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Soil greenhouse gas emissions and grazing management in northern temperate grasslands

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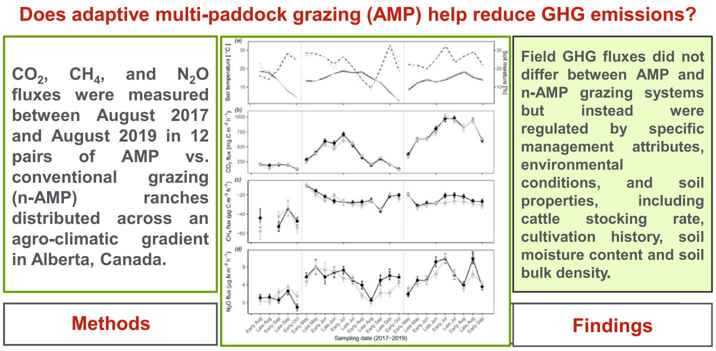
HIGHLIGHTS

- Does adaptive multi-paddock grazing reduce greenhouse gas emissions from grasslands?
- CO_2, CH_4, and N_2O fluxes were measured in 24 ranches from 2017 to 2019.
- Grazing system does not affect greenhouse gas emissions from temperate grasslands.
- Seasonal mean CO_2 emissions increased with increasing cattle stocking rate.
- CO_2 emissions increased while CH_4 uptake decreased with increasing soil moisture.

GRAPHICAL ABSTRACT



Does adaptive multi-paddock grazing (AMP) help reduce GHG emissions?

CO_2, CH_4, and N_2O fluxes were measured between August 2017 and August 2019 in 12 pairs of AMP vs. conventional grazing (n-AMP) ranches distributed across an agro-climatic gradient in Alberta, Canada.

Methods

Field GHG fluxes did not differ between AMP and n-AMP grazing systems but instead were regulated by specific management attributes, environmental conditions, and soil properties, including cattle stocking rate, cultivation history, soil moisture content and soil bulk density.

Findings

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ABSTRACT

Adaptive multi-paddock (AMP) grazing, a grazing system in which individual paddocks are grazed for a short duration at a high stock density and followed by a long rest period, is claimed to be an effective tool to sustainably manage and improve grasslands and enhance their ecosystem services. However, whether AMP grazing is superior to conventional grazing (n-AMP) in reducing soil greenhouse gas (GHG) emissions is unclear. Here, we measured CO_2, CH_4, and N_2O fluxes between August 2017 and August 2019 in 12 pairs of AMP vs. n-AMP ranches distributed across an agro-climatic gradient in Alberta, Canada. We found that field GHG fluxes did not differ between AMP and n-AMP grazing systems, but instead were regulated by specific management attributes, environmental conditions, and soil properties, including cattle stocking rate, cultivation history, soil moisture content, and soil bulk density. Specifically, we found that seasonal mean CO_2 emissions increased with increasing cattle stocking rates, while CH_4 uptake was lower in grasslands with a history of cultivation. Seasonal mean CO_2 emissions increased while CH_4 uptake decreased with increasing soil moisture content. In addition, CH_4 uptake decreased with increasing soil bulk density. Observed N_2O emissions were poorly predicted by the management, environmental conditions, and soil properties investigated in our study. We conclude that AMP grazing does not have an advantage over n-AMP grazing in reducing GHG fluxes from grasslands. Future efforts to develop optimal management strategies (e.g., the use of sustainable stocking rates and avoided cultivation) that reduce GHG emissions should also consider the environmental conditions and soil properties unique to every grassland ecosystem.

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1. Introduction

Atmospheric concentrations of greenhouse gases (GHGs) have increased exponentially over the past century due to human activities (Ritchie and Roser, 2020), with livestock production being one of the main contributors (Cardoso et al., 2016; Herrero et al., 2016). Of the GHGs exchanged by grasslands, carbon dioxide (CO_2) is the primary flux from soil and vegetation, nitrous oxide (N_2O) is emitted from the soil, and methane (CH_4) is emitted by livestock and from anaerobic soils while being consumed at low rates by microbial oxidation in aerobic soils (Soussana et al., 2004). The balance of GHG exchange between grasslands and the atmosphere depends on environmental conditions, vegetation type/cover, soil properties, and management practices (Conant et al., 2001; Derner et al., 2006; Koncz et al., 2017). Management practices also affect GHG exchange by altering vegetation and soil properties (Reynolds et al., 2007). Quantitative information on the fluxes of all three major GHGs (i.e., CO_2, CH_4, and N_2O) under different management strategies is essential to refine and develop best management practices to build climate resilient landscapes and reduce the climate footprint of agricultural lands (Lal, 2004). However, such investigations are difficult to undertake at a regional scale due to the complexity of grassland ecosystems in terms of environmental conditions, the wide range of management practices to which they are exposed (Hoffmann et al., 2016), and the financial resources required to conduct such studies.

Livestock grazing management practices and land use legacy can vary greatly with respect to stocking rate, the length of the recovery period after individual grazing events, animal density, and cultivation history, all of which influence GHG fluxes in grazed grasslands (Ma et al., 2006; Saggar et al., 2007; Soussana et al., 2004). For example, moderate to heavy stocking rates can alter plant community composition, which has been found to reduce forage production but increase soil organic carbon (SOC), in a shortgrass steppe and a northern mixed prairie (Frank et al., 1995; Schuman et al., 1999; Derner et al., 2006). A recent study showed that a loss of SOC through CO_2 emissions to the atmosphere occurred on pastures under heavy stocking, yet carbon sequestration resumed when grazing was returned to moderate levels (Owensby and Auen, 2020). Another study demonstrated that N_2O emission pulses decreased with increasing livestock stocking rates at ten steppe grassland sites in Inner Mongolia (Wolf et al., 2010).

Adaptive multi-paddock grazing (AMP) has been used in various forms since the mid-20th century, and is considered an important tool to manage grazing lands for sustainable livestock (i.e., sheep and cattle) productivity (Wang et al., 2015). Under AMP grazing, small paddocks are grazed at a high animal density for a short period of time, which is then followed by a long recovery period prior to regrazing (Bork et al., 2021). The AMP grazing has been found to increase soil organic matter, increase water infiltration and water holding capacity, and also improve nutrient availability and forage production (Teague et al., 2011; McDonald et al., 2019; Döbert et al., 2021). To the best of our knowledge, no field study has been conducted to test whether AMP-grazed grasslands are superior to conventionally grazed land (n-AMP) in terms of reducing overall GHG emissions, including increasing CH_4 uptake, even though a recent lab incubation study using soils from grasslands subject to these treatments showed that soils from AMP-grazed grasslands had greater CH_4 uptake, particularly when incubated at a higher temperature (Shrestha et al., 2020).

In addition to grazing management practices, soil properties and environmental conditions can profoundly influence the balance of GHG fluxes within grasslands (Hütsch, 2001; Price et al., 2004; Wolf et al., 2010; Zhu et al., 2015). For example, soil properties such as soil texture, bulk density, and SOC content can affect water holding capacity and aeration, and therefore the gas diffusivity of soils (availability of oxygen) and associated microbial processes, thereby altering ecosystem-atmosphere GHG exchange (Butterbach-Bahl et al., 2013; Wang et al., 2019). Increasing soil temperatures have been found to increase average seasonal CO_2 emissions (Luo et al., 2001), while increasing soil moisture can hamper CH_4 uptake by reducing gas diffusivity (Yao et al., 2019). The role of grasslands as a net sink/source of GHGs depends highly on environmental conditions, especially the amount of precipitation (Jaksic et al., 2006; Nagy et al., 2007). As GHG fluxes in grasslands are simultaneously affected by many environmental factors and management practices, researchers need to decouple these natural and anthropogenic effects to tackle the complexities of emission dynamics from grazed pastures and develop GHG mitigation strategies.

Studies designed to simultaneously assess the fluxes of all three major trace GHGs in grassland ecosystems subject to different grazing management practices are needed to identify grazing and land use activities that mitigate ongoing GHG emissions. Here, we build on a laboratory incubation experiment conducted by Shrestha et al. (2020) and report on in-situ CO_2, CH_4, and N_2O fluxes measured between August 2017 and September 2019 within grasslands from 12 ranch pairs (AMP vs. n-AMP) distributed across a wide agro-climatic gradient in Alberta, Canada. Our study addresses two core questions: 1) Are grasslands subject to AMP different from conventional grazing in terms of reducing GHG emissions? and 2) What is the role of select management and environmental conditions, along with soil properties, in regulating GHG fluxes?

2. Material and methods

2.1. Study site description

A total of 12 ranch pairs were established across south-central Alberta, Canada, as part of a larger interdisciplinary study of grazing impacts on prairie grassland ecosystems. Each pair was comprised of neighboring AMP and n-AMP ranches, where the latter exhibited ‘conventional’ grazing management. Detailed information on ranch selection can be found in Bork et al. (2021) and key metrics examined are listed in Table 1. Among key metrics, cattle stocking rate was computed from survey information on the number of animals and the specific length of grazing, reported in animal-unit-months per hectare. Rest to graze ratio is the number of days of rest per day of active grazing during the growing season (May 1 to August 1). Mean paddock and herd sizes were used to compute mean cattle densities (animal-units ha^{-1}) during grazing. The study ranches span a broad agro-climatic (i.e., soil, climate, and vegetation) gradient across northern temperate grasslands.

Table 1
Description of predictor variables by subgroup used in the analysis of field GHG fluxes among ranches.

Subgroup	Predictor variable	Description
Management	Cultivated	Presence/absence of known cultivation history in a ranch, which occurred at least 10 years prior
	Stocking rate	Measure of grazing intensity, computed from survey information on the number of animals and the specific length of grazing, reported in animal-unit-months (AUM) per ha. An AUM is a 454 kg cow, with or without a calf, grazing for one month.
	Rest to graze ratio	The number of days of rest per day of active grazing during the growing season (May 1 to August 1)
	Animal density	Animal unit per hectare
Environmental	Soil temperature	Actual soil temperature (°C) at the time of GHGs sampling in the field
	Soil moisture	Actual soil moisture (%) at the time of GHGs sampling in the field
Soil properties	Clay	Percent clay (%)
	Bulk density	Weight of soil in a given volume (g cm^{-3})
	SOC	Soil organic carbon

Selected ranches were, in order of declining aridity, situated within the Mixedgrass Prairie, Aspen Parkland, Foothills Fescue, and Boreal transition ecoregions. Soils coinciding with these natural ecoregions were Orthic Brown Chernozems (Mixedgrass Prairie), Orthic Black to Eluviated Black Chernozems (Foothills and Parkland), and Dark Gray Chernozems to Gray Luvisols (Boreal Transition). Soil organic matter content ranged from 2.5 to 3.4% in Brown, 3.5 to 5.5% in Gray, and 5.5 to 8.5% in Black Chernozem soils (Canadian Society of Soil Science, n.d.). The 30-yr normal (1984–2014) mean annual precipitation (MAP) ranged from 332.3 to 533.3 mm, with mean annual temperatures (MAT) ranging from 2.0 to 4.1 °C (ClimateAB, n.d.).

2.2. Measurement of GHG fluxes and environmental variables

Growing season GHG fluxes were measured in the field bi-weekly from mid-August to mid-October in 2017, early May to mid-October in 2018, and early May to early September in 2019 using dark static chambers ($65.5 \times 17 \times 15.5$ cm height) at six random sampling points within a representative area of each study ranch. Ambient air samples (20 mL) were collected prior to placing the chamber-lids over the static chambers (ambient condition, $t = 0$) and again at 10, 20, and 30 min after placing the chamber-lid over the static chamber, using an airtight syringe (Norm-Ject, Henke Sass Wolf, Tuttlingen, Germany) through a rubber septum. Samples were then stored in pre-evacuated 12 mL soda glass Isomass Exetainers (Labco Limited, Lampeter, Wales, UK) to provide a positive pressure in the Exetainer. Collected gas samples were transported in dark boxes to the Forest Soil Laboratory at the University of Alberta, Edmonton, and were analyzed using a Varian CP-3800 gas chromatograph (Varian Canada, Mississauga, Canada) equipped with a thermal conductivity detector, a flame ionization detector and an electron capture detector for determining the CO_2, CH_4, and N_2O concentrations, respectively. We did not consider N_2O emissions from urine and dung because the fractional area covered with urine after a grazing event is typically in the order of 1%, making it difficult to robustly capture urine and dung effects on N_2O emissions using randomly placed static chambers, even though the chambers were moved every two weeks in trying to capture the grazing effects on GHG emissions. The CH_4 emissions from enteric fermentation of ruminant livestock were not considered as our exclusive focus here was on grazing-induced fluxes of CH_4 within the underlying soil.

Fluxes of GHGs were calculated based on concentrations of GHGs at 0, 10, 20, and 30 min samplings using Eqs. (1) and (2) (Kwak et al., 2016).

$$Efflux = \frac{\Delta c \times T \times V}{\Delta t \times A} = \frac{\Delta c \times T \times h}{\Delta t} \tag{1}$$

$$T = \frac{44.6\, mol\, m^{-3} \times 273.15}{273.15 + T_A} \tag{2}$$

where Δc is the change in the concentrations of GHGs in the selected time interval (μmol mol^{-1}), T is a temperature adjustment for molecular volume of gas (mol m^{-3}), V is the volume of the static gas chamber (m^3), A is the area of ground covered by the Hutchinson chamber (m^2), h is the height of the static chamber (m), Δt is the time interval between samplings (s), and T_A is the actual air temperature (°C).

Soil temperature and moisture content were recorded at the time of GHG flux measurements. Soil temperature was measured using a digital thermometer, and volumetric soil moisture content was measured using a Fieldscout TDR 300 soil moisture meter (Spectrum Technologies, Inc., IL, USA).

2.3. Soil sampling and analysis of soil properties

Soil samples were collected at random locations within 1.5 m of the GHG collection points in each of the 24 study ranches, during the last week of August 2017. After removing the litter and mulch, the two mineral soil cores (3.8 cm diameter, 15 cm deep) were combined for further analysis. Soil texture, bulk density, and SOC were analyzed for each sample. Soil texture was determined using the hydrometer method (Kroetsch and Wang, 2007). About 5% of each soil sample was randomly extracted and used to determine bulk density using the core method (Hao et al., 2008). Total SOC was determined using a Vario El Cube CHNS automated elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). A sulfanilamide analytical standard

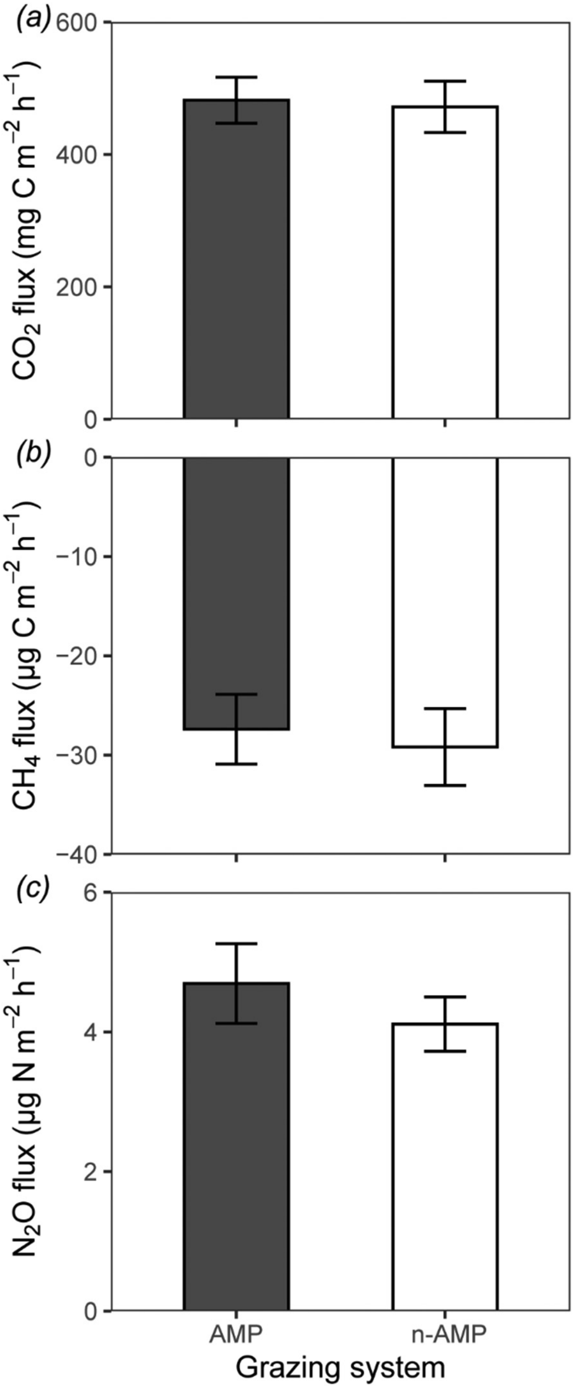

Fig. 1. Effect of grazing system (AMP and n-AMP) on mean seasonal fluxes of (a) CO_2, (b) CH_4, and (c) N_2O, within grasslands of Alberta, Canada. Error bars represent ±1SE ($n = 12$). We note that soil organic carbon stock (0-60 cm) does not differ between grazing systems ($P > 0.05$).

Table 2
Repeated-measures ANOVA result of grassland CO_2, CH_4, and N_2O fluxes (mg C m^{-2} h^{-1}).

Year	Factor	df	CO_2 flux		CH_4 flux		N_2O flux	
			F	P	F	P	F	P
2017	GS	1	0.82	0.37	0.02	0.89	2.02	0.15
	Date	4	11.61	**<0.01**	0.01	0.93	0.62	0.43
	Date × GS	4	1.27	0.26	0.02	0.89	5.39	**0.02**
2018	GS	1	1.63	0.21	0.03	0.86	0.24	0.63
	Date	10	190.98	**<0.01**	69.32	**<0.01**	29.39	**<0.01**
	Date × GS	10	2.11	0.15	0.06	0.81	4.37	**0.03**
2019	GS	1	0.08	0.78	0.002	0.95	0.03	0.86
	Date	8	134.68	**<0.01**	2.30	0.12	7.77	**<0.01**
	Date × GS	8	0.26	0.61	3.75	0.06	1.18	0.28

P values less than 0.05 are shown in bold.
df indicates degrees of freedom.
GS is grazing system, which represents the contrast of AMP and n-AMP ranches.

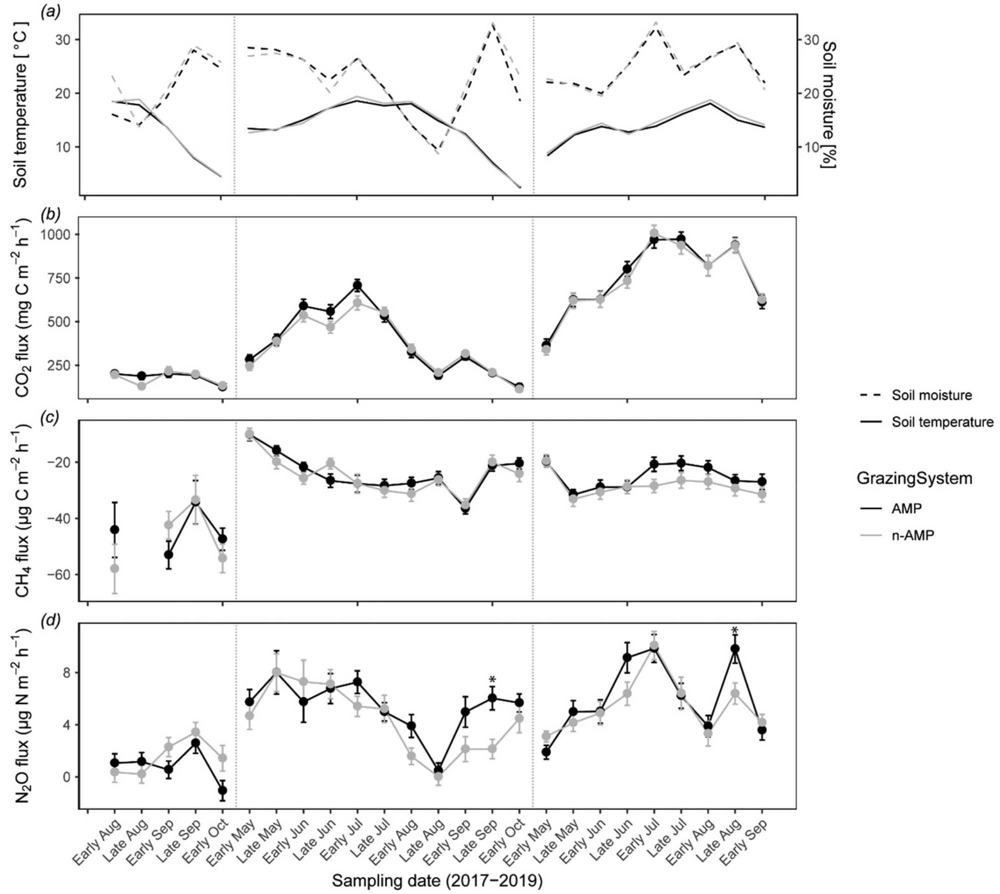

Fig. 2. Dynamics of (a) soil temperature and moisture, and fluxes of (b) CO_2, (c) CH_4, and (d) N_2O, within grasslands associated with AMP and n-AMP grazing during field sampling time from 2017 to 2019. *significant differences between AMP and n-AMP: ($P \leq 0.05$). Error bars represent ±1SE ($n = 12$).

for C was run after every 10th sample to correct for drift in the instrument (Sokolova and Vorozhtsov, 2014). Samples that had a pH ≥ 6.4 were acid-fumigated with HCl to remove carbonates prior to measuring organic C; samples with pH < 6.4 were assumed to have negligible inorganic C (Walthert et al., 2010).

2.4. Data analysis

All statistical analyses were performed using R (version 3.5.2., R Development Core Team, Vienna, Austria). The overall effects of grazing system (AMP vs. n-AMP) and sampling date on GHG fluxes were evaluated for each year (2017, 2018, and 2019) using a repeated-measures analysis of variance (ANOVA) for a two-way factorial design. Grazing system and sampling date were fixed effects in this analysis, with each ranch pair nested within each sampling time included as a random factor. Where grazing system by sampling date effects occurred ($P < 0.05$), pairwise comparisons of GHG readings within a sampling date were used to identify the timing of any difference in GHG emissions.

To further interpret GHG dynamics, linear mixed-effects models were used to evaluate the effects of grazing practices and cultivation history, over and above environmental and soil effects, on seasonal

Table 3
Final coefficients for the models relating seasonal mean grassland GHG fluxes of CO_2 and CH_4, to individual fixed-effect factors including management, environmental, and soil properties.

Response	Model	Cultivated	Stocking rate	Soil moisture	Stocking rate:soil moisture	Bulk density	R^2_m	R^2_c
CO_2	Candidate model 1		**+40.49**	**+89.99**	**+53.18**		0.70	0.76
	Candidate model 2		**+53.61**	**+65.75**			0.63	0.71
CH_4	Candidate model 1	**+7.66**		**+6.70**		**+3.44**	0.80	0.81
	Candidate model 2	**+12.72**		**+5.70**			0.75	0.76

Values are regression coefficients. Those in bold indicate significant effects ($P < 0.05$). R^2_m and R^2_c represent the level of deviance of the variable explained by all fixed effects, and both the fixed and random effects, respectively. Stocking rate:soil moisture represents an interaction term.

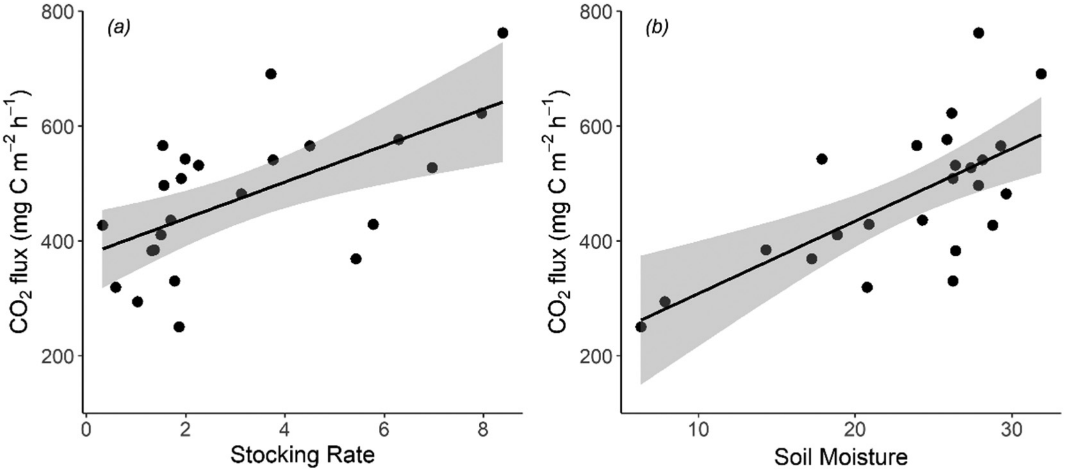

Fig. 3. The relationship between seasonal mean CO_2 flux and (a) cattle stocking rates and (b) soil moisture. Solid line in black shows overall trend across all ranches with 95% confidence intervals in shade ($n = 24$).

mean GHG fluxes. Independent variables were allocated to three subgroups (Table 1), including 1) grazing management practices (comprised of cattle stocking rates, whether the pasture had been previously cultivated, rest to graze ratio, and cattle stock density), 2) environmental variables (soil temperature and moisture content taken at the time of GHG flux measurements in the field), and 3) soil properties (clay content, bulk density, and SOC content). Prior to statistical analyses, all independent variables were analyzed for their association with one another (Pearson's correlations; Fig. S1) to identify redundancy among variables.

The most parsimonious linear mixed-effect model was selected in two stages. First, models of independent variables were analyzed within each sub-group (Tables S2–S4). In correspondence with sample size (12 ranch pairs), a maximum of 3 independent variables were included in candidate models to avoid overfitting (Babyak, 2004). Variables that were correlated ($P < 0.05$) with each other were not included in the same model to overcome problems related to multicollinearity (van der Plas et al., 2020). Candidate models at this initial analytical step were the same for each of the dependent GHG variables. Subsequently, the most parsimonious model was chosen from each sub-group and they were run together to determine comparative model fit (Table S5). To compare and select the best model, Akaike information criterion (AIC) values corrected for small sample sizes (AICc) were calculated, with the best model identified by the lowest AICc value. Models with a $\Delta \leq 2$ AICc were considered to be similar in their explanatory ability. If the *null* model was one of the most parsimonious models, no model was selected. Given our primary interest in the effects of management practices, we ensured that each model contained at least one management variable. After the most parsimonious models were selected for each GHG, β coefficients were determined to assess the direction (positive vs negative) and effect size (magnitude of the standardized β's) of each independent variable on GHG activity.

The best model for each individual GHG flux is presented in Table 3, along with final regression goodness of fit metrics (R^2) and standardized β coefficients. All independent variables were centered and standardized using a "scale" function. Assumptions of normality and homogeneity of variance were examined using the Shapiro-Wilk and Levene's tests, respectively. Assumption of sphericity for repeated-measures ANOVA was verified by Mauchy's test. All assumptions were met for the analyses and no transformation of data was required. Significance was set at $\alpha = 0.05$ for all analyses unless otherwise stated.

3. Results

Seasonal mean CO_2, CH_4, and N_2O fluxes did not differ between the AMP and n-AMP ranches (Fig. 1). Temporal patterns of CO_2 and CH_4 fluxes were comparable between the AMP and n-AMP ranches (Table 2, Fig. 2b, c). Instead, there was a larger pulse of N_2O emissions observed within grasslands from the AMP ranches compared with n-AMP ranches, albeit only in late September of 2018 and late August of 2019 (Table 2, Fig. 1d). Fluxes of CO_2 and N_2O showed a distinct and consistent seasonal pattern, with the highest emission rates in mid-

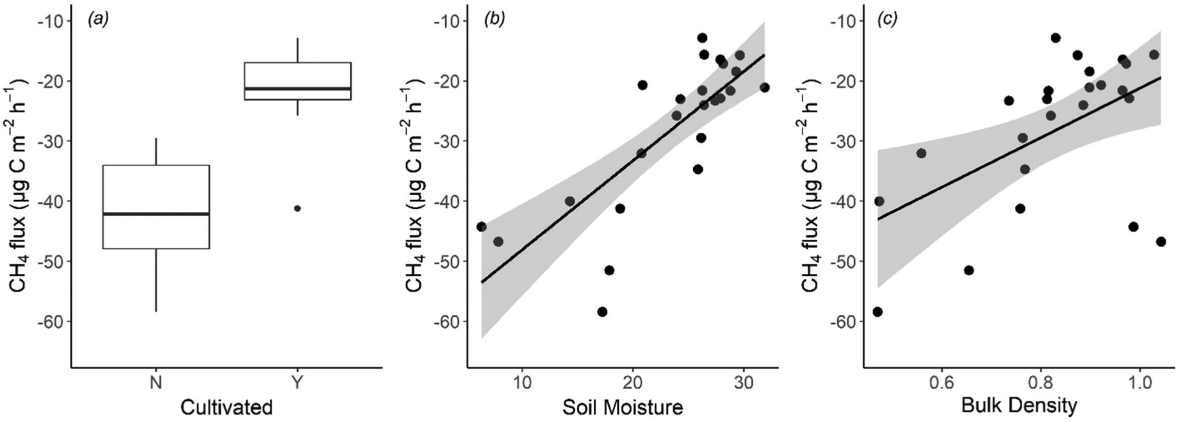

Fig. 4. The relationship between seasonal mean CH_4 flux and (a) cultivation history, (b) soil moisture, and (c) soil bulk density. Solid line in black shows overall trend across all ranches with 95% confidence intervals in shade ($n = 24$).

summer (July) (Fig. 2b, d). Uptake of CH_4 was prevalent throughout the sampling period (Fig. 1c). Within both AMP and n-AMP ranches, CO_2 and N_2O fluxes were mostly positive, ranging from 112 to 1006 mg m^{-2} h^{-1}, and from −1 to 10 μg m^{-2} h^{-1}, respectively (Fig. 2b, d). In contrast, all grasslands were CH_4 sinks, with uptake rates ranging from −58 to −10 μg m^{-2} h^{-1} (Fig. 1c).

When GHGs were examined relative to specific management practices across all ranches as a subgroup, varying fixed effects were evident, depending on the individual GHG examined (Tables S2–S4). Cattle stocking rate had the strongest association with seasonal mean CO_2 flux (Table S2), while cultivation history was the principal factor accounting for variation in CH_4 fluxes (Table S3). Among environmental variables, soil moisture content had the strongest association with CO_2 (Table S2) and CH_4 (Table S3) fluxes. Finally, among the soil properties, bulk density was most important for regulating the activity of seasonal mean CH_4 flux (Table S3). In contrast, observed N_2O emissions were poorly explained by management, environmental and soil properties since their explanatory power did not differ from the *null* model (Table S4).

When fixed factors from the leading models of the grazing management, environmental and soil subgroups were tested together, they were able to explain 63 to 80% of the variation in GHG fluxes (Table 3). For the seasonal mean CO_2 flux, the final model was able to explain 70% of the total variance, with cattle stocking rate, soil moisture content, and their interaction, being the most important explanatory variables (Table S5). Final beta coefficients showed that seasonal mean CO_2 emissions increased with increases in both cattle stocking rate and soil moisture content (Table 3, Fig. 3). The final model explained 80% of the total variation in seasonal mean CH_4 flux, with cultivation history and bulk density being the most influential variables, followed by soil moisture content (Table 3). In particular, prior cultivation of grasslands was found to decrease seasonal mean CH_4 uptake from −42.16 to −21.35 μg m^{-2} h^{-1} (Fig. 4a). Seasonal mean CH_4 uptake also decreased with increasing soil moisture content and bulk density (Fig. 4b, c).

4. Discussion

Under field conditions, many biotic and abiotic factors act in concert to regulate biogeochemical cycling, making it imperative to evaluate GHG fluxes from grazing lands in-situ. Moreover, examining grasslands directly exposed to grazing, in this case by cattle, is more representative of the pragmatic and flexible management taking place on grazing lands, as compared with many field studies conducted using simulated grazing (i.e., clipping or mowing) in small plots (Teague et al., 2013). Studies on operationally grazed lands are more likely to lead to a robust conclusion on the potential impact of specialized grazing systems, including AMP management, in mitigating GHG emissions. Our results demonstrate that GHG fluxes generally differed little between grasslands grazed with AMP and n-AMP systems, and instead GHGs were regulated by specific conditions such as cultivation history, cattle stocking rate, soil moisture content, and bulk density.

Our findings show that grasslands were a source of CO_2 and N_2O emissions but a CH_4 sink throughout the growing season, regardless of the grazing system. The overall CH_4 sink effect aligns with other studies on managed grasslands in Switzerland and the Great Plains of North America (Imer et al., 2013; Liebig et al., 2010). Fluxes of all three GHGs were highly variable across the growing season, with the highest emission rates during the summer months when precipitation (and therefore soil moisture content) and temperature were relatively high. The lack of an AMP grazing effect on seasonal mean GHG fluxes or CH_4 uptake in this study contrasts previous findings that AMP grazing can enhance the CH_4 sink capacity of grasslands (Dowhower et al., 2020). Additionally, we found higher N_2O emissions were present in AMP-grazed grasslands, but only late in the growing season of both 2018 and 2019. Notably, these field results do not corroborate findings from a recent laboratory incubation study using soil samples from the same ranch sites (Shrestha et al., 2020). Incubation for up to 102 d at varying temperatures and moisture contents resulted in greater CH_4 uptake in soils from AMP grazed grassland than in the n-AMP grasslands, particularly in the early incubation period (day 1 and day 13) and under higher (25 °C) soil temperature (Shrestha et al., 2020). While the incubation study was designed to isolate the effects of microclimate on soil-derived GHG emissions in the absence of vegetation, the field-based GHG fluxes reported on here represent the combined effects of soil, vegetation, and microclimatic conditions. For example, while the incubation study suggested that soil microbes within AMP-grazed soils favor greater CH_4 uptake (Shrestha et al., 2020), this benefit may be offset in the field by the exudation of C substrate from plant roots that stimulates microbial activity and fuels methanogenesis (Waldo et al., 2019).

The lack of grazing system effects on seasonal mean GHG fluxes in the current field study also could be due to our simplified categorical differentiation between grazing treatments as either AMP or n-AMP, because both treatments exhibited significant internal variation in specific management practices (Bork et al., 2021). In this case, the studied grasslands encompassed a continuum of management practices, with the simple binary separation of AMP and n-AMP ranches therefore inadequate to test for grazing induced responses (Hunt et al., 2014; McDonald et al., 2019).

Among grazing management practices, livestock stocking rate remained the most straight forward and arguably the most important grazing management decision (Animut et al., 2005; Pinares-Patiño et al., 2007). Of the management factors tested, cattle stocking rate was the key factor regulating seasonal mean CO_2 flux. We show that seasonal mean CO_2 fluxes increased with cattle stocking rate across all ranches, which is consistent with a recent study showing that a loss of SOC through CO_2 emissions to the atmosphere only occurred under heavy stocking as compared with moderate stocking (Owensby and Auen, 2020). One possible explanation is the stimulatory effect of higher stocking rates on C cycling (e.g., via soil organic matter decomposition), and therefore on CO_2 emission. For example, increased excretal deposition by cattle under heavy stocking may stimulate soil organic matter mineralization and thereby promote CO_2 emission by microbes (Soussana et al., 2004). Compared with moderate stocking rates, heavy stocking rates cause progressive reductions in forage production (Holechek et al., 2004; Zhang et al., 2015; Porensky et al., 2016), which eventually leads to reduced C inputs and losses of SOC, although such C losses in the Great Plains region have not been detected by standard tests for soil organic matter (Derner and Schuman, 2007). Our results suggest that the maintenance of moderate stocking rates is an important option for reducing CO_2 emissions in these northern temperate grasslands.

Our results also demonstrated that grasslands with a history of cultivation had lower CH_4 uptake. The lower CH_4 uptake in cultivated grasslands probably can be attributed to cultivation-induced reductions in soil aggregates, and associated increases in soil compaction, both of which could reduce gas diffusion (i.e., O_2 and CH_4) into soil (Ding et al., 2004) or decrease methanotrophic activity. Methanotrophs are highly sensitive to changes in microaerophilic conditions (Van Bodegom et al., 2001) and do not have competitive advantages over limited O_2 availability in compacted soils (Crill et al., 1994; Goldman et al., 1995). Thus, it may be difficult for methanotrophs to reestablish their community in cultivated soils (Crill et al., 1994), even after these lands have been converted back into grassland for more than a decade, such as those in our study.

Among the microclimatic factors tested, soil moisture content was a key driver for both CO_2 and CH_4 fluxes, which is consistent with Shrestha et al. (2020) and many other studies (e.g., Horz et al., 2005; Xu et al., 2003). Seasonal mean CO_2 emissions increased with soil moisture content, presumably because soil water can stimulate the growth and activity of grass roots and microbes (Tang et al., 2019), leading to increased root respiration and microbial mineralization, and in turn, enhanced CO_2 release (Curtin et al., 2012; Savadogo et al., 2007; Wu et al., 2010). While hump-shaped relationships between CH_4 uptake and water filled pore space were frequently observed (Dijkstra et al., 2011), we show that the rate of CH_4 uptake was inversely associated with increasing soil moisture content. One possible explanation is that the increase in soil moisture content might have hampered CH_4 uptake by reducing diffusive CH_4 and O_2 transport in these grassland soils, in turn reducing CH_4 oxidation (Hartmann et al., 2011; Wu et al., 2010; Yao et al., 2019). Although soil moisture content also has been found to be a key factor driving N_2O emission by altering microbial nitrifying and denitrifying processes (Cai et al., 2016; Oertel et al., 2016), we did not find any significant effect of soil moisture content on seasonal mean N_2O emissions. This is likely due to the large temporal and spatial variability of N_2O emission resulting from the uneven distribution of excretal returns (covering 1–2% of the grassland annually), soil heterogeneity, and the episodic nature of N_2O emissions (Saggar et al., 2004; Saggar et al., 2007).

Among the soil properties tested in our study, bulk density was the main driver of CH_4 fluxes in the final model, with higher soil bulk density associated with lower CH_4 uptake. Decreased CH_4 uptake with increasing soil bulk density is likely the result of reduced diffusion of O_2 and CH_4 gases into the soil, and consequent reductions in the soil microbial processes responsible for CH_4 oxidation - an aerobic process (Ding et al., 2004; Grosso et al., 2000). None of the soil properties (including SOC, texture, and bulk density) were selected in the final model reporting on field-based CO_2 emissions, suggesting that the effects of these soil properties on CO_2 flux remained relatively small compared to specific management (i.e., stocking rate) and microclimatic environmental (i.e., soil moisture content) drivers.

5. Conclusions

We conclude that overall field-based GHG fluxes did not differ between grasslands subject to AMP and n-AMP grazing, and that AMP grazing does not have an advantage over n-AMP grazing in mitigating GHG emissions. Instead, GHG fluxes were regulated by specific conditions, such as prior cultivation history, cattle stocking rate, soil moisture content, and bulk density. Specifically, CO_2 emissions increased with increasing cattle stocking rate, while CH_4 uptake potential was lower in grasslands having a known history of cultivation. Therefore, avoiding the use of high stocking rates on grasslands and halting the continued conversion of grasslands may be impactful strategies for reducing GHG fluxes in these northern temperate grasslands. Future efforts to develop optimal management strategies towards reducing GHG emissions from grazing lands should take environmental and soil conditions (i.e., soil moisture content and bulk density) into consideration given their significant effects on field GHG emissions.

CRediT authorship contribution statement

Zilong Ma: Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Bharat M. Shrestha:** Investigation, Writing – review & editing. **Edward W. Bork:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **Scott X. Chang:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **Cameron N. Carlyle:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **Timm F. Döbert:** Data curation, Writing – review & editing. **Laio Silva Sobrinho:** Investigation. **Mark S. Boyce:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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