disturbance and disturbance intensity: Response of soil nutrient concentrations of alpine meadow to plateau pika bioturbation in the Qinghai-Tibetan Plateau, China. *Geoderma*, *307*, 98–106. https://doi.org/10.1016/j.geoderma.2017.07.041

Yuan, X., Qin, W., Chen, Y., Xu, T., Chen, K., & Zhu, B. (2021). Plateau pika offsets the positive effects of warming on soil organic carbon in an alpine swamp meadow on the Tibetan Plateau. *Catena*, *204*, 105417. https://doi.org/10.1016/j.catena.2021.105417

Zhang, W., Liu, C. Y., Zheng, X. H., Fu, Y. F., Hu, X. X., Cao, G. M., & Butterbach-Bahl, K. (2014). The increasing distribution area of zokor mounds weaken greenhouse gas uptakes by alpine meadows in the Qinghai-Tibetan Plateau. *Soil Biology and Biochemistry*, *71*, 105–112. https://doi.org/10.1016/j.soilbio.2014.01.005

Zhang, W. N., Wang, Q., Zhang, J., Pang, X. P., & Guo, Z. G. (2020). Clipping by plateau pikas and impacts to plant community. *Rangeland Ecology & Management.*, *73*(3), 368–374. https://doi.org/10.1016/j.rama.2020.01.010

Zhang, J. C., Xu, Y. Q., & Lu, Y. H. (2015). Microbial mechanisms of methane production and oxidation in terrestrial ecosystems. *Acta Ecologica Sinica*, *35*(20), 6592–6603. https://doi.org/10.5846/stxb201507091459

Zhao, J. X., Tian, L. H., Wei, H. X., Zhang, T., Bai, Y. F., Li, R. C., & Tang, Y. H. (2019). Impact of plateau pika (*Ochotona curzoniae*) burrowing-induced microtopography on ecosystem respiration of the alpine meadow and steppe on the Tibetan Plateau. *Plant and Soil*, *458*, 217–230. https://doi.org/10.1007/s11104-019-04122-w

Zhou, Y., Jing, L., Jiao, S. W., Chen, A. P., Li, N. N., Lei, J.,. L., Yang, M., Jia, Y. F., & Lu, C. (2020). Dynamics of greenhouse gas emission induced by different burrowing activities of fossorial vertebrates in the Qinghai-Tibetan Plateau alpine meadow ecosystem. *International Journal of Biometeorology*, *64*(1), 115–122. https://doi.org/10.1007/s00484-019-01802-1

Zhu, X., Luo, C., Wang, S., Zhang, Z., Cui, S., Bao, X., & Zhou, Y. (2015). Effects of warming, grazing/cutting and nitrogen fertilization on greenhouse gas fluxes during growing seasons in an alpine meadow on the Tibetan Plateau. *Agricultural and Forest Meteorology*, *214*, 506–514. https://doi.org/10.1016/j.agrformet.2015.09.008

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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