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Moderate grazing helps reduce greenhouse gas emissions from typical steppe

Wang, H[1]; Li, FY[1]

[1] Key Laboratory of Ecology & Resource Use of the Monoglian Plateau, School of Ecology & Environment, Inner Mongolia University, Hohhot, 010021, China

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Abstract

Grasslands represent a significant ecosystem that exerts a profound influence on atmospheric greenhouse gas levels in the context of global change. Appropriate grassland management represents an effective means of reducing greenhouse gas (GHG) emissions from grasslands. However, the information on the management effects on GHG emissions from natural grasslands is still insufficient for developing the best practice in grasslands for both production and carbon. The effects of three major management measures, fencing, grazing, and mowing, on ecosystem respiration (CO_2), methane (CH_4) uptake, and nitrous oxide (N_2O) emissions were investigated in a typical grassland area of Xilingol, Inner Mongolia. The results demonstrated that moderate grazing reduced aboveground biomass, decreased CO_2 emissions, promoted belowground nutrient cycling, and increased CH_4 uptake. While mowing increased pasture production and soil carbon and nitrogen content, it was accompanied by higher CO_2 emissions. Reducing grazing frequency slowed biomass loss to some extent, while reducing N_2O emissions. Climatic conditions largely control grassland GHG emissions or uptake, and different management practices control GHGs mainly by affecting the soil micro-environment and soil nutrient content. The results of the study provide data support for carbon sequestration and emission reduction in grasslands. It can be concluded that moderate grazing intensity and frequency are the optimal management practices to mitigate GHG emissions from grasslands. Furthermore, the advantages and disadvantages of increased pasture production and increased GHG emissions from mowing should be weighed to further optimize grassland management.

Introduction

Grassland degradation can induce biodiversity loss and productivity decline, reduce carbon (C) and nitrogen (N) cycling and other ecosystem services, and increases greenhouse gases (GHGs) emissions contributing to global warming (Bai *et al.* 2018). It is imperative to implement sustainable management measures to enhance grassland production while concomitantly minimizing the adverse environmental impact (Taube *et al.* 2014). The main management methods for the Inner Mongolian steppe grasslands are grazing, mowing for hay, and enclosure (Dong *et al.* 2020). Grazing regulates grassland GHG emissions by altering of vegetation and soil physicochemical properties through livestock foraging, trampling and excreta deposition (Tang *et al.* 2019). Mowing or hay harvesting removes a large part of plant aboveground biomass and nutrients, thus alters C and N cycling processes that occur within the ecosystem and thereby altering greenhouse gases flux (Niu *et al.* 2013). However, the effects of these management measures on grassland GHG emissions are unclear. The function of grassland ecosystems in C sequestration and emission reductions under various grassland management remains a matter of contention, largely due to the high spatial heterogeneity and discrepancies in research methodologies (Piao *et al.* 2022). Further investigation is required to ascertain the implications of differing management practices on GHG emissions in grassland ecosystems.

Here, at a typical steppe located in central of Inner Mongolia, China, we determined the GHGs fluxes in grasslands subjected to experimental mowing, grazing and enclosing (no grazing nor mowing), and analyzed the mechanisms underlying the GHGs variation across management practices. We hypothesized that: (i) grazing at moderate intensity increases ecosystem respiration rate (ER, i.e., CO_2 emission) and N_2O emission, but decreases CH_4 uptake; (ii) In contrast to grazing, mowing decreases ER and N_2O emission, but increases CH_4 uptake; (iii) Management regulates GHG fluxes mainly by altering plant production and soil moisture.

Methods

GHG fluxes measurement in this research was carried out at the designated experimental grassland located at the Observation and Research Station for the Typical Steppe Ecosystem of the Ministry of Education of China (44°10' N, 116°28' E, 1101 m a.s.) with a mean annual temperature of -0.5 °C and a mean annual precipitation of 315 mm. The natural vegetation is typical steppe in this region with *Leymus chinensis* (Trin.) Tzvel., *Stipa krylovii* Roshev and *Cleistogenes squarrosa* (Trin.) Keng. as the dominant species.

A randomized block design was used to arrange four treatments of management practices, with three replications in 12 grassland plots, and the plot size is 33 m × 33 m. The four management practices were (i) whole plant growing season grazing (WG): from May to September; (ii) Spring and summer grazing (SG): only in May and July; (iii) Autumn mowing (AM): mowing around August 20th, leaving a stubble at 6 cm and removing the hay; and (iv) enclosed grassland (EN): no grazing nor mowing. Six sheep were introduced to the grassland for grazing on the 20th day and removed when the stubble height of the dominant grassland species reached approximately 6 cm.

GHG fluxes assessment were conducted via the static chamber technique coupled with gas chromatography test, from June to September. Three gas chamber bottom frames with grooves were set up in each plot for natural sampling. The surface air temperature (AT), soil temperature (ST) and soil volumetric moisture content (SM) was recorded during the collection of gas samples. Gas collection was made once a week during the growing season. At the same time, we monitored plant species richness (SR), aboveground biomass (AGB) and belowground biomass (BGB) and measured soil ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), soil inorganic nitrogen (SIN), pH, soil total organic carbon (TOC), total carbon (TC), total nitrogen (TN) and bulk density (BD),

2.4. Statistical analyses

One-way analysis of variance (ANOVA) was used in IBM SPSS Statistics.27.0 to assess changes in GHG fluxes, and the environmental factors, including climatic (precipitation, temperature), soil physical (AT, ST, SM, pH, BD, texture) and chemical (TOC, TC, TN, NH_4^+-N, NO_3^--N, C/N, SIN), as well as plant (AGB, BGB, SR) factors, across management practices. An analysis using boosted regression trees model (BRTs) was performed to explore the relative importance of various environmental variables on GHG emissions and uptake by *gbm* package in R v.4.2.1.

Results

Management implications on vegetation and soil

Grassland vegetation and soil were significantly affected by management practices. Compared to EN, grazing (both WG and SG) reduced AGB by 44.03%. Mowing (AM) increased plant AGB by 17.39%, while it did not affect BGB. Compared to EN, WG and AM significantly increased AT and ST, while SG had no such an overall significant effect. Compared to EN, both WG and SG increased soil BD but decreased soil inorganic nitrogen; WG, SG and AM significantly increased TC, SG significantly increased TN, WG significantly increased the C/N ratio, and AM significantly enhanced TOC (Table 1).

Table1. Plant and soil properties of the grassland under different managements

	Managements			
	EN	WG	SG	AM
AT	26.53±0.45**bc**	27.78±0.59**ab**	26.12±0.48**c**	28.27±0.58**a**
ST	22.29±0.33**c**	24.21±0.53**ab**	22.68±0.76**bc**	24.48±0.57**a**
SM	7.90±0.17	8.01±0.24	7.73±0.26	7.93±0.29
AGB	86.18±3.43**b**	47.77±2.73**c**	57.21±2.27**c**	99.06±4.49**a**
BGB	357.97±69.82	362.08±48.01	418.24±22.23	382.48±76.23
SR	5.63±0.30**b**	6.61±0.36**ab**	6.10±0.38**b**	7.21±0.31**a**
PH	8.45±0.16	8.41±0.17	8.42±0.15	8.44±0.18
Sand (%)	74.48±1.37	71.81±1.43	71.23±1.01	74.11±0.48
Silt (%)	22.86±1.22	25.23±1.26	25.66±0.87	23.06±0.38
Clay (%)	2.66±0.27	2.96±0.18	3.11±0.12	2.83±0.13
BD ($g \cdot m^{-3}$)	1.23±0.02 **b**	1.29±0.01 **a**	1.33±0.01 **a**	1.25±0.01 **b**
TOC ($g \cdot kg^{-1}$)	11.5±0.31 **b**	12.09±0.31 **ab**	12.11±0.28 **ab**	12.41±0.25 **a**
TC ($g \cdot kg^{-1}$)	16.51±0.4 **b**	18.65±0.48 **a**	18.31±0.41 **a**	18.36±0.38 **a**
TN ($g \cdot kg^{-1}$)	1.44±0.04 **b**	1.53±0.04 **ab**	1.57±0.04 **a**	1.53±0.04 **ab**
NH_4^+-N ($mg \cdot kg^{-1}$)	3.07±0.35	2.86±0.29	2.92±0.31	3.00±.29
NO_3^--N ($mg \cdot kg^{-1}$)	6.53±0.89	5.32±0.31	5.03±0.53	6.54±0.59
SIN ($mg \cdot kg^{-1}$)	9.6±0.71 **a**	8.18±0.22 **b**	7.95±0.26 **b**	9.55±0.41 **a**
C/N	11.55±0.18 **b**	12.24±0.23 **a**	11.74±0.23 **ab**	12.04±0.16 **ab**

Values are mean ± S.E. (standard error). Different letters indicate significant differences among management practices within the rows ($P < 0.05$).

Management implications on GHG emissions

Grassland ecosystem respiration (CO_2 release) showed a nearly unimodal curve throughout the plant growing period with peaks observed in late July. CO_2 release was significantly lower under the two grazing management and EN than under AM and EN. The studied steppe functioned as a CH_4 sink throughout the plant growing period with peak uptake occurring in Jun. The soil CH_4 absorption under WG was significantly higher than that under EN and AM. The N_2O emissions during the growing season were more volatile and variable and showed two peaks. The average N_2O emission rates were the lowest under SG, which was significantly lower than the highest rate under AM, EN and WG. (Fig. 1)

Factors driving the emission of the three GHGs under different managements

BRTs model demonstrated the relative contribution of all factors to GHGs fluxes, which explained 86.69 %, 59.28 %, and 59.92 % of the variation in CO_2, CH_4, and N_2O fluxes, respectively. Climatic, soil physical and chemical factors were the major explanatory factors for GHG emissions in grasslands, but their contribution differed to each of the three GHGs. Climatic factors (46 %) had the biggest contribution to CO_2 release followed by soil physical factors (25 %); climate (35 %) and soil chemical (32 %) and physical factors (26 %) are major factors affecting for N_2O emission; while CH_4 uptake was more regulated by soil physical (40 %) and chemical factors (25 %) than by climate factors (21 %). In addition, plant factors also had a certain contribution to variation in GHGs emissions. (Fig. 2)

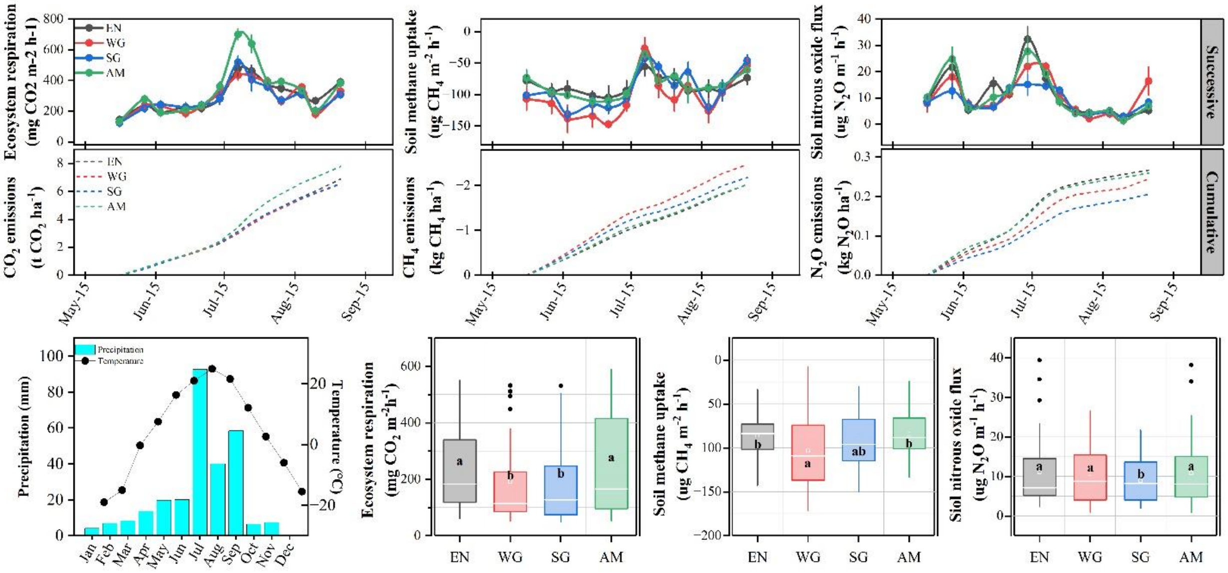

Fig. 1 GHG flux to different managements in growing period and monthly mean temperature and precipitation in the experimental period

Discussion [Conclusions/Implications]

The emission of GHGs from grassland ecosystems is a complex biological and ecological process, and is affected by numerous factors (Dangal *et al.* 2020). Light grazing may induce plant over-compensatory growth thus increase ER (Zhou *et al.* 2017), while mowing has no effect or reduces ER (Jia *et al.* 2012). Grazing reduces plant AGB and plant respiration thus decreases ER, while mowing increases ST that stimulates soil microbial activity and respiration thus enhances ER (Benot *et al.* 2014). Grazing reduces AGB and increases ST, which, in turn, stimulates methanotrophic activities and thus CH_4 uptake (Zhou *et al.* 2007). The increased ST was accompanied by decreased SM and increased soil aeration, which enhances the CH_4 diffusion from atmospheric to the soil (Liu *et al.* 2007). CH_4 uptake is typically inversely correlated with SIN content because NH_4^+-N can be oxidized by methanotrophic instead of CH_4, whereas NO_3^--N enhances soil oxidation potential, influences the activity of methanotrophic, and might reduce the CH_4 uptake (Zheng *et al.* 2024). N_2O is mainly generated through the processes of nitrification and denitrification, which can easily be altered by the variations in soil temperature, moisture, and nutrients induced by grazing and mowing (Xia *et al.* 2022). Soil inorganic nitrogen content may be the reason for a reduction in N_2O emissions under SG, as studies have shown that SIN is a substrate for nitrification and denitrification, and has a significant controlling effect on soil N_2O emissions (Müller *et al.* 2002).

Our BRTs mode indicates that temperature or precipitation are the major controlling factor for GHG emission and uptake in typical steppes, followed by soil physical and chemical properties. The effects of climate and grassland management on grasslands are inextricably linked (Reichstein *et al.* 2013). Some studies have indicated that climate (precipitation) exerts a more pronounced influence on CO_2 release than grassland management (grazing and mowing) (Zhang et al., 2023). However, global-scale studies have demonstrated that grassland management (grazing) exerts a more pronounced effect on grassland carbon stocks than climate change (Zhou *et al.* 2019).

While the climatic factors are dominant in controlling GHGs emissions form ecosystems, different management practices equally affect the GHGs fluxes by altering plant standing biomass and thereby influences soil physical and chemical properties and soil microbial activities. Further investigation into the mechanisms underlying these interactions is essential, especially under the implication from both natural and anthropogenic factors. The implementation of effective emission reduction strategies demands a comprehensive understanding of these complex interactions.

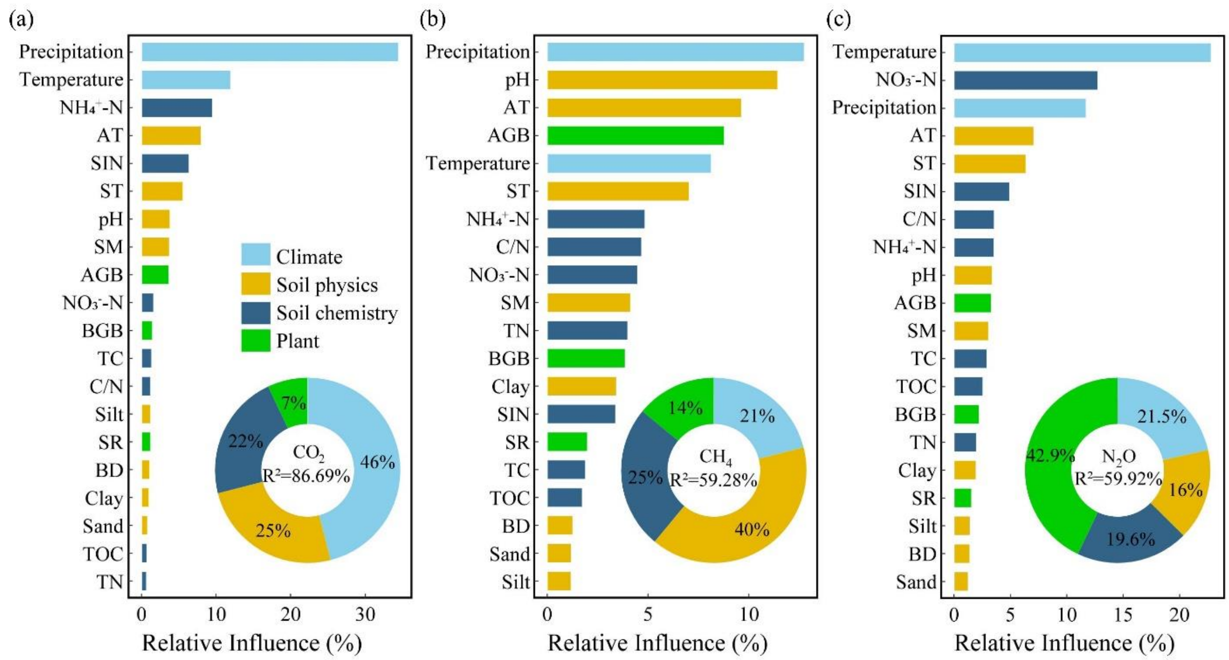

Fig. 2 Relative contribution of environmental factors to the ecosystem respiration (a), soil methane uptake (b), and soil nitrous oxide emission (c) under grazing, mowing, or enclosure based on the boosted regression trees (BRTs) model.

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