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Xiang Wang
Lanzhou University

Hongbiao Zi
Lanzhou University

Jianbin Wang
Lanzhou University

Zhenhua Zhang
Northwest Institute of Plateau Biology

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Grazing-induced changes in soil microclimate and aboveground biomass modulate freeze–thaw processes in a Tibetan alpine meadow

Xiang Wang [a], Hongbiao Zi [a], Jianbin Wang [a], Xiaowei Guo [c], Zhenhua Zhang [c], Tao Yan [a], Qiang Wang [a,*], Jin-Sheng He [a,b,**]

[a] State Key Laboratory of Herbage Improvement and Grassland Agro-Ecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, 768 Jiayuguan W Road, 730020, Lanzhou, China

[b] Department of Ecology, College of Urban and Environmental Sciences, Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, 5Yiheyuan Rd., 100871 Beijing, China

[c] Qinghai Haibei National Field Research Station of Alpine Grassland Ecosystem and Key Laboratory of Adaptation and Evolution of Plateau Biota, Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810008, China

A R T I C L E I N F O

Key words:
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Permafrost region

A B S T R A C T

Grazing is the most important disturbance to grasslands, especially on the Tibetan Plateau, which sustains the livelihoods of tens of thousands of herders. However, the effects of grazing intensity and associated changes in vegetation on freeze–thaw processes (FTPs) in seasonal permafrost regions remain unclear. Here, two years of continuous in situ observations from a controlled grazing intensity experiment were used to examine FTPs and influencing factors in an alpine meadow on the Eastern Tibetan Plateau. Our results showed that a higher grazing intensity led to a shorter frozen period, extended freezing and thawing periods, and earlier initiation of freezing and thawing periods. Furthermore, grazing increased soil temperature and active ($> 0\ ^\circ C$) and effective ($> 10\ ^\circ C$) accumulated temperatures. The soil diurnal temperature range increased linearly with grazing intensity, whereas soil moisture did not vary with soil temperature. Our results demonstrated that the freezing and frozen periods were mainly influenced by soil temperature and the diurnal temperature range, whereas soil moisture played a critical role in the variation in the thawing period. The reduction in aboveground biomass elicited changes in FTPs, including shortening of the frozen period and lengthening of the thawing and freezing periods. Collectively, our results highlight that the combination of grazing-induced changes in vegetation and changes in subsurface temperature and moisture leads to changes in freezing and thawing processes.

1. Introduction

The Tibetan Plateau is located at high altitudes and has the largest area of seasonal permafrost at low and middle latitudes worldwide (Zhao et al., 2004; Zou et al., 2017). As Earth's Third Pole, the Tibetan Plateau is highly sensitive to both climate change and anthropogenic activity (Guo et al., 2012; Wu and Zhang, 2008; Yang et al., 2010). Under global warming scenarios, the active layer thickness of permafrost increases, and the maximum frozen depth decreases on the Tibetan Plateau, which is aggravated by anthropogenic activities such as livestock grazing (Cheng and Wu, 2007; Guo et al., 2012; Xue et al., 2009; Zhao et al., 2004). Grazing has profound consequences on alpine ecosystem functions on the Tibetan Plateau (Dorji et al., 2018), including plant productivity, community structure and composition (Chen et al., 2011), and soil microclimate (soil temperature and moisture) (Yan et al., 2018).

The soil microclimate can shape plant communities, soil microbial communities, and element balance and is an important variable controlling the processes and functions of terrestrial ecosystems (Castano et al., 2018; von Haden et al., 2019). Generally, the soil microclimate is regulated by biological (e.g., vegetation cover and litter layer and their mediated incoming/outgoing radiation) and abiotic (e.g., soil compaction, snowpack, and air temperature and moisture) factors (Harte et al., 1995). Although differences in soil microclimates among management

* Corresponding author.
** Corresponding author at: State Key Laboratory of Herbage Improvement and Grassland Agro-Ecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, 768 Jiayuguan W Road, 730020 Lanzhou, China.
E-mail addresses: wqiang@lzu.edu.cn (Q. Wang), jshe@pku.edu.cn (J.-S. He).

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practices have been demonstrated (Castano et al., 2018; von Oppen et al., 2022), the magnitude of the effect of grazing on soil microclimates in the Tibetan Plateau remains uncertain. Grazing significantly affects grassland composition, structure, and surface soil compaction in alpine ecosystems through defoliation (removal of plant shoot tissue) and trampling (Liu et al., 2015). Therefore, grazing alters the energy exchange between plant-soil-atmosphere systems by reducing the insulating effects of vegetation and deadfall (Chen et al., 2009; Liu et al., 2009; von Oppen et al., 2022). We further speculated that short-term grazing-induced reductions in aboveground biomass and the litter layer would significantly magnify soil temperature changes, while soil moisture changes may not be significant. These changes in soil temperature and moisture will have a significant effect on the surface microclimate (Aalto et al., 2013; Babić et al., 2016; Li et al., 2000; Shao et al., 2017; Yan et al., 2018). However, in situ monitoring on the effects of grazing on the soil microclimate in alpine meadows on the Tibetan Plateau, especially regarding the changes in freeze–thaw processes (FTPs) in soil caused by the plant communities and soil microclimate, are still scarce.

Soil temperature and moisture and vegetation cover are important factors that affect FTPs (Ji et al., 2022; Jia et al., 2020; Yi et al., 2013). As a common environmental disturbance in alpine meadows on the Tibetan Plateau, FTPs strongly affect soil microbial activity, diversity, and respiration (Lv et al., 2022; Wang et al., 2019; Yang et al., 2023). Recently, increasing evidence has revealed the effects of grazing on greenhouse gas emissions and nutrient cycling during the freeze–thaw period (Hamamoto et al., 2020; Li et al., 2021; Wang et al., 2021). However, the potential effects of grazing on FTPs and the underlying mechanisms responsible for these changes have not yet been identified in alpine ecosystems. Encouragingly, the research community has started addressing the interactions between FTPs and vegetation cover and soil temperature and moisture (Jia et al., 2020; Yang et al., 2020; Zhu et al., 2017). Both field experiments and simulation studies have shown that increased vegetation cover delays permafrost thawing in the Arctic (Blok et al., 2010; Yi et al., 2007). The freezing and thawing on the Tibetan Plateau are advanced through the insulating effect of vegetation (Hu et al., 2008). The changes in freeze–thaw cycles caused by fluctuations in the soil thermal system can alter the exchange of heat and water between the land surface and the atmosphere (Guo et al., 2010; Guo et al., 2011), thus affecting vegetation coverage (Chen et al., 2016). Soil temperature and moisture are closely correlated in the active layer of the Tibetan Plateau (Chang et al., 2015). Soil water migrates from warmer to cooler soil layers during FTPs, and this migration, which is controlled by the soil temperature gradient, may alter the thermal and hydrological properties of the soil layer (Jiang et al., 2018). In general, low vegetation coverage and soil moisture on the Tibetan Plateau will positively drive the FTPs (Ding et al., 2023; Jiang et al., 2018). Thus, studying the effects of grazing intensity on FTPs is critical for understanding grazing-related ecological processes in alpine meadow ecosystems.

Here, the effects of different grazing intensities on soil microclimate and FTPs in an alpine meadow were investigated over a two-year period. Our objectives were to determine (i) the response of soil microclimate (soil temperature and moisture) to grazing intensity and (ii) the impact of grazing intensity on FTPs (i.e., changes in start and end dates and duration of FTPs) and the driving factors. We hypothesized that different grazing intensities would advance or delay FTPs by changing the aboveground vegetation coverage and soil microclimate (soil temperature and moisture) of alpine meadows, which are crucial for understanding belowground phenological dynamics.

2. Materials and methods

2.1. Study site

The study site is set in the northeastern Tibetan Plateau (Fig. 1a),

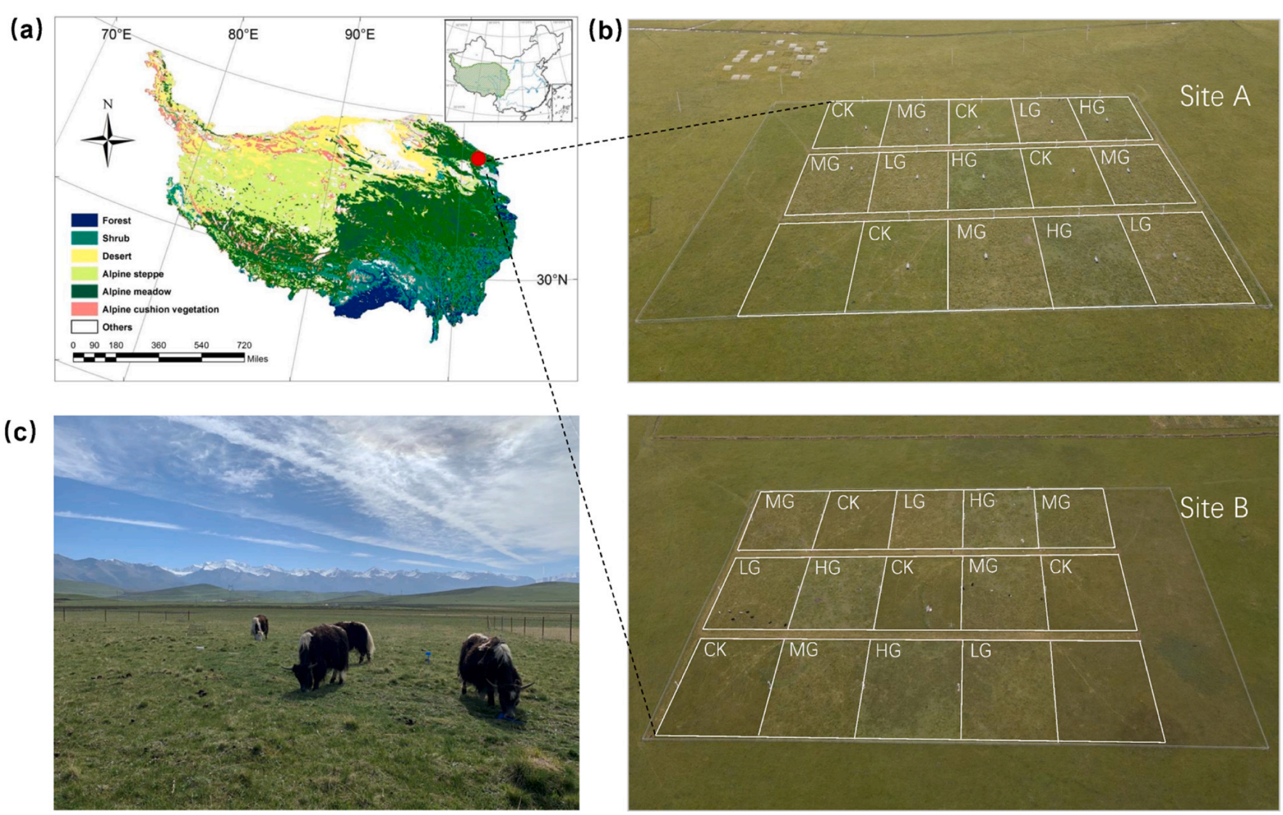

Fig. 1. Geographical location (a) and landscape (b) of the studied long-term grazing experiment platform and yak grazing in the sites (c) in an alpine grassland on the Tibetan Plateau. CK, control; LG, Light grazing; MG, Moderate grazing; HG, Heavy grazing.

close to the Haibei Alpine Grassland Ecosystem Research Station (101°19′ E, 37°36′ N; 3215 m a.s.l.). The region experiences lengthy, cold winters and brief, cool summers owing to the continental monsoon climate. From 1981–2014, the mean annual temperature and precipitation were − 1.1 °C and 487.8 mm (Wang et al., 2020). The hourly minimum was − 37.1 °C in January and the maximum was 27.6 °C in July. Approximately 84% of the precipitation occurred from May to September. The major alpine meadow species are *Elymus nutans*, *Stipa aliena*, *Kobresia humilis*, *Poa pratensis*, *Gentiana straminea*, and *Helictotrichon tibeticum* (Gu et al., 2022).

2.2. Experimental design

A large grazing platform was established in 2019. Two relatively flat, homogeneous alpine grassland sites (each site covered 3.73 ha and was subjected to identical experimental treatments) were selected to reduce the impact of environmental heterogeneity. A randomized block design was used in the experiment. There were three blocks with four grazing intensity treatments in each block, and 12 plots (40 m × 50 m) at each site (Fig. 1b, c).

The design was based on local habitat productivity and the rangeland carrying capacity calculation method published in the agricultural industry standard NY/T 635–2015 (Ministry of Agriculture, People's Republic of China). The grazing intensity treatments were: (i) no grazing (control, CK), (ii) light grazing (0.5 yak/ha: feeding rate 25–35%, LG), (iii) medium grazing (1.0 yak/ha: feeding rate 45–55%, MG), and (iv) heavy grazing (2.0 yak/ha: feeding rate 75–85%, HG). In the grazing intensity plot, 0, 2, 4, and 8 yaks (approximately 200 kg each) were grazed to represent the four grazing levels. All livestock were mature and approximately 3–5 years old. After two consecutive days (48 h) of grazing in one block, yaks were moved to the next block to continue grazing for two consecutive days (48 h), that is, rotational grazing among each block, with each block grazed for approximately 4 days/month and a 2-week interval between each grazing. Grazing began in 2019 and was conducted from June to September yearly (Table S4).

2.3. Measurements of temperature, moisture, and precipitation

Soil temperature and moisture, air temperature, and precipitation were continuously monitored for two years (July 2020–July 2022). We installed ZL6 TEROS11 sensors (Meter Group, Inc., USA) in each plot to automatically monitor soil temperature (ST_5, ST_10, and ST_20) and moisture (SM_5, SM_10, and SM_20) at depths of 5, 10, and 20 cm, respectively. The ZL6 data logger stored data every 30 min. Air temperature and precipitation data were obtained using an AWS310 automatic weather station (Vaisala, Vantaa, Finland).

The mean air temperature was − 0.73, − 1.39, − 1.24, and − 0.55 °C and the total precipitation was 392.43, 434.6, 515.9, and 578.4 mm in 2019, 2020, 2021, and 2022, respectively (Fig. 2a, Table 1). The mean air temperature represented 44% of its range (−0.02 to −1.93 °C) over the last 33 years (Fig. 3a). The annual precipitation during the experimental period represented 57% of its range over the last 33 years (352.6–573.0 mm from 1990 to 2022; Fig. 3b). Although the mean air temperature and annual precipitation during the experiment were slightly lower than the average during the 33 years before to the experiment, their ranges overlapped, and the means did not differ significantly (Fig. S1).

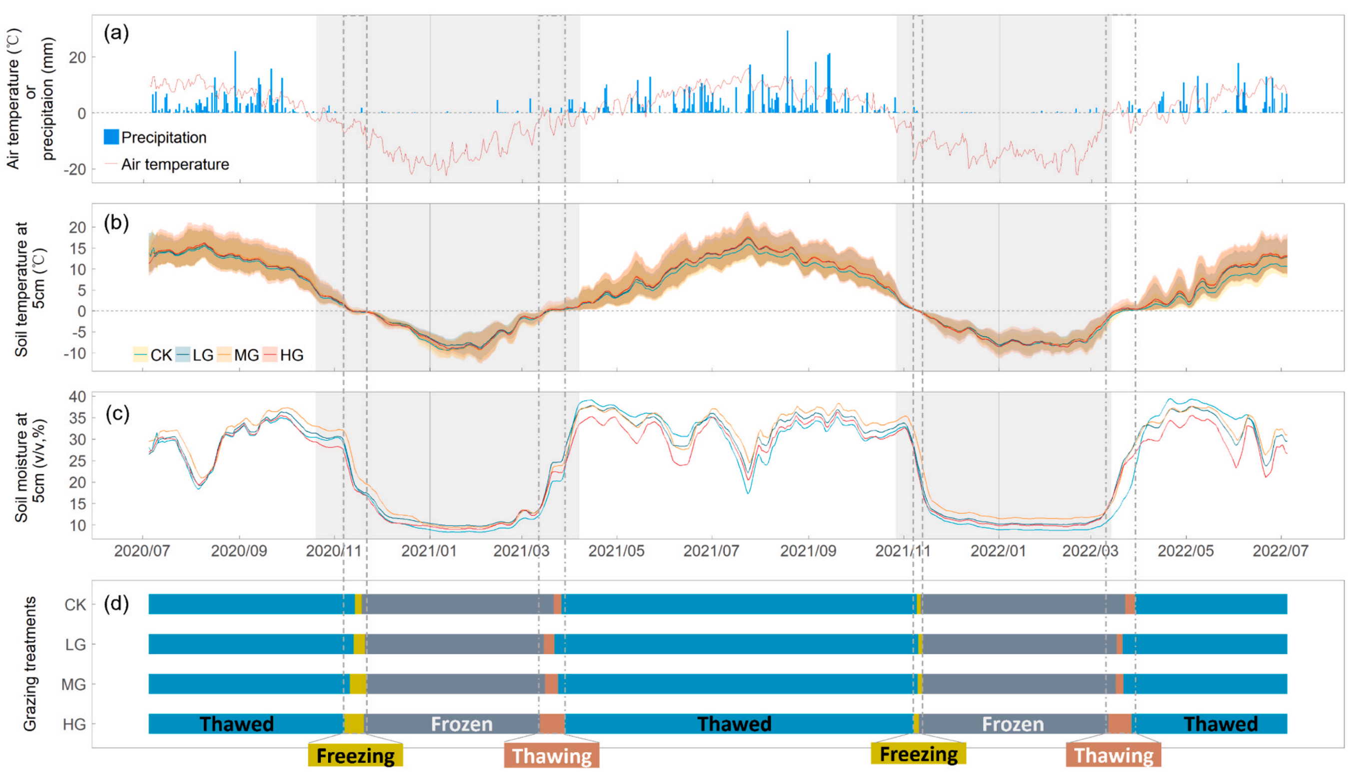

Fig. 2. Temporal dynamics of average daily air temperature (°C) and precipitation (mm) from 5 July 2020–4 July 2022 (a), soil temperature at 5 cm depth (b), soil moisture at 5 cm depth and precipitation (c) in the in-situ grazing intensity experiment. Colored lines indicate smoothed (7-days running mean) time series of soil temperature and soil moisture at 5 cm depth under each grazing intensity treatment. Times series of soil temperature also shown as colored areas between smoothed (7-days running mean) daily maximum and smoothed (7-days running mean) daily minimum values. Soil freeze-thaw periods from early autumn to late spring (d) with different grazing intensities. Freezing, soil freeze-thaw cycles during the autumn–winter season; Frozen, complete freezing without thawing each day; Thawing, soil freeze-thaw cycles during the winter–spring season; Thawed, complete thawing without freezing each day. The dotted lines (i.e., the boxes) show the start and end dates (i.e., duration) of the soil freeze-thaw periods. Shading periods represent the nongrowing season. CK, Control; LG, Light grazing; MG, Moderate grazing; HG, Heavy grazing.

Table 1
Climate characteristics of the study site.

Overall	2019	2020	2021	2022
Mean annual temperature (°C)	-0.73	-1.39	-1.24	-0.55
Annual precipitation (mm)	392.43	434.59	515.87	518.41
Growing Season				
Length (day)	183	187	187	211
Mean air temperature (°C)	7.17(−6.64 to 13.22)	6.35 (−3.10 to 13.71)	6.84 (−2.07 to 16.09)	6.37 (−7.49 to 17.99)
Precipitation (rainfall, mm)	349.21	394.21	469.14	498.09
Non-growing Season				
Length (day)	182	179	178	154
Mean air temperature (°C)	-8.57 (−22.00 to 2.09)	-9.47 (−21.91 to 2.91)	-9.74 (−22.54 to 2.25)	-10.03 (−22.15 to 1.34)
Precipitation (snowfall, mm)	43.22	39.88	46.74	20.32

Note: Values in brackets are the ranges of the daily mean temperature.

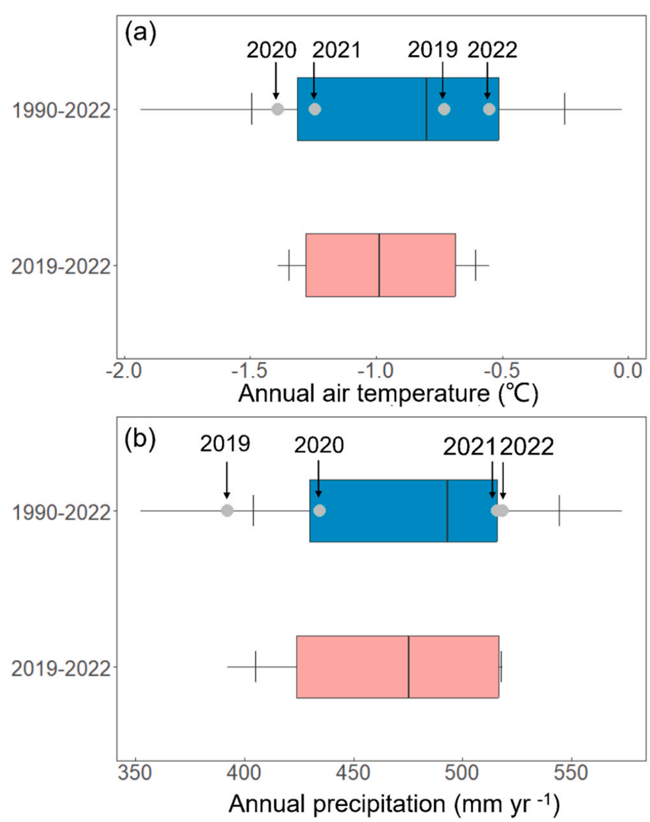

Fig. 3. Box plots of annual air temperature (a), annual precipitation (b) from near meteorological stations during the current period of study (2019–2022) and 33 years (1990–2022) in the past. The box plots show the median, interquartile ranges and 10th and 90th percentiles of the climatic variables.

2.4. Measurements of aboveground biomass

Five 0.5 m × 0.5 m quadrats were randomly selected from each experimental plot during the peak biomass period (late August) of 2020 and 2021. The plant species composition, canopy height, and species-specific coverage within each quadrat were recorded. All the plant species within each quadrat were cut close to the ground. Plants were dried at 65 °C for 48 h to determine aboveground biomass (AGB).

2.5. Definitions of the growing season, non-growing season, and FTPs

Based on previous studies (Bergeron et al., 2007; Körner and Paulsen, 2004; Piao et al., 2007; Tanja et al., 2003; Wang et al., 2011), the start of the non-growing season was defined as the first day when the 7-day smoothed daily mean temperature remained < 0 °C for at least five consecutive days. Similarly, the start of the growing season was defined as the first day when the 7-day smoothed daily mean temperature remained > 0 °C for at least five consecutive days (Wang et al., 2014).

According to the definition of freezing and thawing of bulk soils by Wang et al. (2014) and with reference to the studies of Konestabo et al. (2007) and Zhu et al. (2012), as the day of freezing or thawing of bulk soil was identified when the following conditions were met: (1) daily minimum ST_5 cm (ST_{min}_5) < 0 °C and (2) daily maximum ST_5 cm (ST_{max}_5) > 0 °C for at least 3 h. The winter–spring season (March) are considered as the thawing period, whereas the autumn–winter (November) season are considered as the freezing period. Thus, the 7-days smoothed ST_{min}_5 and ST_{max}_5 were used to define frozen and thawed bulk soil. When ST_{min}_5 > 0 °C for at least five consecutive days, the soil was considered to be thawed (thawed period), and when ST_{max}_5 < 0 °C for at least five consecutive days, the soil was considered frozen (frozen period) (Guo et al., 2011).

2.6. Statistical analysis

A linear mixed model (R package: lmerTest) was used to assess the significance of the effects of grazing on the mean annual soil temperature, mean growing and non-growing ST, mean growing soil moisture, mean ST_{max}_5 and ST_{min}_5 cm, accumulated temperature, start and end dates of FTPs, and FTP periods. In the model, we used the measured years of grazing and block as fixed effects and the site as a random effect. Multiple comparisons were performed using Tukey's HSD test (R package: multcomp).

To assess the direct and indirect effects of various factors on the durations of the thawing, freezing, and frozen phases following grazing, a piecewise structural equation model (SEM) was built. Path coefficients were reported as standardized effect sizes. The overall fit of the model was assessed using Shipley's D-separation test, Fisher's C-statistic (if $P > 0.05$, then there is no path missing, and the model is a good fit), and AIC. The SEM was built using piecewiseSEM in the R package. All analyses were performed using R 4.2.1 (R Core Team, 2022).

3. Results

3.1. Grazing altered soil temperature

Grazing significantly decreased AGB, and the differences among LG, MG, HG, and CK were − 33.43%, − 42.01%, and − 64.20%, respectively (Fig. S5). Grazing significantly increased the mean annual and growing season soil temperature by 0.66 °C (0.58–0.73 °C) and 0.94 °C (0.74–1.13 °C), respectively ($P < 0.05$ for all; Table 2, Figs. 2a, 4a, b, Table S2). During the non-growing season, LG significantly increased the soil temperature, whereas MG and HG did not (Fig. 4c). Grazing significantly increased the number of days with maximum soil temperature at the depth of 5 cm (ST_{max}_5 cm > 10 °C; ranging from 24 to 32 days, $P < 0.05$ for HG and MG; Table 3), and the soil accumulated temperature with ST_{max}_5 cm > 0 °C and ST_{max}_5 cm > 10 °C (ranging from 430° to 709°C with ST_{max}_5 cm > 0 °C and from 497° to 839°C with ST_{max}_5 cm > 10 °C, $P < 0.05$ for HG; Table 3). However, the number of days with ST_{max}_5 cm > 0 °C showed no significant difference between the groups ($P > 0.05$ for all, Table 3). Grazing significantly changed the soil diurnal temperature up to a depth of 5 cm (SDT_5 cm). Notably, the annual mean SDT_5 ($R^2 = 0.99$, $P < 0.01$; Fig. 5a) and mean SDT_5 in the

Table 2
Results (F-values) for effects of grazing intensities (GI), study years (SY), block and their interactions on annual soil temperature (AST), annual soil moisture (ASWC), growing-season soil temperature (GST), growing-season soil moisture (GSWC), non-growing-season soil temperature (NST), non-growing-season soil moisture (NSWC) and its maximum (ST_{max}) and minimum (ST_{min}) soil temperature. Soil temperature and moisture were measured at 5 cm soil depth. The effects of grazing intensities were analyzed using the linear mixed-effects model method, indicated by * ** when $P < 0.001$, * * when $P < 0.01$, * when $P < 0.05$.

	AST	GST	GSWC	NST	ST_{max}	ST_{max}
GI	7.01 * **	19.54 * **	43.29 * **	4.06 * *	17.51 * **	2.71 *
SY	4.73 *	14.77 * **	95.25 * **	116.19 * **	4.36 *	4.49
Block	0.72	0.88	18.44 * **	0.30	56.47 * **	14.48 * **
GI × SY	0.79	2.01	116.75	0.16	3.12 *	0.51
GI × Block	5.14 * *	11.73 * **	84.45 * **	2.04	16.12 * **	2.59
SY × Block	0.36	1.29	0.02	0.07	0.32	0.19
GI × SY × Block	0.64	2.54	0.38	0.21	1.45	0.21

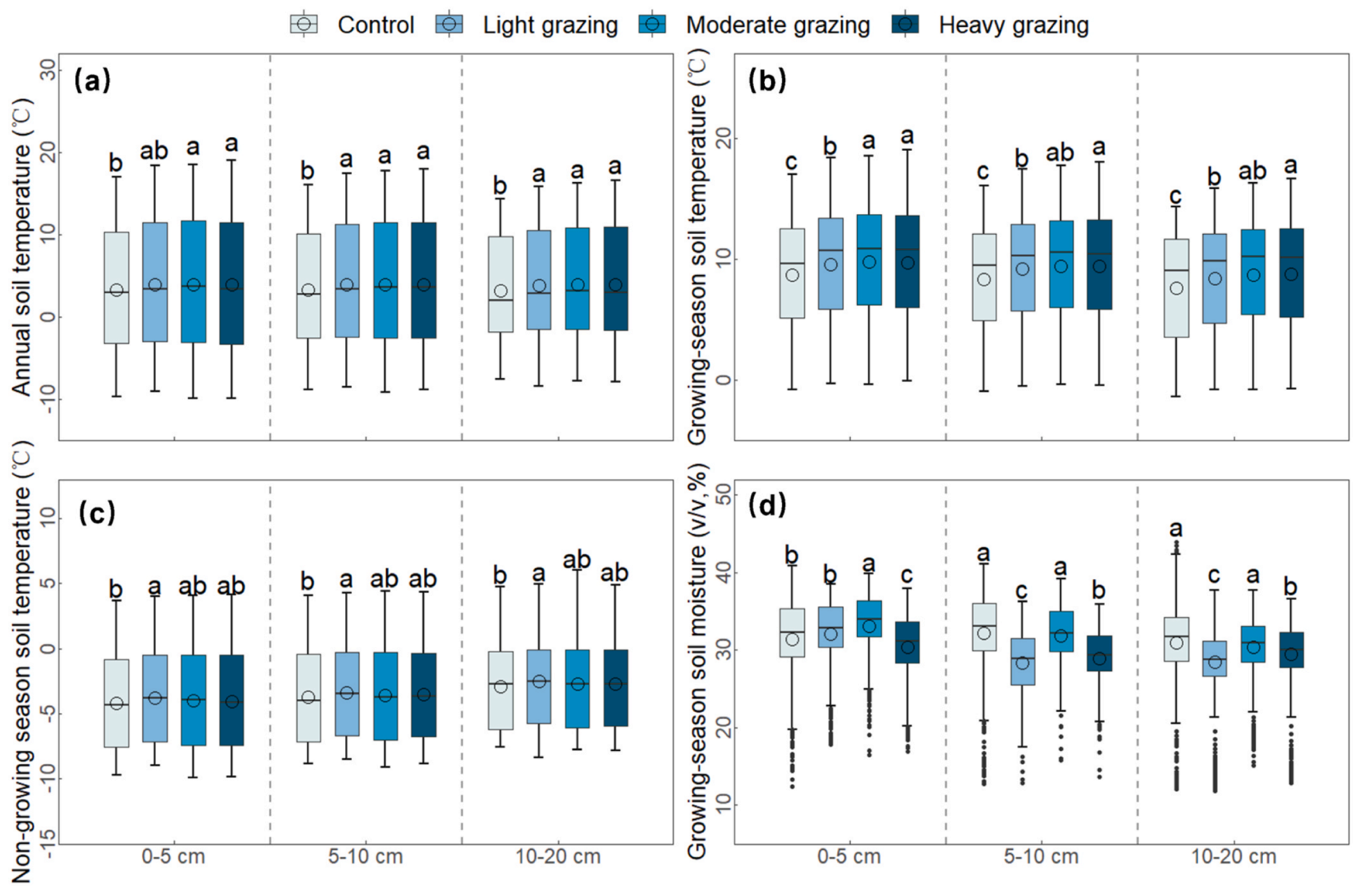

Fig. 4. Box plots of annual soil temperature (a), growing-season soil temperature (b) Non-growing season soil temperature (c) and growing-season soil moisture (d). The black cycles represent the mean value. Different letters indicate significant differences based on Tukey's HSD tests at α = 0.05.

growing ($R^2 = 0.97$, $P < 0.05$; Fig. 5b) and non-growing seasons were significantly and positively correlated with grazing intensity ($R^2 = 0.95$, $P < 0.05$; Fig. 5c; Table S1).

3.2. Grazing altered soil moisture

Soil moisture showed significant shifts during thawing, snowmelt, and precipitation events (Fig. 2c). Grazing significantly altered soil moisture during the growing season ($P < 0.001$; Table 2, Table S2) but had different impacts on the top (0–5 cm), middle (5–10 cm), and bottom soil (10–20 cm). In the topsoil, MG significantly increased soil moisture by 1.7%, whereas HG significantly decreased it by 1.06% ($P < 0.05$; Fig. 4d). In the middle and bottom soil layers, both LG and HG significantly decreased soil moisture (−3.82% and −3.17% for 5–10 cm, −2.43% and −1.43% for 10–20 cm, respectively; $P < 0.05$; Fig. 4d, Table 2, Table S2).

3.3. Associations of grazing intensity with freeze–thaw periods

Grazing altered the start and end dates of the FTPs (Fig. 1d). In 2022, grazing advanced the mean start and end dates of the thawing period by 8–10 days and 2–8 days, respectively (Fig. S4, Table S3). Grazing intensity changed during each period of the FTPs, and the freezing period was extended by 3, 6, and 8 days for LG, MG, and HG, respectively ($P < 0.05$; Table 4). HG significantly extended the thawing period by 12 and 8 days in 2021 and 2022, respectively ($P < 0.05$; Table 4). Grazing significantly shortened the frozen period by 8–12 days in 2021–2022 ($P < 0.05$; Table 4). LG significantly extended the thawing period in 2022 by 9 days. Overall, grazing significantly shortened the entire freeze period (freezing and frozen), and the differences for LG, MG, and HG were 9, 10, and 10 days, respectively. The LG treatment significantly prolonged the soil thaw period.

SEM revealed that grazing intensity affected FTPs by influencing

Table 3
Number of days with maximum soil temperature (ST_{max}) > 0 °C and > 10 °C and annual soil accumulated temperature with maximum soil temperature (ST_{max}) > 0 °C and > 10 °C for each grazing treatment.

Grazing Intensity	ST_{max} > 0 °C (days)	ST_{max} > 0 °C (°C)	ST_{max} > 10 °C (days)	ST_{max} > 10 °C (°C)
CK	234.3 ± 3.20 a	2415 ± 181.2 b	134.3 ± 9.3 b	1956 ± 224.6 b
LG	242.6 ± 1.73 a	2845 ± 159.0 ab	158.5 ± 5.53 ab	2453 ± 197.2 ab
MG	241.5 ± 2.08 a	3014 ± 178.8 ab	162.5 ± 5.04 a	2672 ± 191.0 ab
HG	242.8 ± 1.30 a	3124 ± 179.5 a	166.3 ± 5.96 a	2795 ± 194.1 a

Note: Values represent the mean±standard error (n = 6). Letters (a and b) within a column represent significant difference between parameters (Tukey's HSD tests, $P < 0.05$). CK, Control; LG, Light grazing; MG, Moderate grazing; HG, Heavy grazing

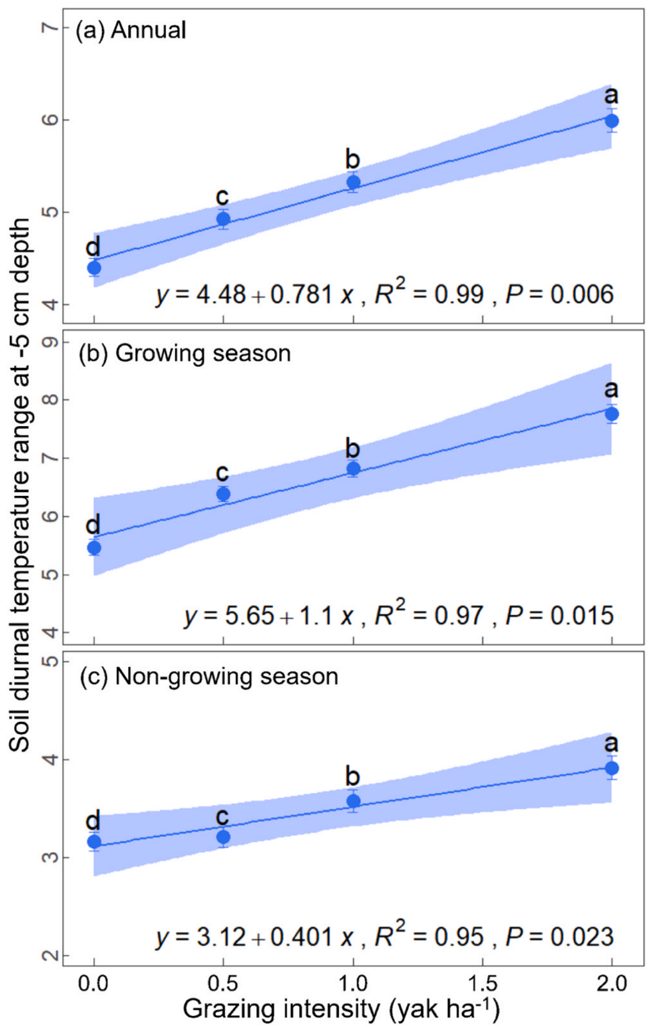

Fig. 5. Linear relationships for grazing intensity with annual soil diurnal temperature range (a), growing season soil diurnal temperature range (b), and non-growing season soil diurnal temperature range (c) at 5 cm depth. Data are means ± SEs. All relationships are significant ($P < 0.05$).

AGB. AGB had a significant positive effect on the frozen period ($P < 0.05$; Fig. 6b) and a significant negative effect on the freezing and thawing periods ($P < 0.05$, $P < 0.001$; Fig. 6a, c). ST_5 cm and SDT_5 cm had significant positive effects on the freezing period ($P < 0.01$ and $P < 0.001$, respectively), but negative effects on the frozen period ($P < 0.001$ and $P < 0.01$, respectively). AGB affected the thawing period by influencing SM_5 cm (P < 0.05; Fig. 6c).

Table 4
Effects of grazing intensity on durations of freezing, thawing, frozen and thawed period and the duration of the entire freeze-thaw period.

Grazing Intensity	Freezing (days)	Frozen (days)	Thawing (days)	Thawed (days)	Freezing And Frozen (days)	Thawing and Thawed (days)
2020–2021						
CK	4 ± 1.30 b	123 ± 3.91 a	5 ± 0.41 b	230 ± 4.17 a	127 ± 3.71 a	239 ± 3.66 a
LG	7 ± 2.13 a	115 ± 3.62 a	7 ± 1.48 b	236 ± 4.67 a	122 ± 3.45 a	242 ± 3.45 a
MG	10 ± 2.15 a	114 ± 4.94 a	8 ± 1.06 b	232 ± 2.92 a	128 ± 1.58 a	239 ± 3.57 a
HG	12 ± 2.02 a	112 ± 4.71 a	17 ± 1.06 a	225 ± 2.86 a	124 ± 1.33 a	241 ± 2.91 a
2021–2022						
CK	2.5 ± 0.67 a	133 ± 3.03 a	6 ± 0.63 b	225 ± 2.21 b	137 ± 6.49 a	231 ± 2.60 b
LG	2.7 ± 0.92 a	125 ± 1.76 b	4 ± 0.55 b	234 ± 0.82 a	128 ± 2.31 b	238 ± 0.91 a
MG	2.83 ± 0.70 a	125 ± 1.61 b	5 ± 0.65 b	233 ± 1.97 ab	127 ± 3.34 b	236 ± 1.64 ab
HG	3.17 ± 0.94 a	122 ± 1.61 b	14 ± 1.65 a	226 ± 4.19 b	127 ± 2.94 b	237 ± 2.69 ab

Note: Values represent the mean±standard error (n = 6). Letters (a and b) within a row represent significant difference between parameters (Tukey's HSD tests, $P < 0.05$). CK, Control; LG, Light grazing; MG, Moderate grazing; HG, Heavy grazing

4. Discussion

4.1. Effects of grazing intensity on soil microclimate

Grazing experiments were conducted on the Tibetan plateau for three years, and we found that grazing significantly affected soil temperature and moisture. Grazing significantly increased the mean annual and growing season soil temperatures. This result was very similar to that of a previously published study (Yan et al., 2018). These changes are mainly caused by a reduction in vegetation due to grazing, which insulates the soil heat flux and is the main source of heat energy in the soil (Shao et al., 2017). However, during the non-growing season, grazing did not increase soil temperature under any treatment except LG, which did not match the results by Yan et al. (2018). This is because the CK treatment retained the entire AGB, which isolated the soil-to-air heat flux and reduced the solar radiation effect on the soil, combined with the reflection of solar radiation by snow, resulting in relatively low temperatures (von Oppen et al., 2022; Yi et al., 2013).

Our study suggests that grazing increased the daily soil diurnal temperature range and soil accumulated temperature while increasing soil temperature (Fig. 5, Table 3). Qin et al. (2022) showed that an increase in daily maximum and minimum temperatures advanced autumn phenology in the Tibetan Plateau. In this study, ST_{max}_5 cm increased as grazing intensity increased and was the main factor influencing SDT_5 cm (Fig. S2). This is because, in low-cover grasslands, the positive effect on maximum temperature is greater than that on minimum temperature, resulting in an increasing trend in the diurnal temperature range (Shen et al., 2017). As the vegetation cover of grasslands decreases, evapotranspiration, which can reduce the maximum temperature, tends to

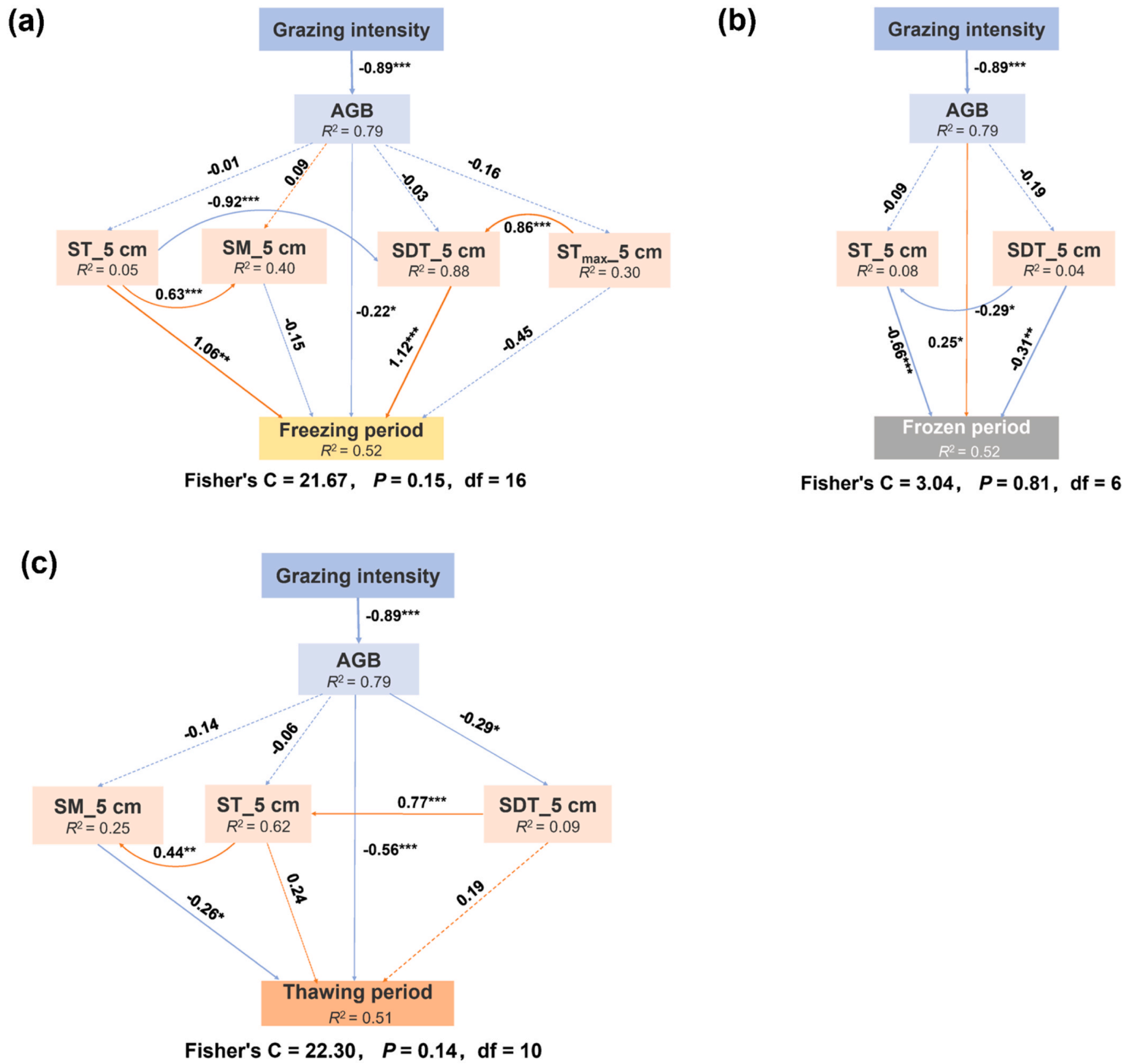

Fig. 6. Piecewise structural equation model testing the direct and indirect effects of grazing intensity on freezing, frozen and thawing periods. Freezing, frozen and thawing periods represent the duration of these stages. Variables include above-ground biomass (AGB), soil temperature at 5 cm depth (ST_5 cm), soil moisture at 5 cm depth (SM_5 cm), soil diurnal temperature range at 5 cm depth (SDT_5 cm) during the freeze–thaw period, maximum soil temperature at 5 cm ($ST_{max\_}5$ cm) during the freeze–thaw period. Orange and blue arrows represent the positive and negative paths, respectively. Solid and dashed arrows represent significant ($P < 0.05$) and nonsignificant ($P > 0.05$) paths, respectively. The width of the arrow indicates the strength of the relationship. Numbers adjacent to arrows are standardized path coefficients. * , * *, and * ** indicate significant effects at $P < 0.05$, 0.01, and 0.001, respectively.

decrease, and the degradation of grasslands may lead to daylight warming and an increased diurnal temperature range (Chen et al., 2009). The accumulated temperature, that is, the temperature above or at a given threshold, and its corresponding duration are major indices of energy resources (Miao et al., 2009). The climate regionalization makes the definite that 10 ℃ is the initial temperature of thermophilic plants, and for all higher living organisms, 0 ℃ is the lowest temperature to maintain activity; temperature is the primary index here (Xu and Li, 2016). An increase in soil temperature caused by grazing increases the accumulated temperature of the soil and extends the number of effective accumulation days, which extends the plant growth period and increases the growth rate, thus compensating for the loss of plants due to foraging.

In the present study, changes in soil moisture were mainly controlled by snowmelt and precipitation, and sharp changes in soil moisture in all treatments were attributed to rainfall and snowmelt (Fig. 2c). This suggests that snow accumulation during winter is crucial for ecosystem hydrology. In the topsoil, MG significantly increased and HG significantly decreased soil moisture. The effects of grazing on soil moisture are also influenced by factors such as evaporation, transpiration, and soil porosity (Bremer et al., 2001). In the MG, all soil layers showed higher moisture content, probably due to moderate soil compaction and reduction in continuous soil porosity (Gan et al., 2012; Schrama et al., 2013). The topsoil in the LG was slightly compacted, resulting in higher soil moisture; however, the greater retention and evapotranspiration of plants lowered the bottom and middle soil moisture. For each soil layer in the HG, the soil moisture was lower because of sparse plants on the surface layer, higher temperature, vigorous evaporation, less snow accumulation, and the inability to transfer water downward owing to soil compaction.

4.2. Grazing intensity-induced freeze–thaw period dynamics

Under global warming scenarios, the Tibetan Plateau has shown an accelerating warming trend (Duan and Xiao, 2015; IPCC et al., 2013). Changes in FTPs that may have been caused by grazing reinforce this warming trend, cause water and heat redistribution, and change various ecological processes in grassland ecosystems (Chen et al., 2011; Guo et al., 2011; Schuur et al., 2015; Wolf et al., 2011). However, current in situ experiments on grazing and FTPs are limited. The FTP start and end dates were altered by grazing activity (Fig. 2d). In this study, grazing increased ST_5 cm during the FTPs (Fig. S3). The effect of different grazing intensities on alpine grassland vegetation cover may be the main reason for the increase in soil temperature (Yi et al., 2013). During the spring soil thawing period, grazing significantly increased soil moisture. We hypothesized that the effect of grazing on soil moisture was the primary reason for the potential spring thaw variation (Fig. S3).

SEM was employed to explore the magnitude of the contribution of each factor to grazing-led alterations in the FTPs. Grazing intensity altered soil FTPs, mainly by changing AGB (Fig. 6). A study on the Tibetan Plateau suggested that increased vegetation activity may attenuate surface warming (Shen et al., 2015). Grazing reduces vegetation cover on the ground surface, resulting in greater exposure of the ground surface to solar radiation, a reduction in the role of vegetation as an insulator of soil heat fluxes (Shao et al., 2017), and a more drastic variation in soil temperature. This explains why the grazing-led reduction in AGB negatively affected the freezing and thawing periods and a positive effect on the frozen period. In addition, AGB did not significantly affect soil temperature or moisture, nor did it affect the freezing and frozen periods, indicating that there were no correlation between AGB and soil temperature and moisture (Fig. 6a, b). The non-synchrony of soil temperature and moisture and grazing intensity during the freeze–thaw period may be the key reason for the dissociating of AGB and soil temperature and moisture. ST_5 and SDT_5 cm had significant positive and negative effects on the freezing and frozen periods, respectively. The SM_5 cm had a significant negative effect on the thawing period. Grazing increased soil temperature during the freezing and frozen periods; however, soil temperature did not vary with grazing intensity (Fig. S3). The increase in soil temperature also explains why grazing advanced and extended the freezing period thus shortening the frozen period.

5. Conclusions

In summary, grazing extended the freezing and thawing periods and shortened the frozen period, whereas grazing intensity increased the change in FTPs. Changes in soil temperature and soil diurnal temperature had a key effect on the freezing and frozen periods, and soil moisture influenced the thawing period. For instance, HG can produce warming and drying effects on soil in alpine meadows by increasing soil temperature and decreasing soil moisture. Furthermore, grazing-induced AGB reduction was the main factor governing the FTP dynamics. Thus, our results provide direct in situ evidence that grazing regulates FTPs by shaping the soil microclimate (soil temperature and moisture) and inducing AGB removal. Future studies should focus on the magnitude of the long-term grazing effect on the freeze–thaw process and associated ecological processes, including soil microbial activity, soil respiration, and carbon budget.

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.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108659.

References

Aalto, J., le Roux, P.C., Luoto, M., 2013. Vegetation mediates soil temperature and moisture in arctic-alpine environments. Arct., Antarct., Alp. Res. 45 (4), 429–439. https://doi.org/10.1657/1938-4246-45.4.429.

Babić, K., Rotach, M.W., Klaić, Z.B., 2016. Evaluation of local similarity theory in the wintertime nocturnal boundary layer over heterogeneous surface. Agric. For. Meteorol. 228–229, 164–179. https://doi.org/10.1016/j.agrformet.2016.07.002.

Bergeron, O., et al., 2007. Comparison of carbon dioxide fluxes over three boreal black spruce forests in Canada. Glob. Change Biol. 13 (1), 89–107. https://doi.org/10.1111/j.1365-2486.2006.01281.x.

Blok, D., et al., 2010. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. Glob. Change Biol. 16 (4), 1296–1305. https://doi.org/10.1111/j.1365-2486.2009.02110.x.

Bremer, D.J., Auen, L.M., Ham, J.M., Owensby, C.E., 2001. Evapotranspiration in a Prairie Ecosystem. Agron. J. 93 (2), 338–348. https://doi.org/10.2134/agronj2001.932338x.

Castano, C., et al., 2018. Soil microclimate changes affect soil fungal communities in a Mediterranean pine forest. N. Phytol. 220 (4), 1211–1221. https://doi.org/10.1111/nph.15205.

Chang, J., Wang, G., Li, C., Mao, T., 2015. Seasonal dynamics of suprapermafrost groundwater and its response to the freeing-thawing processes of soil in the permafrost region of Qinghai-Tibet Plateau. Sci. China Earth Sci. 58 (5), 727–738. https://doi.org/10.1007/s11430-014-5009-y.

Chen, H., Zhu, Q., Wu, N., Wang, Y., Peng, C.H., 2011. Delayed spring phenology on the Tibetan Plateau may also be attributable to other factors than winter and spring warming. E93; author reply Proc. Natl. Acad. Sci. USA 108 (19), E95. https://doi.org/10.1073/pnas.1100091108.

Chen, S., et al., 2009. Energy balance and partition in Inner Mongolia steppe ecosystems with different land use types. Agric. For. Meteorol. 149 (11), 1800–1809. https://doi.org/10.1016/j.agrformet.2009.06.009.

Chen, S., et al., 2016. Response of freeze-thaw processes to experimental warming in the permafrost regions of the central Qinghai-Tibet Plateau. Cryosphere Discuss. 2016, 1–24. https://doi.org/10.5194/tc-2016-80.

Cheng, G., Wu, T., 2007. Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. J. Geophys. Res. 112 (F2) https://doi.org/10.1029/2006jf000631.

Ding, B., et al., 2023. Comparative study of seasonal freeze–thaw on soil water transport in farmland and its shelterbelt. Catena 225. https://doi.org/10.1016/j.catena.2023.106982.

Dorji, T., et al., 2018. Grazing and spring snow counteract the effects of warming on an alpine plant community in Tibet through effects on the dominant species. Agric. For. Meteorol. 263, 188–197. https://doi.org/10.1016/j.agrformet.2018.08.017.

Duan, A., Xiao, Z., 2015. Does the climate warming hiatus exist over the Tibetan Plateau. Sci. Rep. 5, 13711. https://doi.org/10.1038/srep13711.

Gan, L., Peng, X., Peth, S., Horn, R., 2012. Effects of grazing intensity on soil thermal properties and heat flux under Leymus chinensis and Stipa grandis vegetation in Inner Mongolia, China. Soil Tillage Res. 118, 147–158. https://doi.org/10.1016/j.still.2011.11.005.

Gu, H., et al., 2022. Leaf N:P stoichiometry overrides the effect of individual nutrient content on insect herbivore population dynamics in a Tibetan alpine grassland. Agric., Ecosyst. Environ. 336. https://doi.org/10.1016/j.agee.2022.108032.

Guo, D., Yang, M., Wang, H., 2010. Sensible and latent heat flux response to diurnal variation in soil surface temperature and moisture under different freeze/thaw soil

conditions in the seasonal frozen soil region of the central Tibetan Plateau. Environ. Earth Sci. 63 (1), 97–107. https://doi.org/10.1007/s12665-010-0672-6.
Guo, D., Yang, M., Wang, H., 2011. Characteristics of land surface heat and water exchange under different soil freeze/thaw conditions over the central Tibetan Plateau. Hydrol. Process. 25 (16), 2531–2541. https://doi.org/10.1002/hyp.8025.
Guo, D., Wang, H., Li, D., 2012. A projection of permafrost degradation on the Tibetan Plateau during the 21st century. J. Geophys. Res. Atmos. 117 (D5) https://doi.org/10.1029/2011jd016545.
von Haden, A.C., Marín-Spiotta, E., Jackson, R.D., Kucharik, C.J., 2019. Soil microclimates influence annual carbon loss via heterotrophic soil respiration in maize and switchgrass bioenergy cropping systems. Agric. For. Meteorol. 279. https://doi.org/10.1016/j.agrformet.2019.107731.
Hamamoto, T., Uchida, Y., von Rein, I., Mukumbuta, I., 2020. Effects of short-term freezing on nitrous oxide emissions and enzyme activities in a grazed pasture soil after bovine-urine application. Sci. Total Environ. 740, 140006 https://doi.org/10.1016/j.scitotenv.2020.140006.
Harte, J., et al., 1995. Global warming and soil microclimate: results from a meadow-warming experiment. Ecol. Appl. 5 (1), 132–150. https://doi.org/10.2307/1942058.
Hu, H., et al., 2008. Influences of alpine ecosystem degradation on soil temperature in the freezing-thawing process on Qinghai–Tibet Plateau. Environ. Geol. 57 (6), 1391–1397. https://doi.org/10.1007/s00254-008-1417-7.
IPCC, 2013. Climate Change: The Physical Science Basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Ji, X., Liu, M., Yang, J., Feng, F., 2022. Meta-analysis of the impact of freeze–thaw cycles on soil microbial diversity and C and N dynamics. Soil Biol. Biochem. 168. https://doi.org/10.1016/j.soilbio.2022.108608.
Jia, D., et al., 2020. Variations in the top-layer soil freezing/thawing process from 2009 to 2018 in the Maqu area of the Tibetan Plateau. Theor. Appl. Climatol. 143 (1–2), 21–32. https://doi.org/10.1007/s00704-020-03382-2.
Jiang, H., et al., 2018. The impacts of soil freeze/thaw dynamics on soil water transfer and spring phenology in the Tibetan Plateau. Arct., Antarct., Alp. Res. 50 (1) https://doi.org/10.1080/15230430.2018.1439155.
Konestabo, H.S., Michelsen, A., Holmstrup, M., 2007. Responses of springtail and mite populations to prolonged periods of soil freeze-thaw cycles in a sub-arctic ecosystem. Appl. Soil Ecol. 36 (2–3), 136–146. https://doi.org/10.1016/j.apsoil.2007.01.003.
Körner, C., Paulsen, J., 2004. A world-wide study of high altitude treeline temperatures. J. Biogeogr. 31 (5), 713–732. https://doi.org/10.1111/j.1365-2699.2003.01043.x.
Li, J., Zhao, Y., Zhang, A., Song, B., Hill, R.L., 2021. Effect of grazing exclusion on nitrous oxide emissions during freeze-thaw cycles in a typical steppe of Inner Mongolia. Agric., Ecosyst. Environ. 307. https://doi.org/10.1016/j.agee.2020.107217.
Li, S.G., et al., 2000. Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. Agric. For. Meteorol. 102, 125–137.
Liu, N., Kan, H.M., Yang, G.W., Zhang, Y.J., 2015. Changes in plant, soil, and microbes in a typical steppe from simulated grazing: explaining potential change in soil C. Ecol. Monogr. 85 (2), 269–286. https://doi.org/10.1890/14-1368.1.
Lv, Z., Gu, Y., Chen, S., Chen, J., Jia, Y., 2022. Effects of autumn diurnal freeze-thaw cycles on soil bacteria and greenhouse gases in the permafrost regions. Front Microbiol 13, 1056953. https://doi.org/10.3389/fmicb.2022.1056953.
Miao, Q., Ding, Y., Wang, Y., Duan, C., 2009. Impact of climate warming on the distribution of China's thermal resources. J. Nat. Res. 24, 935–945.
von Oppen, J., et al., 2022. Cross-scale regulation of seasonal microclimate by vegetation and snow in the Arctic tundra. Glob. Change Biol. 28 (24), 7296–7312. https://doi.org/10.1111/gcb.16426.
Piao, S., Friedlingstein, P., Ciais, P., Viovy, N., Demarty, J., 2007. Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades. Glob. Biogeochem. Cycles 21 (3), 1–11. https://doi.org/10.1029/2006gb002888.
Qin, G., Adu, B., Li, C., Wu, J., 2022. Diverse responses of phenology in multi-grassland to environmental factors on Qinghai–Tibetan Plateau in China. Theor. Appl. Climatol. 148 (3–4), 931–942. https://doi.org/10.1007/s00704-022-03963-3.
Schrama, M., et al., 2013. Herbivore trampling as an alternative pathway for explaining differences in nitrogen mineralization in moist grasslands. Oecologia 172 (1), 231–243. https://doi.org/10.1007/s00442-012-2484-8.
Schuur, E.A., et al., 2015. Climate change and the permafrost carbon feedback. Nature 520 (7546), 171–179. https://doi.org/10.1038/nature14338.
Shao, C., et al., 2017. Grazing effects on surface energy fluxes in a desert steppe on the Mongolian Plateau. Ecol. Appl. 27, 485–502. https://doi.org/10.1002/eap.1459.
Shen, M., et al., 2015. Evaporative cooling over the Tibetan Plateau induced by vegetation growth. Proc. Natl. Acad. Sci. USA 112 (30), 9299–9304. https://doi.org/10.1073/pnas.1504418112.
Shen, X., Liu, B., Lu, X., 2017. Effects of land use/land cover on diurnal temperature range in the temperate grassland region of China. Sci. Total Environ. 575, 1211–1218. https://doi.org/10.1016/j.scitotenv.2016.09.187.
Tanja, S., et al., 2003. Air temperature triggers the recovery of evergreen boreal forest photosynthesis in spring. Glob. Change Biol. 9 (10), 1410–1426. https://doi.org/10.1046/j.1365-2486.2003.00597.x.
Wang, F., et al., 2021. Grazing reduces the soil-atmosphere exchange of greenhouse gases during Freeze-Thaw Cycles in Meadow Steppes in Inner Mongolia. Front. Ecol. Evol. 9. https://doi.org/10.3389/fevo.2021.795203.
Wang, H., et al., 2020. Alpine grassland plants grow earlier and faster but biomass remains unchanged over 35 years of climate change. Ecol. Lett. 23 (4), 701–710. https://doi.org/10.1111/ele.13474.
Wang, Q., et al., 2019. Annual ecosystem respiration is resistant to changes in freeze-thaw periods in semi-arid permafrost. Glob. Change Biol. https://doi.org/10.1111/gcb.14979.
Wang, T., et al., 2011. Controls on winter ecosystem respiration in temperate and boreal ecosystems. Biogeosciences 8 (7), 2009–2025. https://doi.org/10.5194/bg-8-2009-2011.
Wang, Y., et al., 2014. Non-growing-season soil respiration is controlled by freezing and thawing processes in the summer monsoon-dominated Tibetan alpine grassland. Glob. Biogeochem. Cycles 28 (10), 1081–1095. https://doi.org/10.1002/2013gb004760.
Wolf, B., et al., 2011. Modeling N2O emissions from steppe in Inner Mongolia, China, with consideration of spring thaw and grazing intensity. Plant Soil 350 (1–2), 297–310. https://doi.org/10.1007/s11104-011-0908-6.
Wu, Q., Zhang, T., 2008. Recent permafrost warming on the Qinghai-Tibetan Plateau. J. Geophys. Res. 113 (D13) https://doi.org/10.1029/2007jd009539.
Xu, M., Li, Z., 2016. Accumulated temperature changes in desert region and surrounding area during 1960–2013: a case study in the Alxa Plateau, Northwest China. Environ. Earth Sci. 75 (18) https://doi.org/10.1007/s12665-016-6084-5.
Xue, X., Guo, J., Han, B., Sun, Q., Liu, L., 2009. The effect of climate warming and permafrost thaw on desertification in the Qinghai–Tibetan Plateau. Geomorphology 108 (3–4), 182–190. https://doi.org/10.1016/j.geomorph.2009.01.004.
Yan, Y., et al., 2018. Grazing modulates soil temperature and moisture in a Eurasian steppe. Agric. For. Meteorol. 262, 157–165. https://doi.org/10.1016/j.agrformet.2018.07.011.
Yang, M., Nelson, F.E., Shiklomanov, N.I., Guo, D., Wan, G., 2010. Permafrost degradation and its environmental effects on the Tibetan Plateau: a review of recent research. Earth-Sci. Rev. 103 (1–2), 31–44. https://doi.org/10.1016/j.earscirev.2010.07.002.
Yang, S., et al., 2020. Evaluation of reanalysis soil temperature and soil moisture products in permafrost regions on the Qinghai-Tibetan Plateau. Geoderma 377. https://doi.org/10.1016/j.geoderma.2020.114583.
Yang, S., He, Z., Chen, L., 2023. Different responses of CO_2 and CH_4 to freeze-thaw cycles in an alpine forest ecosystem in northwestern China. Sci. Total Environ. 863, 160886 https://doi.org/10.1016/j.scitotenv.2022.160886.
Yi, S., et al., 2013. Representing the effects of alpine grassland vegetation cover on the simulation of soil thermal dynamics by ecosystem models applied to the Qinghai-Tibetan Plateau. J. Geophys. Res. Biogeosci. 118 (3), 1186–1199. https://doi.org/10.1002/jgrg.20093.
Yi, S., Woo, M.-k, Arain, M.A., 2007. Impacts of peat and vegetation on permafrost degradation under climate warming. Geophys. Res. Lett. 34 (16) https://doi.org/10.1029/2007gl030550.
Zhao, L., et al., 2004. Changes of climate and seasonally frozen ground over the past 30 years in Qinghai–Xizang (Tibetan) Plateau, China. Glob. Planet. Change 43 (1–2), 19–31. https://doi.org/10.1016/j.gloplacha.2004.02.003.
Zhu, F., et al., 2017. Spatiotemporal variations of annual shallow soil temperature on the Tibetan Plateau during 1983–2013. Clim. Dyn. 51 (5–6), 2209–2227. https://doi.org/10.1007/s00382-017-4008-z.
Zhu, J., He, X., Wu, F., Yang, W., Tan, B., 2012. Decomposition ofAbies faxonianalitter varies with freeze–thaw stages and altitudes in subalpine/alpine forests of southwest China. Scand. J. For. Res. 27 (6), 586–596. https://doi.org/10.1080/02827581.2012.670726.
Zou, D., et al., 2017. A new map of permafrost distribution on the Tibetan Plateau. Cryosphere 11 (6), 2527–2542. https://doi.org/10.5194/tc-11-2527-2017.