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Methane emissions in grazing systems in grassland regions of China: A synthesis

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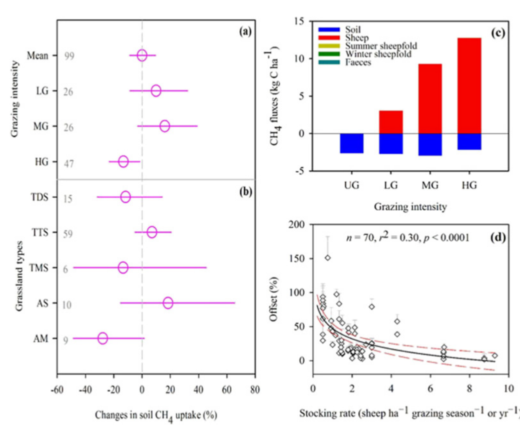
HIGHLIGHTS

- Changes in soil CH_4 uptake depend on grazing intensity.
- The CH_4 uptake by grassland soils could offset the CH_4 emissions.
- Regulating the stocking rate in grasslands might help mitigate CH_4 emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of grazing on methane (CH_4) budgets are important for understanding the balance of greenhouse gas emissions and removals in grassland ecosystems. However, the CH_4 budgets of grazing systems, that is simultaneously considering CH_4 uptake by grassland soils and emissions from ruminant enteric fermentation, livestock folds and animal feces, are poorly investigated, particularly for Chinese grasslands, and thus, remained unclear currently. Here, a synthesis of 43 individual studies was carried out to assess the grazing season/annual CH_4 budgets and their responses to grazing in grassland ecosystems of China. The results showed that heavy grazing (HG) significantly decreased, while light grazing (LG) and moderate grazing (MG) had no significant effects soil CH_4 uptake, as compared to un-grazing sites. Grazing has shifted Chinese grasslands from a sink to source for atmospheric CH_4, and the grazing season/annual CH_4 budgets increased with increasing grazing intensity, while the offset of CH_4 uptake by grassland soils to total CH_4 emissions from sheep, sheepfolds and feces were exponentially decreased with increasing grazing intensity. Moreover, the herbage biomass (HBM), organic matter intake (OMI) and live weight gain (LWG) were decreased while CH_4 emission intensities (i.e., CH_4 emission per HBM, OMI, and LWG) were linearly increased with increasing grazing intensity. Our results demonstrate that mediating grazing intensity, e.g., from HG to LG, could yield the optimal balance between maintaining productive grasslands

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and meanwhile mitigating CH_4 emissions. This study could help for building strategies with implications for grassland management in China with similar CH_4 emission problems.

1. Introduction

Grassland ecosystems play a considerable role in affecting methane (CH_4) sources or sinks (Wang et al., 2009; Wang et al., 2014a; Wang et al., 2014b). Anthropogenic CH_4 sources include livestock enteric fermentation, sheepfolds and feces (Chen et al., 2011a; Dumortier et al., 2017; Liu et al., 2009a). CH_4 also is eliminated from the atmosphere by grassland soils due to microbial oxidation by methanotrophs (Conrad, 2009; Zhou et al., 2008). Anthropogenic CH_4 emissions contribute to 50–65% of the total CH_4 emissions (Stocker et al., 2013), and 25% of this amount is caused by the domestic ruminants (Ghosh et al., 2015). High-intensity ruminant grazing may shift the grassland ecosystems from CH_4 sinks to sources (Wang et al., 2009) and thus, playing a critical role in global CH_4 budgets. However, numerous studies have mainly focused on soil CH_4 uptake in grassland grazing systems (Chen et al., 2010; Holst et al., 2008; Tang et al., 2013), but CH_4 emissions from ruminant enteric fermentation, livestock folds and animal feces have seldomly been considered alongside soil CH_4 uptake, making it difficult to holistically evaluate the total CH_4 budgets for grazing system in Eurasian grasslands (Wang et al., 2015). Consequently, understanding these processes is crucial to recognize the sources and sinks of CH_4 and contribute to better mitigate anthropogenic CH_4 emissions in grasslands.

China's grasslands, covering approximately 40% of land area and accounting for about 6–8% of the total world grassland area, mainly consisting of temperate grasslands and alpine grasslands (Chen and Wang, 2000). Given their large surface areas, changes in Chinese grasslands may have significant impacts on the regional balance of CH_4 emissions and removals. During the past several decades, an unprecedented increase in grazing pressure has led to severe grassland degradations in China, which have significant reduced soil CH_4 uptake (Chen et al., 2011b; Tang et al., 2013; Wang et al., 2014b), while simultaneously increased CH_4 emissions from livestock grazing system across these regions (Liu et al., 2009a; Soussana et al., 2007; Wang et al., 2014a; Zhang et al., 2015). Grazing affects both the soil CH_4 uptake and CH_4 emissions of ruminants mainly through grazing intensity (Soussana et al., 2007). However, changes in CH_4 uptake by grassland soils and in CH_4 emissions from grazing livestock may be partially offset (the ratio of soil CH_4 uptake by grassland to total emission from sheep, sheepfolds and feces) in grazed systems, but their net balance remains unclear under different grazing intensities.

The improvements of productivity for animals and grasslands and, meanwhile mitigation their greenhouse gas emissions are two key components for the sustainable management of grazing grasslands (Zhang et al., 2015). Optimizing the interaction between these two key components is a significant challenge that needs to be considered. Overgrazing reduces the plant and animal productivity in grassland ecosystems and meanwhile, increases animal CH_4 emissions due to increased grazing intensity. High grazing intensity could lead to a decrease in the organic matter digestibility of forage ingested by livestock, which can decrease livestock performance (e.g., less organic matter intake and live weight gain) while increase CH_4 emission intensity from grazing livestock (i.e., in terms of CH_4 emission per unit of organic matter intake or live weight gain) (Wang et al., 2014b). Moreover, increase in grazing intensity also can significantly increase CH_4 emission intensity under heavy grazing compared to light and moderate grazing (Ma et al., 2018a). Therefore, optimizing the stocking rates are required to benefit utilization of natural grassland resources. However, decreases in grazing intensity (i.e., reducing livestock numbers) to improve grassland ecosystems may be detrimental to the household incomes for local farmers (David et al., 2013; Zhang et al., 2015). Currently, there is an increasing requirement for the environmentally friendly managing natural resources in China, in which optimizing grazing intensity for natural grasslands is one of the fundamental issues. Therefore, it is critically important for making balances among the grazing intensity, improving production yields, and simultaneously mitigating CH_4 emissions in grazing systems. However, this issue has rarely been examined in previous studies.

Here, we performed a synthesis of 43 grazing experiments across grasslands of China (Supplementary S1), in order to reveal the general response patterns of soil CH_4 uptake, the emissions of CH_4 from sheep enteric fermentation, livestock sheepfolds and feces under different grazing intensities and, then to evaluate the CH_4 budgets in grassland grazing systems. Moreover, we also used two case studies for typical steppes in the Inner Mongolian and agro-pastoral region of China to explore the optimal solutions for animal productivity improvement and CH_4 emission mitigation. We addressed the following questions: 1) how does grazing affect CH_4 budgets (soil CH_4 uptake and CH_4 emissions of ruminant enteric, livestock sheepfolds and feces) in the grassland ecosystems of China? 2) Do relationships between stocking rates and livestock performance or herbage biomass exist, and are they compatible with CH_4 emissions from grazing systems?

2. Materials and methods

2.1. Data compilation

To identify relevant studies regarding the effect of grazing on CH_4 uptake or emissions on grassland ecosystems in China, we conducted a comprehensive search of the Web of Science and the Chinese Magazine Network (CNKI) database (before 2018). The following criteria were applied to include appropriate studies. (1) Only field experiments initiating CH_4 flux measurements under different grazing intensities and un-grazing (fencing) were involved in this study; (2) The simulated grazing experiments (e.g. mowing and trampling studies) were eliminated; (3) CH_4 flux values should be explicitly indicated by their means, standard deviations (SD), standard errors (SE), and sample sizes (n); (4) Grazing intensity, soil fluxes measurement period, animals and grassland type are described clearly. These searches resulted in over 43 papers that studied CH_4 dynamics across the Chines grasslands (Fig. 1, Supplementary S1). For soil CH_4 flux, the preferred unit was flux per unit area per year (kg ha^{-1} yr^{-1}), and thus, all other flux units (e.g., μg m^{-2} h^{-1}, mg m^{-2} d^{-1}) were converted to this value. Data were taken directly from tables in the available literatures, otherwise, they were extracted from figures using graph data extractor software (Graph Data Extractor by Dr. A J Matthews).

2.2. CH_4 budget estimation

To calculate the grazing season/annual CH_4 budgets in grassland ecosystems, we considered only the direct exchanges of CH_4 between grazing systems and the atmosphere (i.e., including the CH_4 uptake by soils and CH_4 emissions from sheep, sheepfolds, and feces). If some studies focus on the other animals such as cattle, goat or dairy cows, we converted their stocking rates to the standardized sheep unit (sheep ha^{-1} yr^{-1}) according the conversion coefficients provided by Yang and Yang (2000), and Liu et al. (2009b). Gaussian random error propagation theory was adopted to calculate the uncertainties (SD/SE) of each part (i.e., CH_4 emissions from sheep, sheepfolds, and feces) and their contributions to the total CH_4 budgets (Ma et al., 2018a; Schönbach et al., 2012). We merged the CH_4 emission factors (EF) of sheep, i.e., the CH_4 emission coefficients of summer sheepfolds (SS), winter sheepfolds (WS) and feces of grazed grasslands in China, from peer-reviewed publications (EF data of different grassland types are listed in the Supplementary S2). Then, we applied the following equations to calculate grazing season/annual CH_4 emissions from sheep, sheepfolds and feces under different stocking rates (SRs) according to Ma et al. (2018a).

In this study, sheep enteric CH_4 emissions were estimated using the averaged EFs 10.3 ± 1.9, 9.2 ± 2.4, and 8.7 ± 2.8 (mean ± SE) kg CH_4–C sheep^{-1} yr^{-1} in LG, MG and HG sites for temperate grasslands (i.e., desert, typical, and meadow steppes), respectively. These EFs under different grazing intensities were collected from previous studies in temperate typical steppes of northern China (Liu et al., 2009a; Schönbach et al., 2012; Wang et al., 2015) (details please see Supplementary S2). We assumed that sheep (with different varieties and live weights) that grazed under the same grazing intensity in different grassland types (e.g., temperate desert, typical, or meadow steppes) shared same EF as no data was available for temperate desert and meadow steppes in China. For alpine grasslands, however, we did not find the matched data under different grazing intensities in alpine grasslands (i.e., alpine steppes and meadows) due to lacking measurements, thus we estimated livestock CH_4 emission using the EF 4.9 ± 0.1 (mean ± SE) kg CH_4–C sheep^{-1} yr^{-1} in alpine grasslands. Undoubtedly, these abovementioned assumptions may cause some uncertainties for our analysis, suggesting that much more research is needed to clarify the spatial patterns of EFs under different grazing intensities across different grassland types in Chinese grassland ecosystems.

To the best of our knowledge, only two studies have quantified CH_4 emissions from sheepfolds in temperate typical steppes of northern China (Liu et al., 2009a; Chen et al., 2011a). In this study, CH_4 emissions from summer sheepfolds (SS) and winter sheepfolds (WS) were estimated using the values 59.39 ± 14.72 kg CH_4–C ha^{-1} yr^{-1} (abbreviated as A) (Liu et al., 2009a) and 2.10 ± 3.15 kg CH_4–C ha^{-1} yr^{-1} (abbreviated as B) (Chen et al., 2011a) for all grassland types (including temperate and alpine grasslands) in China, which also may induce some uncertainties in our analysis, highlighting the importance of conducting more research to clarify the spatial patterns of CH_4 emissions from sheepfolds under different grassland types in different regions. For the temperate grassland types, the CH_4 emissions from feces were estimated using a value of 11.03 ± 3.07 mg CH_4–C sheep^{-1} day^{-1} (abbreviated as C) reported by Wang et al. (2013). For the alpine grassland types, the CH_4 emissions from feces were estimated by combining the value of 0.0162 ± 0.0018 kg CH_4–C ha^{-1} day^{-1} kg^{-1} for manure dry

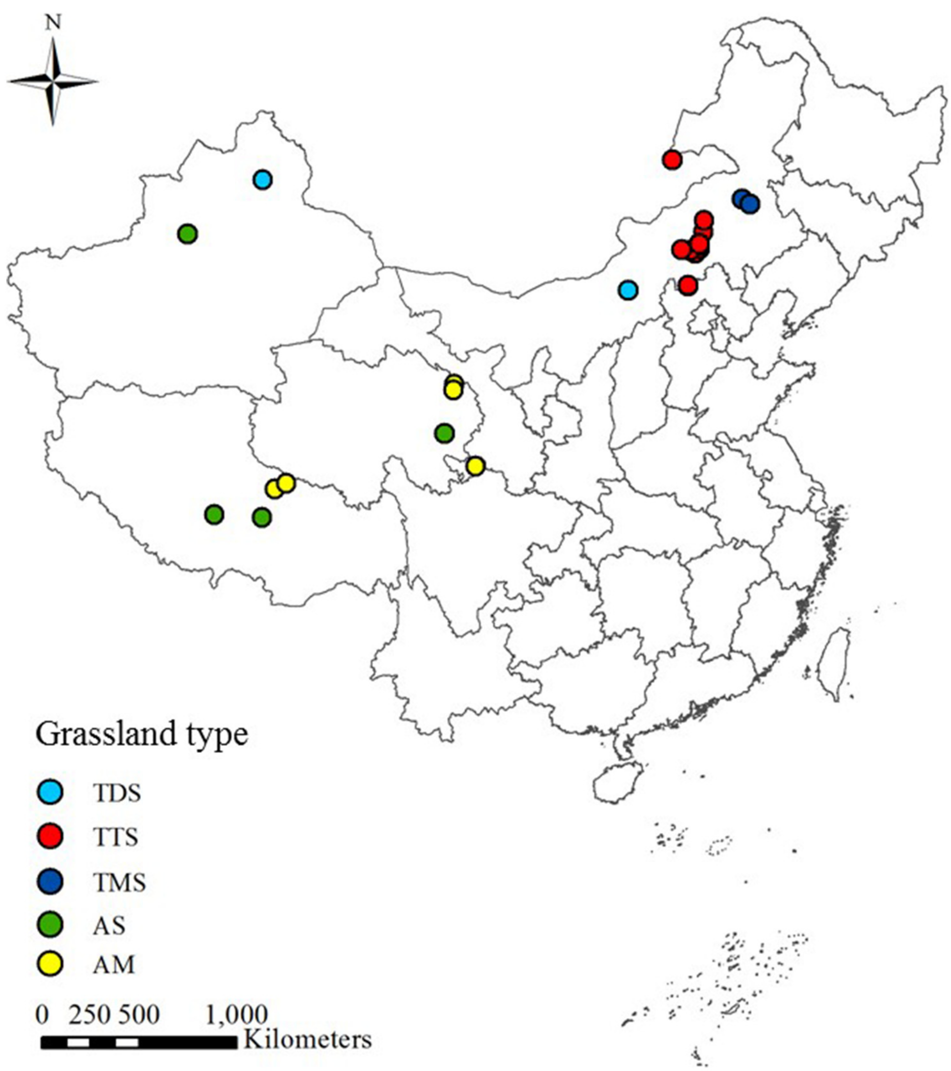

Fig. 1. Spatial distribution of methane (CH_4) flux measurements for grazing experiments involved in this study. The different color dots in the map represent the grassland types. TDS, TTS, TMS, AS and AM are the abbreviations of temperate desert steppe, temperate typical steppe and temperate meadow steppe, alpine steppe and alpine meadow, respectively.

weight (abbreviated as D) (Cai et al., 2013; Ge et al., 2014) and the value of 0.54 ± 0.02 kg day^{-1} (abbreviated as E) for daily produced dry dung (Feng et al., 2005). The following equations were used to calculate the grazing season/annual CH_4 emissions from sheep, SS, WS and feces:

$$Sheep_{CH_4} = EF \times SR \quad (1)$$

$$Sheep_{CH_4SE} = EF_{SE} \times SR \quad (2)$$

$$SS_{CH_4} = (24 \times A \times \text{sheepfold area} \times \text{grazing days}) \quad (3)$$

$$SS_{CH_4\ SE} = (24 \times ASE \times \text{sheepfold area} \times \text{grazing days}) \quad (4)$$

$$WS_{CH_4} = (24 \times B \times \text{sheepfold area} \times \text{feeding days}) \quad (5)$$

$$WS_{CH_4\ SE} = (24 \times BSE \times \text{sheepfold area} \times \text{feeding days}) \quad (6)$$

$$Feces_{temperate\ CH_4} = (C \times SR \times \text{grazing days})/106 \quad (7)$$

$$Feces_{temperate\ CH_4SE} = (CSE \times SR \times \text{grazing days})/106 \quad (8)$$

$$Feces_{alpine\ CH_4} = (D \times E \times SR \times \text{grazing days})/(365 \times 106) \quad (9)$$

$$Feces_{alpine\ CH_4SE} = \left(\sqrt{\left(D2 \times E_{CH_4\ SE}{}^2 + E2 \times D_{CH_4\ SE}{}^2\right)} \times \text{grazing days}\right) / \left(365 \times 10^6\right) \quad (10)$$

$$T_{CH_4} = Soil_{CH_4} + Sheep_{CH_4} + SS_{CH_4} + WS_{CH_4} + Feces_{CH_4} \quad (11)$$

$$T_{CH_4SE} = \sqrt{Soil_{CH_4\ SE}{}^2 + Sheep_{CH_4\ SE}{}^2 + SS_{CH_4SE}{}^2 + WS_{CH_4\ SE}{}^2 + Feces_{CH_4\ SE}{}^2} \quad (12)$$

where EF is the sheep CH_4 emission factor (kg CH_4–C $sheep^{-1}$ yr^{-1}), SR is the stocking rate (sheep unit ha^{-1} grazing $season^{-1}$ or yr^{-1}), and EF_{SE} (kg CH_4–C $sheep^{-1}$ yr^{-1}) is the standard error of EF. SS_{CH_4} and WS_{CH_4} denoting sheepfold CH_4 emissions during the summer and winter seasons, respectively. $Feces_{temperate\ CH_4}$ and $Feces_{alpine\ CH_4}$denoting feces CH_4 emissions (kg CH_4–C ha^{-1}) during the grazing periods in temperate and alpine regions, respectively. The values 24, 365 and 10^6 are the conversion coefficients to convert hours to days, years to days, and milligrams (mg) to kilograms (kg) respectively. T_{CH_4} and T_{CH_4SE} denoting grazing season/annual CH_4 budgets (kg CH_4–C ha^{-1}) and their uncertainties, respectively. Negative and positive values for CH_4 fluxes indicated CH_4 sink and source, respectively.

In addition, relevant experimental information was also collected, including grazing intensity, grassland type, grazing duration, mean annual precipitation (MAP) and mean annual temperature (MAT). To explore the CH_4 emission intensity (i.e., CH_4 emission from per unit of plant productivity or animal performance), we collected grassland herbage mass (HBM), live weight gain (LWG), and organic matter intake (OMI) for different grazing treatments from two long-term grazing experiments in China (Glindemann et al., 2009; Schönbach et al., 2012; Ma et al., 2014; Wang et al., 2015). Due to large variations in the grassland types (i.e., temperate desert, typical, and meadow steppes and alpine meadow and steppe) and productivities, the stocking rates were grassland type-dependent across Chinese grasslands. In this study, we characterized grazing intensity as un-grazing (UG), light grazing (LG), moderate grazing (MG) and heavy grazing (HG) based on the authors8 qualitative classification from the original papers.

2.3. Statistical analyses

We used the natural log of response ratio (lnRR) to analyze the changes in soil CH_4 fluxes estimated as $\ln(RR) = \ln(X_{grazing}/X_{control})$, where $X_{grazing}$ and $X_{control}$ denoting soil CH_4 fluxes in grazed and control plots, respectively. We analyzed the weighted ln(RR) means of the examined soil CH_4 uptake and their 95% confidence intervals (CIs) at overall level using MetaWin 2.1 software (Sinauer Associates Inc., Sunderland, MA, USA). If 95% CI cover zero, it implies no significant impact by grazing treatment. The percentage changes of soil CH_4 uptake were calculated on the basis of $[e^{(\text{weighted } \ln(RR))} - 1] \times 100\%$. A nonlinear regression analysis was conducted to investigate the relationships between the offset value and SR. Moreover, the linear regression analysis was conducted to investigate the relationships between SR and sheep CH_4 emission intensity (i.e., CH_4 emission per HBM, OMI, and LWG). The regression analyses were performed with R i386 3.3.1 (R Development Core Team). Data were expressed as mean ± 1 standard error (SE) without explanation note.

3. Results

3.1. Effects of grazing on the soil CH_4 uptake

Overall, the grassland soils functioned as sink for atmospheric CH_4 across different grazing intensities and grassland types (Table 1). Compared to UG, HG significantly reduced the soil CH_4 uptake (Fig. 2a), whereas LG and MG have no significant effect on it. However, there was no significantly difference for different grassland types under grazing (Fig. 2b).

3.2. The grazing season/annual CH_4 budgets of grazing systems

Livestock grazing system is composed by the soil, vegetation and livestock, in which these components frequently interacting with each other. Therefore, besides soil CH_4 uptake, we further analyzed the grazing-associated CH_4 emissions, e.g., emission from sheep, sheepfold and feces across the grassland grazing systems in China, in order to systematically evaluate the CH_4 budgets under different grazing intensities. For sheep CH_4 emission, it was increased with increasing grazing intensity for all grassland types (Table 1). Similarly, CH_4 emissions from summer and winter sheepfolds and feces were increased with increasing grazing intensity (Table 1). Taking the temperate typical steppes as an example, the annual sheep CH_4 emissions were 7.63, 12.73 and 25.41 kg CH_4–C ha^{-1} for LG, MG, and HG sites, respectively. The summer sheepfold emissions during the grazing periods were 0.0066, 0.0123and 0.0260 kg CH_4–C for LG, MG, and HG sites, respectively, and the winter emissions during the feeding periods were 0.0001, 0.0003 and 0.0005 kg CH_4–C for LG, MG, and HG sites, respectively. CH_4 emissions from feces were 0.0030, 0.0056 and 0.0117 kg CH_4–C for LG, MG, and HG sites, respectively (Table 1). By aggregating CH_4 uptake by grassland soils and emissions from sheep, sheepfold and feces for each type of grassland grazing system in China, we found that UG sites exclusively functioned as sinks for atmospheric CH_4, while that grazing has turned grassland from a net sink to net source for atmospheric CH_4, particularly for MG and HG (Table 1).

To better assess the grazing impacts on CH_4 emissions and removals for grassland grazing systems, we calculated the offset (%), i.e., the ratio of soil CH_4 uptake by grassland to total emission from sheep, sheepfolds and feces. Results showed that the offsets ranged from 7 ± 1 to 105 ± 19% across grassland types and grazing intensities, with mean offsets were 81 ± 7, 34 ± 2 and 29 ± 2% for LG, MG and HG, respectively (Table 1). Furthermore, our analysis showed that the offsets exhibited an exponentially decreasing trends with increasing stocking rate (SR) across all studied grasslands (Fig. 3). With increasing SR, the offsets showed a saturation response when SR exceeded 2–4 sheep ha^{-1} yr^{-1}. Compared to LG, MG and HG significantly reduced the offsets and thus, released substantial amounts of CH_4 into the atmosphere.

Table 1
Summary of CH_4 fluxes for soil (kg C ha^{-1} yr^{-1} or grazing season^{-1}), sheep (kg C ha^{-1} yr^{-1} or grazing season^{-1}), summer sheepfold (kg C ha^{-1} grazing season), winter sheepfold (kg C ha^{-1} feeding season), feces (kg C ha^{-1} grazing season) and CH_4 Budget (kg C ha^{-1} yr^{-1} or grazing season^{-1}) under different grazing intensities (GI) from grassland grazing systems across northern China (positive and negative values indicate CH_4 source and sink, respectively).

Grassland[a]	Grazing length	GI	Soil	Sheep	Summer sheepfold	Winter sheepfold	Feces	Budget	Offset (%)
TDS	Grazing season	UG	−3.83 ± 0.27					−3.83 ± 0.27	
		LG	−3.37 ± 0.21	2.76 ± 0.24	0.0017 ± 0.0001	0.0001 ± 0.0001	0.0008 ± 0.0001	0.34 ± 0.67	105 ± 19
		MG	−4.16 ± 0.47	6.77 ± 0.98	0.0062 ± 0.0006	0.0003 ± 0.0003	0.0028 ± 0.0006	3.60 ± 1.05	48 ± 8
		HG	−3.03 ± 0.27	9.19 ± 2.21	0.0093 ± 0.0010	0.0005 ± 0.0005	0.0042 ± 0.0008	7.15 ± 2.23	22 ± 6
TTS	Annual	UG	−2.73 ± 0.21					−2.73 ± 0.21	
		LG	−3.94 ± 0.08	7.63 ± 0.73	0.0066 ± 0.0005	0.0001 ± 0.0001	0.0030 ± 0.0004	3.71 ± 0.73	59 ± 6
		MG	−2.50 ± 0.27	12.73 ± 1.05	0.0123 ± 0.0006	0.0003 ± 0.0001	0.0056 ± 0.0005	10.25 ± 1.08	21 ± 3
		HG	−2.31 ± 0.33	25.41 ± 2.47	0.0260 ± 0.0011	0.0005 ± 0.0002	0.0117 ± 0.0010	23.14 ± 2.50	12 ± 1
TTS	Grazing season	UG	−2.15 ± 0.11					−2.15 ± 0.11	
		LG	−2.79 ± 0.12	3.88 ± 0.29	0.0018 ± 0.0001	0.0001 ± 0.0000	0.0013 ± 0.0002	1.72 ± 0.13	63 ± 7
		MG	−3.00 ± 0.21	11.71 ± 1.39	0.0063 ± 0.0005	0.0004 ± 0.0004	0.0046 ± 0.0006	9.48 ± 1.40	19 ± 3
		HG	−1.71 ± 0.10	21.23 ± 2.39	0.0124 ± 0.0004	0.0007 ± 0.0002	0.0088 ± 0.0008	19.64 ± 2.40	7 ± 1
TMS	Grazing season	UG	−2.16 ± 0.16					−2.16 ± 0.16	
		LG	−1.45 ± 0.27	2.14 ± 0.23	0.0008 ± 0.0001	0.0000 ± 0.0000	0.0008 ± 0.0001	1.22 ± 0.41	43 ± 17
		MG	−3.11 ± 0.13	NA	NA	NA	NA	NA	NA
		HG	−2.58 ± 0.24	NA	NA	NA	NA	NA	NA
AS	Annual	UG	−3.88 ± 0.39					−2.62 ± 0.08	
		HG	−4.68 ± 0.48	10.50 ± 0.06	0.0494 ± 0.0033	0.0009 ± 0.0007	0.0185 ± 0.0011	5.89 ± 0.49	44 ± 5
AS	Grazing season	UG	−2.19 ± 0.23					−2.19 ± 0.23	
		HG	−2.44 ± 0.25	6.04 ± 0.02	0.0284 ± 0.0013	0.0009 ± 0.0005	0.0185 ± 0.0007	3.16 ± 0.16	48 ± 3
AM	Grazing season	UG	−2.62 ± 0.08					−2.62 ± 0.08	
		LG	−2.74 ± 0.25	1.46 ± 0.02	0.0069 ± 0.0009	0.0005 ± 0.0008	0.0104 ± 0.0012	0.04 ± 0.11	97 ± 7
		MG	−1.59 ± 0.19	2.19 ± 0.02	0.0103 ± 0.0014	0.0008 ± 0.0012	0.0156 ± 0.0018	1.16 ± 0.08	48 ± 3
		HG	−2.20 ± 0.28	4.34 ± 0.27	0.0171 ± 0.0016	0.0013 ± 0.0014	0.0260 ± 0.0022	2.23 ± 0.34	43 ± 6

[a] TDS, TTS, TMS, AS, AM are the abbreviations of temperate desert steppe, temperate typical steppe, temperate meadow steppe, alpine steppe and alpine meadow, respectively. CH_4 emissions from sheep, sheepfold and feces were estimated on the basis of the emission factors (EF) that calculated from previous publications (details see in Supplementary S2). NA, not available.

3.3. Relationship between sheep CH_4 emissions and grassland and livestock productivities

According to our abovementioned results, we are keen to know how to improve the productivity of grassland grazing systems and meanwhile reducing their CH_4 emissions, that is, can we make trade-offs between enhancing grassland biomass, meat production and simultaneously mitigating CH_4 emissions. Thus, we reviewed literatures and found only 2 cases simultaneously measured sheep CH_4 emissions, grassland productivity (in terms of herbage biomass (HBM) at the end of the grazing season), and sheep productivity (in terms of daily organic matter intake (OMI) and live weight gain (LWG)) under different grazing intensities from temperate typical steppes in northern China. Results showed that daily sheep CH_4 emissions (g CH_4) were not statistically ($p < 0.05$) differed among different SR, though showing potential to be decreased with increasing SR (Fig. 4a). Across 2 cases, the daily sheep CH_4 emissions were linearly increased ($p < 0.01$) with increasing daily OMI (Fig. 4b), while exhibited no clear trend between daily sheep CH_4 emissions and daily LWG (Fig. 4c). As demonstrated in Fig. 5a–c, the HBM at the end of grazing season, daily OMI and LWG were linearly decreased with increasing SR for both 2 cases.

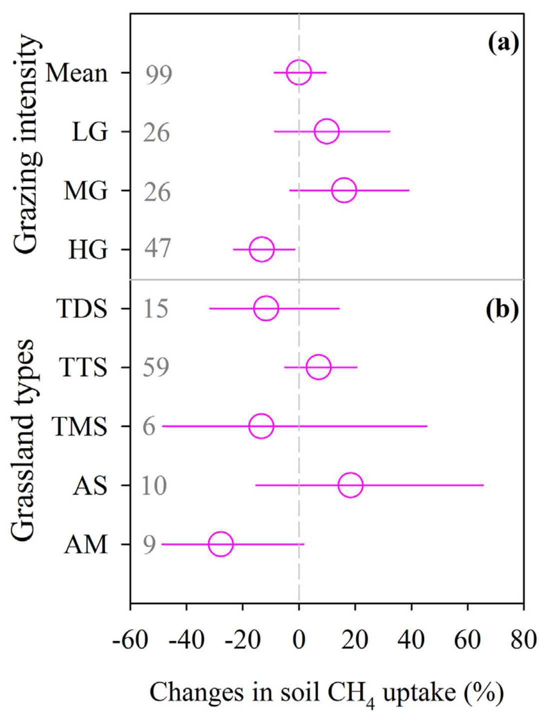

Fig. 2. Response of soil CH_4 uptake to grazing intensity (LG, light grazing; MG, moderate grazing; HG, heavy grazing) for all the grassland types (a) and grazing for each grassland type (TDS, temperate desert steppe; TTS, temperate typical steppe; TMS, temperate meadow steppe; AS, alpine steppe; AM, alpine meadow) (b) on soil CH_4 uptake. Circles represent mean weighted response ratios with their 95% confidence intervals (CI). The numbers represent the experimental observations for response variables. If the 95% CI does not cover the dash line, it indicates a significant impact by grazing intensity or grassland types.

As the metric of greenhouse gas emission intensity was increasingly utilized as a tool for acknowledging potential trade-offs between food (and meat, forage, and fuel) production and climate change mitigation (Van Groenigen et al., 2010; Yao et al., 2017; Ma et al., 2018b), we estimated the CH_4 emission intensities, i.e., CH_4 emission per HBM, OMI, and LWG (these parameters reflect the productivities of grasslands and sheep performance) (Glindemann et al., 2009; Ma et al., 2014). The estimated CH_4 emission intensities were 0.01–0.09 g CH_4 kg^{-1} HBM, 8.43–20.58 g CH_4 kg^{-1} OMI, and 0.17–0.50 g CH_4 kg^{-1} LWG, respectively, for all SRs (Fig. 5). For both 2 cases, the CH_4 emission intensities were linearly increased with increasing SR (Fig. 5).

4. Discussion

4.1. Effects of livestock grazing on CH_4 budgets

This study clearly shows the response patterns of CH_4 uptake by grassland soil, CH_4 emission from sheep, sheepfolds, and feces and CH_4 budgets to different grazing intensities. This is an important feature for evaluation the CH_4 emissions in grazing systems of grassland that individual studies have not revealed. Our results demonstrate that HG has a significant negative effect on CH_4 uptake by grassland soils, averagely,

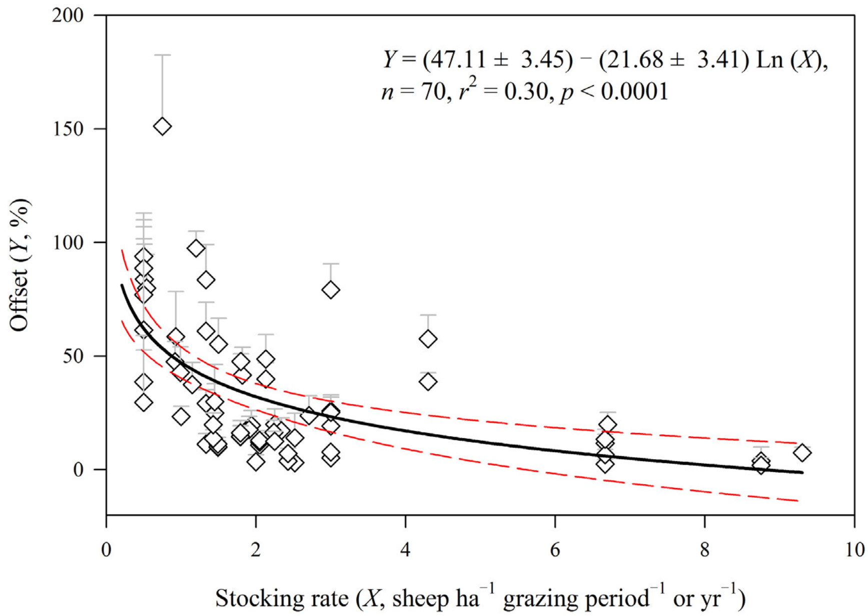

Fig. 3. Relationships of offset (%, the ratio of soil CH_4 uptake to the total emission from sheep, sheepfolds and feces) and stocking rates (SR, sheep ha^{-1} grazing $period^{-1}$ or yr^{-1}) across the Chinese grassland grazing systems. The coefficients and dashed lines indicate 95% confidence intervals.

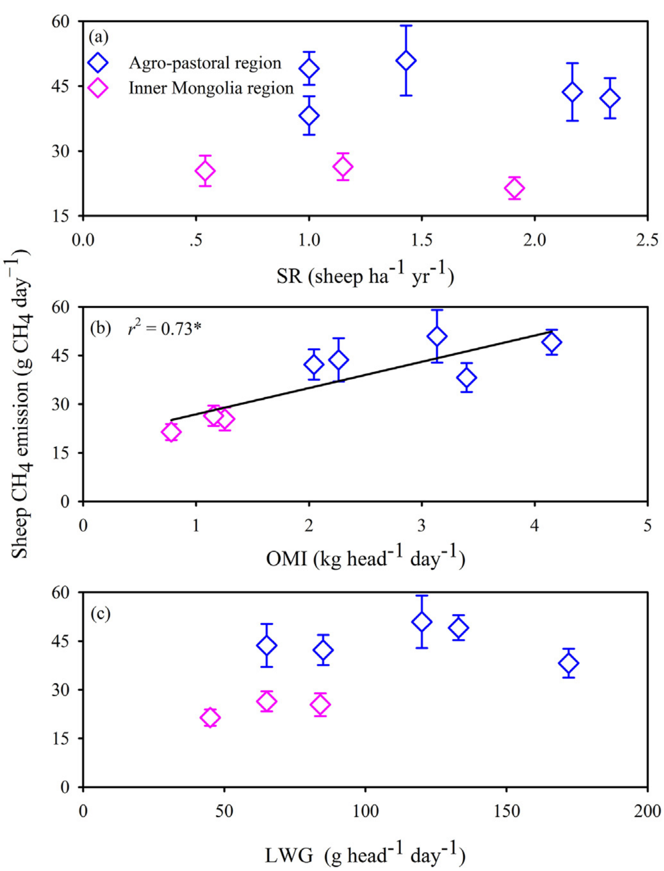

Fig. 4. Correlations of sheep CH_4 emission (g CH_4 day^{-1}) with stocking rate (SR, sheep unit ha^{-1} yr^{-1}) (a), organic matter intake (OMI, kg $sheep^{-1}$ day^{-1}) (b), and live weight gain (LWG, g $sheep^{-1}$ day^{-1}) (c) for typical steppes in agro-pastoral region (blue diamond) and Inner Mongolia region (pink diamond) of northern China, respectively. The datasets for OMI and LWG under different SR are collected from Glindemann et al. (2009) and Ma et al. (2014); datasets for sheep CH_4 emission under different SR are collected from Schönbach et al. (2012) and Wang et al. (2015), respectively. * and ** represent significance at the level of $p < 0.05$ and 0.01. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

decreased approximately 13.2% (95% CI: 24.2%–0.6%), as compared to UG sites. This result is consistent with previous studies (Chen et al., 2011b; Tang et al., 2013; Wang et al., 2014a, Wang et al., 2014b) across various grassland types in northern China. In a previous meta-analysis, we found that HG significantly decreased soil water content, aboveground biomass and meanwhile substantially increased soil bulk density in Eurasian grasslands (Tang et al., 2018). Therefore, the significantly reduced soil CH_4 uptake in HG sites may be closely related to the decreased in soil water content (caused by the lowered aboveground biomass and subsequently enhanced soil evaporation (Krümmelbein et al., 2009; Odriozola et al., 2014)) as lowered soil water content could result in water stress on soil methanotrophs, and thus reduced CH_4 uptake (Liu et al., 2007). Meanwhile, lowered soil water content could increase the osmotic stress on soil methanotrophs (Jäckel et al., 2001; Nazaries et al., 2013) and, thus reduced CH_4 uptake in HG sites. Furthermore, the increased of soil bulk density, decreased soil porosity and gas permeability by grazing livestock trampling (Tang et al., 2013, 2018; Chen et al., 2011b) could limit the diffusions of CH_4 and O_2 in soils (Smith et al., 2003), and thus limited the activities of methanotrophs in HG sites (Chen et al., 2011b; Liu et al., 2007; Zhou et al., 2008). Besides, CH_4 uptake in HG sites could be largely counteracted by CH_4 emissions from livestock feces dropped on the grasslands (Liu et al., 2009a; Ma et al., 2006; Wang et al., 2013). In addition, we found that grazing exerted no significant impacts on soil CH_4 uptake for each grassland type, as compared to UG sites. This may primarily due to the counteractions between positive effects induced by LG and MG, while negative effects caused by HG.

The CH_4 emissions from grazing-associated sectors, e.g., ruminant fermentation, livestock folds, and feces, may largely offset CH_4 uptake by grassland soils, and thus, there is growing numbers of studies have evaluated the CH_4 budgets (i.e., the balance between CH_4 production by livestock, livestock folds and feces and CH_4 consumption by soil methanotrophs (Liu et al., 2009a; Soussana et al., 2007; Schönbach et al., 2012) in grassland grazing systems in Europe (Dengel et al., 2011; Dumortier et al., 2017; Flessa et al., 2002; Soussana et al., 2007) or North America (Liebig et al., 2010) or northern China (Liu et al., 2009a; Wang et al., 2009; Zhuang et al., 2017). For all grassland types presented in this study, grazed grasslands functioned as net CH_4 sources for atmospheric CH_4, in which CH_4 budgets were increased dramatically with increasing grazing intensities from LG to HG, mainly contributed

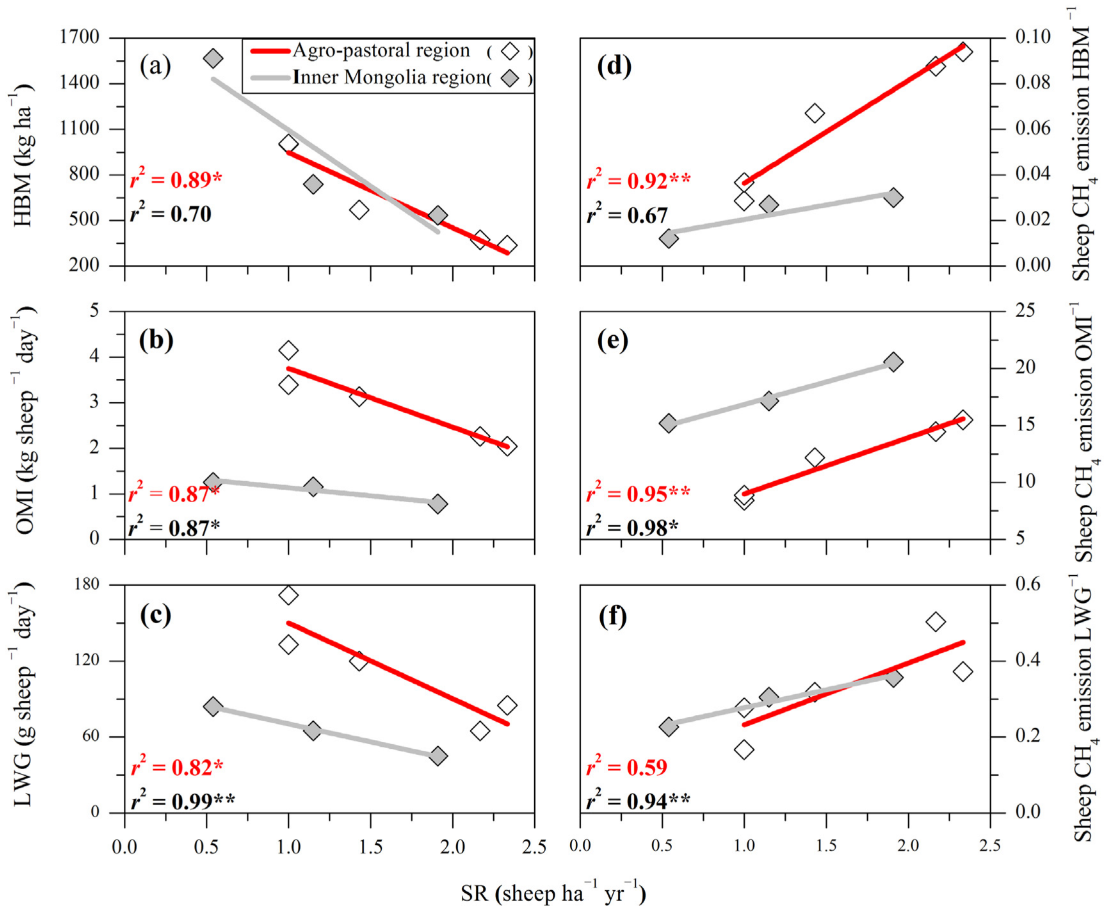

Fig. 5. Correlations of stocking rate (SR, sheep unit ha^{-1} yr^{-1}) with herbage biomass (HBM, kg dry matter ha^{-1}) at the end of the grazing season (a), organic matter intake (OMI, kg sheep^{-1} day^{-1}) (b), and live weight gain (LWG, g sheep^{-1} day^{-1}) (c); correlations of stocking rate (SR, sheep unit ha^{-1} yr^{-1}) with CH_4 emission intensities i.e., CH_4 emission per HBM (kg dry matter ha^{-1}) (d), per OMI (kg sheep^{-1} day^{-1}) (e), and per LWG (g sheep^{-1} day^{-1}) (f), for typical steppes in agro-pastoral region (white diamond) and in Inner Mongolia region (gray diamond) of northern China, respectively. The datasets for HBM, OMI and LWG under different SR are collected from Glindemann et al. (2009) and Ma et al. (2014); datasets for sheep CH_4 emission data under different SR are collected from Schönbach et al. (2012) and Wang et al. (2015), respectively. * and ** represent significance at the level of $p < 0.05$ and 0.01.

by sheep emissions, while sheepfolds and feces played negligible roles (Table 1). This confirmed previous finding in European grasslands (Soussana et al., 2007), North America grasslands (Liebig et al., 2010) or northern Chinese grasslands (Ma et al., 2018a; Schönbach et al., 2012). However, the magnitudes of CH_4 budget varied greatly across grazing systems. Soussana et al. (2007) reported that annual CH_4 budget was 49.3 ± 15.4 kg CH_4-C ha^{-1} yr^{-1} in cattle grazing systems (stocking rate: 0.12–1.32 cattle ha^{-1} year^{-1}) for nine grasslands in Europe, Schönbach et al. (2012) reported that annual CH_4 budgets ranged from −0.2 to 10.1 kg CH_4-C ha^{-1} yr^{-1} in sheep grazing system (stocking rate: 1.7 sheep ha^{-1} yr^{-1}) in typical steppe in Inner Mongolia, China, while, Dumortier et al. (2017) reported that annual CH_4 budget was 75.0 ± 6.8 kg CH_4-C ha^{-1} yr^{-1} in cattle grazing system (stocking rate: 2.3 cattle ha^{-1} yr^{-1}) in Belgium, Europe. These results indicating that CH_4 budget magnitudes may varied greatly across various grazing systems, which may be closely related to ruminant types, stocking rates, diets and climates (Westberg et al., 2001). Across all grassland types in China, the annual CH_4 budgets ranged from 3.71 ± 0.73 to 23.14 ± 0.73 kg CH_4–C ha^{-1} yr^{-1} following the order of LG, MG and HG (Table 1). Similarly, the grazing season CH_4 budgets also showed increasing trends with increasing grazing intensities, which ranged from 0.04 ± 0.11 to 19.64 ± 2.40 kg CH_4–C ha^{-1} (Table 1). These estimations were much larger than the previous annual (Ma et al., 2018a; Schönbach et al., 2012) or grazing season budgets reported for temperate typical steppes in northern China (Liu et al., 2009a; Ma et al., 2018a; Schönbach et al., 2012; Wang et al., 2009). This difference probably ascribing to the stocking rates and emission factors (EF) applied for evaluating the CH_4 budgets across different studies (Ma et al., 2018a). Taking the temperate typical steppe as an example, our EF were 10.3 ± 1.9, 9.2 ± 2.4 and 8.7 ± 2.8 kg CH_4–C sheep yr^{-1} for LG, MG and HG (calculated on the basis of emission factors in Liu et al., 2009a; Schönbach et al., 2012 and Wang et al., 2015 for different grazing intensities, respectively, see Supplementary S2), however, others using the site-specific (6.4 kg CH_4–C sheep yr^{-1}, Liu et al., 2009a) or IPCC for developing countries (3.8 kg CH_4–C sheep yr^{-1}, Wang et al., 2009) or averaged EF for Chinese grazing grasslands (6.7 ± 0.6 kg CH_4–C sheep yr^{-1}, Ma et al., 2018a). The annual CH_4 budgets alpine grasslands (including steppe and meadow) ranged from 0.04 ± 0.11 kg CH_4–C ha^{-1} grazing period^{-1} to 5.89 ± 0.49 kg CH_4–C ha^{-1} yr^{-1} following the order of LG, MG and HG (Table 1). These estimations were close to the previous estimations for extensively and intensively managed alpine meadows on the Tibetan Plateau (Zhuang et al., 2017).

In this study, we found that the offset (i.e., the ratio of soil CH_4 uptake by grassland to total emission from sheep, sheepfolds and feces on the grassland) varied across grassland types and grazing intensities (Table 1). The offsets were largest in LG (81 ± 7%) and lowest in HG (29 ± 2%). Similar results have been reported in temperate grassland in northern China (Ma et al., 2018a). Moreover, a significant exponentially decreasing trend was found between the offsets and SR (Fig. 3). These results indicate that optimizing grazing management practices could substantially mitigate CH_4 emissions in grassland grazing systems. Accordingly, the evaluation of CH_4 budgets across grassland grazing systems is a prerequisite before comprehensively assessing the grazing impacts on climate change (Westberg et al., 2001).

4.2. Relationship between grassland, livestock productivity, and CH_4 emissions under different stocking rates

Across 2 case studies, daily sheep CH_4 emissions showed no significant differences among various SR, though showing trend to be decreased under high SR (≥1.5 sheep ha^{-1} yr^{-1}) (Fig. 3a). A significant positive linear relationship was found between daily sheep CH_4 emissions and organic matter intake (OMI) (Fig. 3b), indicating that daily sheep CH_4 emission amounts were primarily OMI-dependent. This result confirmed the previous findings in other grazing systems (Pinares-Patiño et al., 2007; Westberg et al., 2001). Furthermore, the HBM at the end of grazing season, daily OMI by sheep and LWG were linearly decreased with increasing SR (Fig. 5a–c), suggesting the importance of lowering the SR for improving the productivities for grasslands and sheep.

It is well known that HBM at the end of grazing season is an important indicator for the healthy status of grassland, and daily OMI and LWG are key indicators for meat production in grazing systems (Glindemann et al., 2009; Ma et al., 2014), and the metric of greenhouse gas emission intensity can be utilized as a tool for acknowledging potential trade-offs between food (and meat, forage, and fuel) production and climate change mitigation (Ma et al., 2018b; Van Groenigen et al., 2010; Yao et al., 2017). In our study, the estimated CH_4 emission intensities, i.e., CH_4 emission per HBM, OMI, and LWG, were all linearly increased with increasing SR for both 2 cases (Fig. 5). This result indicates lowering the SR could not only beneficial for maintaining productivities, but also conductive to reducing CH_4 emissions in grassland grazing systems.

In summary, our results showed that the offsets were exponentially decreased with increasing SR across grassland grazing systems in China. Moreover, we found that HBM at the end of grazing season, daily OMI by sheep and LWG were linearly decreased with increasing SR, while the estimated CH_4 emission intensities were linearly increased with increasing SR for both 2 cases in temperate typical steppes in northern China. These results combined together demonstrate that lower grazing intensity, e.g., from HG to LG, could improve the productivity of forage and livestock in grassland grazing systems and meanwhile mitigate CH_4 emissions.

Our synthetic results demonstrate that optimized grazing management can enhance environmental outcomes via improved grassland and livestock productivity and simultaneously reduce CH_4 emissions in two representative temperate steppe regions of northern China. This work may provide a strategy that is relevant to other grassland areas around China or the world with similar CH_4 emissions problems. Besides, our study showing correlations of SR with grassland, and livestock productivities or with CH_4 emission intensities, which may be incorporated into models to improve predictions for the balance of livestock production and environmental benefits in grassland grazing systems.

4.3. Uncertainty and implications

Dependent on the current data availability of grazing experiments in Chinese grasslands, our estimated results may exist some uncertainties but may still provide some insight into the extent to which the CH_4 budget responds to grazing across different grasslands in China. First, in this study, a limited numbers of sheep EF are available from literatures for temperate and alpine grasslands in China. Currently, there is no EF for different grazing intensities in alpine grasslands and temperate desert and meadow steppes in China. So, we used the same EF for alpine grassland grazing systems with different grazing intensities. In the temperate regions, the collected EF datasets for different grazing intensities in typical steppes (Liu et al., 2009a; Schönbach et al., 2012; Wang et al., 2015) were also applied for estimating CH_4 budgets in desert and meadow steppes. These simplified processes would inevitably induce uncertainties for the estimated CH_4 budgets as EF are closely correlated with diet quantity and quality, and climates (Westberg et al., 2001). Therefore, more EF measurement studies should be carried out across different grassland types and grazing intensities in China, particularly for the meadows and steppes distributing in temperate and alpine regions. Second, the most of the selected studies are related to sheep grazing systems, previous studies seldom considered other ruminant species, such as cattle, dairy cow and goats, these animals may have different magnitudes of CH_4 emissions (Westberg et al., 2001). Therefore, it is of necessity to consider CH_4 emissions from grazing animals other than sheep, in order to reliably assess the total CH_4 budgets in livestock grazing systems across different grassland types in China. Third, the most soil CH_4 flux measurements primarily focused on the grazing seasons, while only a few studies measured year-round fluxes. This research deficiency also limited our understanding of annual CH_4 budget in grazing systems in China. Accordingly, it is of importance for measuring the annual soil CH_4 uptake in grasslands for better estimations of annual CH_4 budgets in future studies. Fourth, CH_4 emissions from summer and winter sheepfolds are scarcely measured across Chinese grazing systems. We adapted the reported CH_4 emissions from a summer sheepfold (Liu et al., 2009a) and a winter sheepfold (Chen et al., 2011a) in temperate typical steppes, respectively, and applied these data for other grassland types. This simplified process also lead to uncertainties to our estimations. To date, there is no reports on CH_4 emissions from sheepfold in alpine grasslands, suggesting measurements should be carried out in this region, to fill the knowledge gap in alpine regions. Fifth, our synthesis faces challenge of lacking enough associated measurements for testing the effect of SR on sheep CH_4 emission intensities (i.e., emission per unit of HBM, OMI, and LWG). Filling these data gaps through experimentation and publications will be necessary to provide a stronger empirical basis for future large-scale assessments. More systematical CH_4 and associated data accumulation is beneficial for further validating our results. Besides, in this study, the non-methane greenhouse gas emissions or potentially sequestrations are not considered, such as carbon dioxide (CO_2) and nitrous oxide (N_2O), which also were influenced by grazing intensities. Therefore, fully accounting of greenhouse emissions (CO_2, CH_4, and N_2O) in grassland grazing systems could contribute to the smart-use of grasslands and meanwhile mitigation their greenhouse gas emissions. Additional high-frequency monitoring is needed to determine the net balance of different greenhouse gas under grazing.

Overall, our results indicate that the effects of grazing on the CH_4 budget are strongly mediated by grazing intensity. Changes in livestock numbers may have profound impacts on the CH_4 budget and ecosystem functioning of grasslands. Our results showed that reducing the currently high SRs are essential to the sustainable management of grassland ecosystems in China. Much more relevant studies should be initiated to further reduce the uncertainties of CH_4 budgets in grassland grazing systems across China or the world.

5. Conclusions

Our synthetic analysis showed that grazing, especially heavy grazing significantly reduced soil CH_4 uptake, while promoted CH_4 emissions from sheep, sheepfolds and feces, and thus, shifting the grassland from sinks to sources for atmospheric CH_4 across grassland grazing systems in China. Our results found that the offsets (i.e., the ratio of soil CH_4 uptake to total emission from sheep, sheepfolds and feces) were exponentially decreased with increasing grazing intensities from light to heavy grazing. Meanwhile, the herbage biomass at the end of grazing season, organic matter intake and live weight gain were linearly decreased with increasing stocking rates, while the CH_4 emission intensities (i.e., CH_4 emission per herbage biomass, organic matter intake, and live weight gain) were linearly increased with increasing stocking rates. Accordingly, These findings imply that optimizing grazing management, such as reducing grazing intensity from heavy to light grazing, could improve grassland and livestock productivities and simultaneously mitigating CH_4 emissions from grazing system.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.102.

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