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Grazing increased alpine grassland soil respiration rates on the Tibetan Plateau

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Introduction: Grazing activities were intensive in alpine grasslands and may alter the soil respiration rates across the Tibetan Plateau. However, grazed alpine grassland soil respiration rates and their underlying driving mechanisms remain unclear across the Tibetan Plateau.

Methods: In this study, we synthesized data from 38 groups to clarify the response of CO_2 emission rates to different grazing intensities.

Results: The effect size was 0.039 ± 0.051 of grazed activity on the ecosystem respiration rates, indicating that grazing increased respiration rates by 3.99%. Furthermore, effect sizes were −0.146 ± 0.209 and 0.076 ± 0.046 in alpine steppes and alpine meadows, respectively, indicating a 13.58% reduction and a 7.90% increase. The effect sizes were 0.051 ± 0.112, 0.029 ± 0.075, and 0.055 ± 0.089 in light, moderate, and high grazing intensity, respectively. Moderate grazing mitigated grassland CO_2 emission rates compared with light and high grazing. Both air temperature and soil organic carbon significantly increased grassland ecosystem respiration rate, explaining 38.47% and 22.57% of variance heterogeneity.

Discussion: In addition, both future global warming and increasing soil organic carbon would increase alpine grassland CO_2 emission rates on the Tibetan Plateau.

KEYWORDS

grazing intensity, soil respiration rates, meta-analysis, the Tibetan Plateau, air temperature

1 Introduction

The Tibetan Plateau covered an area of 2.50 million km^2 at an average altitude of 4,000 m (1). Alpine grasslands comprise the largest alpine ecosystem in the world and provide critical ecosystem services on the Tibetan Plateau (2). Grazing is the primary land use practice in alpine ecosystems (3). Overgrazing is a major contributor to grassland degradation, and grazing alters grassland soil carbon flux and the cycling of alpine meadow (4). Carbon flux between grassland and atmosphere is an important part of the terrestrial carbon cycle, and soil respiration accounts for approximately 25% of global carbon dioxide exchange (5).

Ecosystem respiration outside the growing season was at least equivalent to 9.4% of the CO_2 fluxes during the growing season (6). The annual ecosystem respiration rate was 341.5 g CO_2 m^{-2} in alpine grasslands on the Tibetan Plateau (6). The annual cumulative soil CO_2 emissions of alpine meadow and alpine shrub meadow were 284 and 470.8 g m^{-2} on the northeastern Tibetan Plateau, respectively (4). Grazing exclusion increases alpine meadow soils' CO_2 emissions and reduced soil organic carbon stocks (4). However, a 3-year study revealed that grazing increased soil respiration by an average of 13.7% compared to fenced grasslands (7). Grassland soil respiration rates gradually decreased with grazing intensity increasing (8). Grassland soil respiration rose by 5.23%, 2.94%, and 5.65% under light, moderate, and heavy grazing on the Loess Plateau, respectively (9). Heavy grazing significantly increased saline-alkaline grassland heterotrophic respiration (10). In the grazed grasslands, less carbon was lost by shoot respiration, and more was translocated in belowground biomass (11). Furthermore, it was also reported that grazing exclusion significantly decreased annual soil respiration by 21.4% on the Tibetan Plateau (2). There was no significant difference in soil respiration rates between grazing and fencing across all vegetation types (12).

Grazing increases soil respiration primarily by enhancing soil moisture and temperature, which stimulate plant root and microbial activity, and increased aboveground biomass contributes to higher soil respiration through greater organic matter availability and improved decomposition conditions (13). Furthermore, grazing intensity affects soil respiration differently by altering above- and belowground biomass, soil structure, and microbial activity, with light and moderate grazing generally increasing respiration, while heavy grazing tends to reduce it (7). Daily soil respiration was mainly driven by soil temperature in both alpine meadows and steppes (5, 6). Soil CO_2 flux was positively correlated with soil temperature (4). Stepwise regression showed that soil temperature and soil moisture controlled average grassland soil respiration rates (14). Soil temperature explained 63%–83% of seasonal respiration variations on the Tibetan Plateau (15). Changes in soil respiration were primarily driven by variations in autotrophic respiration (9). Increased soil bulk density reduces soil porosity, which restricts the movement of air and water, subsequently inhibiting the respiration processes of soil microorganisms and plant roots (16). A rapid increase in soil respiration was induced by the influx of precipitation, likely driven by enhanced microbial activity and organic matter decomposition (17, 18). Winter soil respiration was driven mainly by microbial oxidation of soil organic matter on the Tibetan Plateau (18). However, mechanisms by which grazing intensity modulates soil respiration in diverse alpine grasslands remain unclear. This meta-analysis systematically quantifies grazing effects across intensities, highlighting the roles of soil temperature, organic carbon, and grazing practices in soil respiration dynamics on the Tibetan Plateau.

This meta-analysis offers a comprehensive quantitative synthesis of grazing impacts, providing insights into ecosystem responses across diverse grassland conditions. We compiled data on soil respiration rates under varying grazing intensities across the Tibetan Plateau to test the hypothesis that grazing activity significantly elevates alpine grassland respiration rates by enhancing soil microbial activity.

2 Materials and methods

2.1 Data compilation and selection criteria

We collected published papers using the keywords "carbon dioxide or CO_2", "grazing", "respiration rate", and "Tibet*" in Web of Science from 1990 to December 2022. After applying inclusion criteria, such as studies that used field-based soil respiration measurements and reported grazing intensity levels, a total of 98 relevant articles were selected. These studies were further categorized based on grazing intensity (light, moderate, and heavy) and grassland type (alpine steppe or meadow) for more detailed analysis. During the data collection process, we extracted soil respiration rate measurements for light, moderate, and heavy grazing directly from the original studies, ensuring consistency and comparability with their respective control treatments. Data were extracted from paper figures by the WebPlotDigitizer software. In this study, we selected 25 published studies, including 38 field experiment results (Figure 1), soil physical characteristics, and plant communities.

The log response ratios were used as a measure of effect size. We performed a random-effect model meta-analysis.

$$\ln R = \mathrm{Ln}\frac{x_e}{x_c} = \ln(x_e) - \ln(x_c)$$

where x_c and x_e are the mean values of each individual trait in control and the treatment groups, respectively.

Grazing on CO_2 rates and confidence interval were calculated using the random-effect model.

The weight of an individual effect of grazing on CO_2 emission rates was determined:

$$w_i^* = 1/(v_i + \tau^2)$$

where v_i and τ^2 represent the intra-study variance and inter-study variance, respectively.

The average effect size was analyzed:

$$\bar{y} = \frac{\sum_{i=1}^{k} w_i^* y_i}{\sum_{i=1}^{k} w_i^*}$$

The heterogeneity test of effect size was measured:

$$Qt = \sum_{i=1}^{k} wi^* (yi - \bar{y})^2$$

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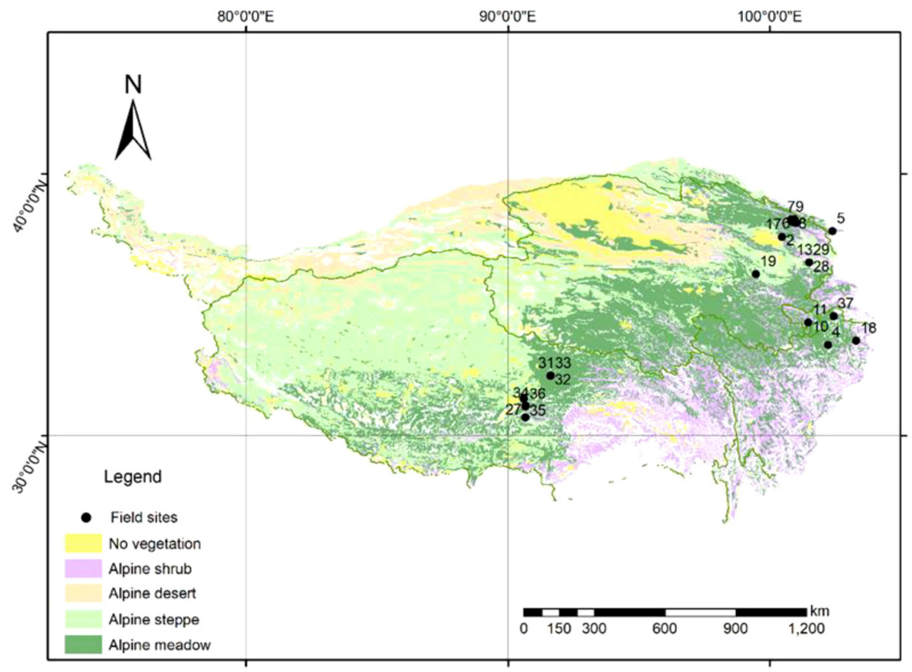

FIGURE 1
Main vegetation types' distribution and 38 research sites on the Tibetan Plateau.

The influence of explanatory variables on effect size was determined:

$$Qm = \sum_{j=1}^{p}\sum_{i=1}^{ni} wi^{*}(yij - \bar{y})^{2}$$

Here, n_i and p meant sample sizes of heterogeneity test value of the control and moderator variable, where i and j meant effect sizes of control and single treatment.

2.2 Statistical analysis

In this study, a random-effects model was employed for the meta-analysis, utilizing the *metafor* 1.9-8 package within the R software environment (version 3.6.2). This approach allowed for the incorporation of variability across studies, providing more robust and generalized results. Meanwhile, residual heterogeneity was tested with categorical and continuous variables using mixed-effect models (mods).

3 Results

3.1 Grazing activity increased alpine grassland respiration rates on the Tibetan Plateau

The effect size was 0.039 ± 0.051 (−0.061–0.139, 95% confidence interval) of grazing activity on ecosystem respiration rates of alpine grasslands (Figure 2). This indicated that grazing increased respiration rates by 3.99% across the Tibetan Plateau, and this was not significant with control. Furthermore, effect sizes were −0.146 ± 0.209 and 0.076 ± 0.046 in alpine steppes and alpine meadows, respectively (p < 0.05). These decreased and increased ranges were −13.58% and 7.9% (Table 1).

3.2 Effects of different grazing intensity on grasslands CO_2 rates through meta-analysis across the Tibetan Plateau

With the grazing intensity increasing, the effect size decreased firstly, then it increased significantly. The effect sizes were 0.051 ± 0.112, 0.029 ± 0.075, and 0.055 ± 0.089 (Table 2), corresponding to an increase of 5.23%, 2.94%, and 5.65%, respectively. This also indicated that different grazing intensities did not significantly affect ecosystem respiration rates on the Tibetan Plateau. Moderate grazing mitigated grassland CO_2 emission rates. Meanwhile, a significant residual heterogeneity existed (p < 0.001), and we would explain this with categorical variables next.

3.3 Effects of climate and soil physical factors on alpine grassland ecosystem respiration rates

Both air temperature and soil organic carbon significantly influenced grassland ecosystem respiration rate through the

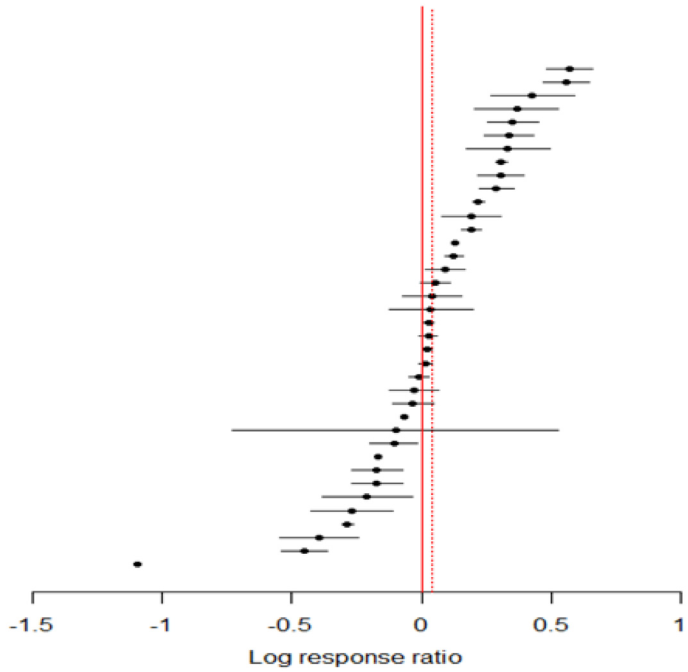

FIGURE 2
Forest plots of 38 effect size estimates for responses of alpine grassland respiration rates to grazing activities. RR, response ratios (effect sizes), and black dots with 95% confidence intervals (CI). The red line and the red dashed line meant RR = 0, and average effect size.

moderator test analysis ($p < 0.001$). These factors could explain 38.47% and 22.57% of variance heterogeneity in the CO_2 emission rates between the control and grazed meadow (Table 3). In addition, soil total nitrogen and longitude explained 7.89% and 1.71% of the variation, and this did not reach significance. However, latitude, precipitation, biomass, and altitude had little influence on the effect size. Furthermore, both global warming and increasing soil organic carbon would increase alpine grassland CO_2 emission rates.

3.4 Publication bias analysis of effect sizes on alpine grassland ecosystem respiration rates

In this study, Egger's regression test for funnel plot asymmetry indicated that the result was not significantly affected by a publication bias using the meta-analytic models ($z = 0.3799$, $p = 0.7040$, Figure 3).

4 Discussion

4.1 Effects of grazing activity and intensities on alpine grassland CO_2 emission rates on the Tibetan Plateau

Alpine grasslands on the Tibetan Plateau sequester carbon at a rate of 32 Tg C per year (35). China's terrestrial ecosystems had a soil respiration rate of 777.90 g C m^{-2} $year^{-1}$, and in recent years, the soil respiration rate in grasslands has gradually increased (35). A strongly increased herd density has promoted alpine grassland ecosystem respiration rates (19). Livestock grazing enclosures could be an effective strategy for reducing CO_2 emissions in alpine meadows (20). The response of these carbon stocks and processes to recent land use changes remains unknown.

In this study, we revealed that grazing slightly increased soil respiration rates of alpine grasslands approximately 3.99% across the Tibetan Plateau. This increase likely results from moderate grazing stimulating certain microbes and enzyme activity, thus

TABLE 1 Effect sizes of graze treatment on soil respiration rates in alpine steppe and meadow on the Tibetan Plateau.

Items	Effect sizes	Increased range (%)	95% confidence interval	p	df
Graze treatment	0.039 ± 0.051	3.99	−0.061–0.139	0.442	37
Alpine steppe	−0.146 ± 0.209 b	−13.58	−0.540–0.248	0.468	5
Alpine meadow	0.076 ± 0.046 a	7.90	−0.015–0.166	0.102	31

Effect sizes meant average ± standard error. Same letters meant no significant differences in the same column.

TABLE 2 Effect sizes of different grazing intensities on soil respiration rates in alpine grasslands on the Tibetan Plateau.

Grazing intensity	Effect sizes	Increased range (%)	95% confidence interval	*p*	df
LG	0.051 ± 0.112 a	5.23	−0.168–0.270	0.648	6
MG	0.029 ± 0.075 b	2.94	−0.118–0.176	0.698	20
HG	0.055 ± 0.089 a	5.65	−0.120–0.230	0.539	9

Effect sizes meant average ± standard error. Same letters meant no significant differences in the same column. LG, MG, and HG meant light grazing, moderate grazing, and high grazing intensity.

TABLE 3 Analysis of air temperature and altitude and other factors on effect sizes.

Moderators	Test of moderators (QM)	*p*	Model	R^2 (%)	df
Temperature	15.613	<0.0001	Y = 0.0220 + 0.0998 x	38.47	36
SOC	5.678	0.0172	Y = −0.2073 + 0.0291 x	22.57	15
TN	1.781	0.1821	Y = 0.3826 − 0.1119 x	7.89	8
Longitude	1.725	0.1890	Y = 1.4482 − 0.0143 x	1.71	36
Latitude	1.009	0.3151	Y = −0.5798 + 0.0177 x	0.14	36
Precipitation	1.044	0.3069	Y= 0.2345 − 0.0004 x	0.00	36
Biomass	0.658	0.4170	Y =0.0217 + 0.0003 x	0.00	28
Altitude	0.367	0.5449	Y = −0.1491 − 0.0001 x	0.00	36

Y means effect size. SOC and TN meant soil organic carbon and total nitrogen.

supporting respiration (21). Grazing also enhances soil moisture and vegetation regeneration, which sustain microbial activity by improving soil structure and carbon access. Similar studies were detected with grazed and fenced meadow soil respiration rates of 295.67 and 284.67 g m^{-2} with an increased range of 3.72% on the northern Tibetan Plateau (22). Meanwhile, Hu reported that grazing activity increased grassland CO_2 emission rates from 610.4 to 625.3 g m^{-2}, approximately 2.38% on the northeast Tibetan Plateau (14). Grazing significantly increased soil respiration by 13.1% (23). Furthermore, some studies indicated that the increased range of alpine grassland soil reparation rates were 43.48% and 29.57% on the north and central Tibetan Plateau (24, 25). However, other studies demonstrated that grazing decreased grassland CO_2 emission rates approximately 56.96%, 23.37%, and 3.34% on the northern, southeastern, and southwestern Tibetan Plateau, respectively. Grazing exclusion increased respiration rates in alpine steppe and alpine meadow (24).

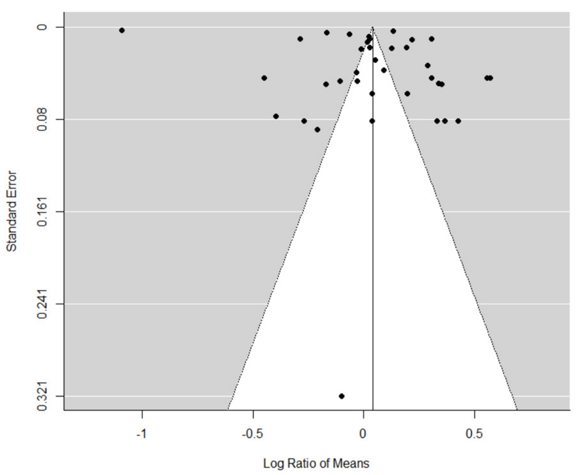

FIGURE 3
Funnel plot of effect sizes of grazing on grassland soil respiration. Egger's regression test for funnel plot asymmetry (z = 0.3799, p = 0.7040).

Robust spatial heterogeneity was observed across the Tibetan Plateau, driven by variations in climate, soil properties, and vegetation. Grazing enhances soil respiration by increasing soil moisture and temperature, and stimulating root exudation and microbial activity. These findings highlight the complexity of grazing impacts on carbon cycling, underscoring the need to consider site-specific factors when assessing its broader effects on soil respiration and CO_2 fluxes.

Previous studies suggested that different grazing intensities should be considered when evaluating future carbon cycles in grazed ecosystems on the Tibetan Plateau (23). Annual soil respiration rate is almost twice as high in a lightly grazed meadow (574.2 g m^{-2}) as in a fenced meadow (268.8 g m^{-2}) on the Tibetan Plateau (26). Increased range of respiration rates were 26.38%, 42.63%, and 43.49% in light, moderate, and high grazed meadows (25). Alpine meadows emitted 196 and 216 g CO_2 m^{-2} in light and high grazed intensity with a range of 30.61% and 34.70% on the northern Tibetan Plateau, respectively (27). The present study indicated that increased range was 5.23%, 2.94%, and 5.65% in light, moderate, ang high grazed meadows across the Tibetan Plateau. This study found that moderate grazing led to the smallest increase in soil respiration compared to light and heavy grazing. The plant–microbe interaction hypothesis suggests that moderate grazing strikes an optimal balance between vegetation cover and microbial activity by preserving root growth and soil structure. Light grazing may not sufficiently activate microbial processes, limiting carbon cycling, while heavy grazing can degrade soil integrity, accelerating decomposition and CO_2 emissions. In contrast, moderate grazing enhances organic matter input and stabilizes microbial communities, effectively reducing carbon loss from excessive decomposition. In conclusion, moderate grazing mitigated alpine grassland soil respiration rates.

4.2 Driven factors on the effect size of grazing on alpine grassland respiration rates across the Tibetan Plateau

Grazing activity altered soil carbon storage in alpine grassland ecosystems by affecting soil respirations (16). Soil temperature and moisture well explained the seasonal variations of ecosystem respiration rates in alpine steppe and alpine meadow (24). Soil moisture and belowground biomass explained approximately 83.1% of the respiration variation of alpine meadows (28). Livestock enclosure decreased the temperature sensitivity value of CO_2 emission (26). Positive correlations between soil temperature and respirations were observed during the 3-year study (15).

In conclusion, we determined that both air temperature and soil organic carbon significantly influenced the effect size of grazing on soil respiration across the Tibetan Plateau. Higher air temperatures likely accelerate the metabolic activity of microbes and plant roots, enhancing their respiration, while the increase in soil organic carbon provides more substrate for microbial decomposition, further promoting CO_2 emissions. The increase in soil temperature caused by grazing helps to alleviate the temperature limitations on soil respiration, making it more effective (23). Meanwhile, the temperature sensitivity of soil respiration was also increased by grazing activity (29, 30). The second possible explanation was a larger stimulation of root biomass by increased soil organic carbon, and then increased CO_2 emissions (31). Furthermore, soil organic carbon was the fundamental substrate for soil microbial respiration (32–34). Consequently, global warming and increasing soil organic carbon through degraded grassland restoration would increase alpine grassland CO_2 emission.

5 Conclusions

Grazing activity lightly increased alpine grassland soil respiration rate across the Tibetan Plateau. Meanwhile, grazing decreased soil respiration rate in alpine steppes. Effect sizes of light and high grazing significantly exceeded moderate grazing. Moderate grazing mitigated grassland soil respiration rates. Both air temperature and soil organic carbon significantly influenced the effect size of grazing on the grassland ecosystem respiration rate. Future warming scenarios and increasing soil organic carbon could promote alpine grassland CO_2 emission on the Tibetan Plateau.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YM: Data curation, Investigation, Writing – original draft. YD: Methodology, Writing – review & editing. KC: Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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