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Growing season grazing promotes the shallow stratification of soil nutrients while non-growing season grazing sequesters the deep soil nutrients in a typical alpine meadow

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ABSTRACT

Grazing management and climate are known to be important drivers influencing soil nutrient accumulation. The change of soil nutrients in pasture depends on the excreta return and the vegetation regeneration. Livestock activities significantly affect plant growth and soil nutrients through feeding, trampling, and excretion. At the same time, grazing time and climate change are stimulating plant growth and altering plant composition. How long-term specific grazing management will affect soil nutrient storage and movement under a warming-humid climate trend needs further study. In 20-year grazing management trial, conducted in a typical alpine meadow in the Qilian Mountains on the Qinghai-Tibet Plateau, sampled and analyzed the soil from under a non-growing season graze pasture (WP) and a growing season graze pasture (SAP) in August 1999 and August 2019 along grazing gradients (GG) at different distances from the pasture entrance (0, 300, 600, 900, 1200, and 1500 m). The experimental results of 2019 compared to 1999 show that SAP and WP increased soil available nitrogen density (SAND) and availability (SAND:soil total nitrogen density [STND] ratio) in the first 300 m along the grazing gradient soil, while SAP showed a decrease in soil available phosphorus density (SAPD) and availability (SAPD:soil total phosphorus density [STPD] ratio), and WP had no significant difference between gradients. Grazing in spring and autumn increased soil organic carbon density (SOCD), and STND in the first 300 m along the gradient soil, whereas it had the reverse effect in WP. At the same time, STPD has no obvious changing trend along the gradient. Growing and non-growing season grazing increased the SOCD:STND ratio in the first 300 m along the grazing gradient but resulted to a lower STND:STPD ratio. The comparison found that long-term grazing from 1999 to 2019 increased the SAND and SAPD. SAP improved soil total C, N, and P density in the topsoil (0–10 cm), but WP improved it throughout the profile (0–40 cm). These findings indicate that time of grazing and the grazing gradient affect the accumulation and migration of different elements under long-term grazing. Furthermore, SAP and WP had a positive effect on the accumulation of topsoil and deep soil nutrients, respectively. We suggest that periodic pasture exchange in SAP and WP should be carried out to maintain the sustainability of the ecosystem. At the same time, for different gradients, especially the first 300 m, regular soil nutrient monitoring and human intervention (such as fertilization) should be carried out to eliminate potential element restrictions and focus on the development of possible problems caused by the livestock locked in the pens at night, such as nutrient enrichment (the excreta as the organic fertilizer and soil improvement material for farmland) and loss (element footprint) in pens, which are of important guiding significance for the grazing system's stable development of alpine meadow.

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1. Introduction

Grasslands are one of the world's largest terrestrial ecosystems, covering 40 % of the global land area and accounting for roughly 30 % of the global carbon (C) stock (Briske, 2017). Grazing is the most common use on grasslands throughout the world, and large mammals graze nearly all natural grasslands (Yu et al., 2019). Climate change, particularly warming and humidifying, is predicted to affect most regions of the Northern Hemisphere and will be especially pronounced at high northern latitudes during this century (Li et al., 2021a; Li et al., 2021b). Grazing and climate change both have a significant effect on belowground C and nitrogen (N) cycling in grassland ecosystems (Wang et al., 2018a). Soil N and phosphorus (P) are essential nutrients that influence the growth and productivity of alpine plants (Liu et al., 2018). To better understand soil nutrient response mechanisms commonly caused by grazing and climate, systematic research on the changes in soil nutrients in alpine grassland ecosystems under long-term various grazing management strategies is required.

Grassland is influenced by herbivores through defoliation, trampling, ingestion, and the excreta return, with defoliation having the most pronounced and intense effects. In a previous study, soil bulk density was found to be significantly higher under heavy trampling at a depth of 0–10 cm than in an untrampled treatment, as was saturated hydraulic conductivity and the number of microbial colonies. This reduces the ability of surface soil to function and mineralize nutrients and promotes soil nutrient accumulation (Chai et al., 2019). Seasonal grazing is one method used to reduce grazing pressure in regional pastures (Xiao et al., 2020). The most significant differences in abiotic and biotic factors between cold-season and warm-season grazing are the temperature, precipitation, as they influence plant regrowth (Liu et al.,2021; Li et al., 2019). Also is because excreta input and nitrification rates increase in warm-season grazing meadows, whereas the decomposition processes of nutrient cycling and microbial activity are slowed during the cold-season due to the lower temperature (Fivez et al., 2014; Gass et al., 2011). Grazing intensity, in conjunction with precipitation and temperature, regulates soil nutrient availability, which influences nutrient cycles and plant growth (Feng et al., 2015). Warming increases the availability of inorganic N in the soil, reducing the demand pressure of vegetation for different N forms (Kuster et al., 2016). Higher manganese concentrations in the leaves of sedges and forbs after warming indicate that carboxylates released by these plants is a key mechanism of Ca-Pi mobilization in alpine meadows (Zhou et al., 2021). The availability of soil P increases with increasing soil moisture; thus, susceptible to rainfall. In degraded arid steppes, a low rate of P fertilization in wet years is recommended to effectively improve steppe plant productivity compared to dry years (Wang et al., 2018b).

Soil nutrient concentrations, farm management, and paddock characteristics typically have significant relationships (Gourley et al., 2015). Plant community spatial segregation is greater at sites with high soil nutrient concentrations, indicating that grazing intensity influences plant community spatial heterogeneity through the nutrients deposited in excreta (Sanaei et al., 2021). Livestock excreta creates nutrient hotspots (Lezama et al., 2016) that increase aboveground biomass through promoting rapid plant growth (Zhang et al., 2020). The vertical distribution of soil nutrients has been attributed to the distribution of roots in the soil and soil processes (Liu et al., 2014; Wen et al., 2021). In addition, warming has been shown to have a positive effect on the fine-root biomass in deeper soil horizons, as well as in colder regions (Wang et al., 2021). Therefore, it is critical to investigate the distribution and change of soil nutrients across pasture types and along grazing gradients under the combined action of climate change and grazing management practices.

Ecosystems at altitude are highly sensitive to climate change. The highest mountains are also among the most vulnerable, and climatic and socio-economic changes are projected to affect them profoundly (Immerzeel et al., 2020). With an average elevation of approximately 4000 m and an area of more than 2.5 × 10^6 km^2, the Qinghai-Tibet Plateau is the highest plateau on Earth, with alpine grasslands covering more than 85 % of the plateau (Shen et al., 2015). Grazing is an important driver of soil nutrients change, and it is critical in alpine areas where the impacts of global warming are likely to affect the availability of soil nutrients and the responses of plants. Therefore, we carried out a long-term continuous grazing experiment on the Qinghai-Tibet Plateau to investigate the spatial distribution of nutrients under different grazing times (growing or non-growing season) and with distance from the pasture entrance (grazing gradient). Our work set out to address three hypotheses: 1) Long-term seasonal grazing increases soil available nutrients through faster root turnover; 2) Non-growing season grazing is conducive to the deep soil nutrients supply and accumulation due to lower vegetation disturbance during the growing season; and 3) soil nutrients respond more strongly to grazing and climate factors in the near gradient. The ultimate goal of our work was to increase our understanding of the spatial distribution of nutrients in alpine systems under climate change and to review current practices.

2. Materials and methods

2.1. Study region description

The research site was located in Zhangye, Gansu Province, China (97°20′–102°12′N, 37°28′–39°04′E). According to the meteorological data provided by the Tutiempo Network (https://en.tutiempo.net/climate, accessed March 25, 2022), the mean annual precipitation was 170 mm and the mean annual temperature was 8.2 °C from 1978 to 2018, and the area belonged to the semi-arid climate zone of the alpine mountains (Fig. 1). According to the FAO world reference base, the soil in the study region is mainly composed of gelic leptosols. The pH of the 0–10 cm layer soil was 5.7 (soil:water ratio of 1:2.5). The proportions of sand, silt, and clay were 56 %, 38 %, and 6 %, respectively. The reference bulk density was 1.61 kg cm^{-3}. The grassland type is classified as cold temperate and slightly dry mountain grassland by the Comprehensive and Sequential Classification system (CSCs) (Ren et al., 2008). The main plant species in the grassland include *Caragana jubata* and *Potentilla fruticosa*; the main gramineous plants include *Poa poophagorum*, *Stipa purpurea*, *Poa alpigena*, and *Leymus secalinus*; and the main Cyperaceae include *Carex kansuensis*. The main broadleaf grasses include *Potentilla anserina*, *Thalictrum alpinum*, *Artemisia annua*, *Ixeridium chinensis*, and *Polygonum viviparum*. Finally, *Oxytropis kansuensis* and *anaphyllis bulleyana* are the main plant species in the study region, which animals do not like to eat. In late April, forage began to turn green, and in early September, it entered the yellowing and withering period.

2.2. Experiment plot and soil sampling

The pasture was established in 1958 and fenced for large-scale grazing in 1991. It employs a grazing system based on seasonal rotation of the same herd. Every year, spring and autumn pasture grazing (SAP) occurs from May to August, and winter pasture grazing (WP) occurs from November to April. In this study, the livestock type is Gansu wapiti (*Cervus elaphus kansuensis*). The age distribution of the livestock gradually decreases from 1 to 14 years old. However, WP has a higher live weight loadings than SAP due to the animal quantity increase and plant quantity decrease. At the study site, animals are penned at night and taken by herders to daytime grazing and then left to wander. Land located nearer to the pens is more often grazed than land at a greater distance. The movement area in a day is very large as a result of the livestock grazing freely in the pasture. At the grazing gradient level, the first 300 m are situated where they just enter the pasture and animals need to empty their digestive tracts for feeding. They also wait return to the pens in the first 300 m, meanwhile, they usually rest and ruminate, which may increase the number of dung and urine return activities. In

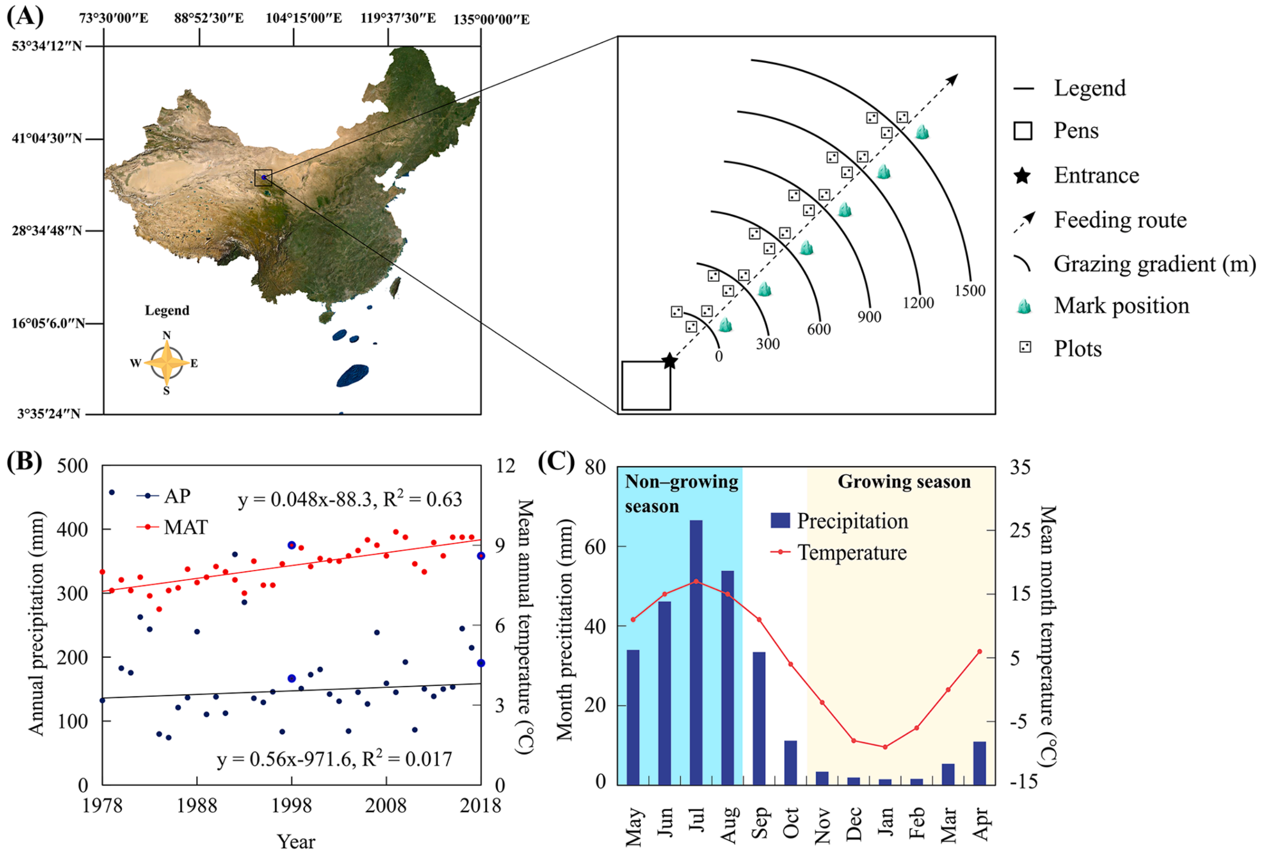

Fig. 1. The study area's satellite map and schematic representation of the sampling line along grazing gradients (A); annual precipitation (AP) and mean annual temperature (MAT) of Zhangye City from 1978 to 2018 (B); monthly precipitation and mean monthly temperature of Zhangye City from 1978 to 2018 (C).

addition, it should be noted that defecation is usually accompanied by urination, but urination is not necessarily accompanied by defecation. Therefore, the disproportionate amount of the dung and urine return may further affect soil nutrients. During the grazing time of the day, with the increase of time, the animal intaking rate shows a trend of increasing first and then stabilizing in the growing season, the foraging rate shows a gradually increasing trend, and the bite per step increases first and then decreases. However, the animal intaking rate and the bite per step are the highest at noon in the non-growing season, and the foraging rate remains relatively stable. Overall, animals move faster on the far gradient, and there is long-term resting and ruminating behavior at the first 300 m (Hou et al., 2003). We hypothesized that since these farm practices have been in place for many years, it might be possible by sampling soil from sampling sites at different distances from the pens, to gain information about the longer-term impact of grazing on soil. In this study, the Gansu wapitit feeding route was selected by observing and consulting with herdsmen. The sample points along the route were set at 0, 300, 600, 900, 1200, and 1500 m from the setting of the pasture entrance according to the local vegetation. It is worth noting that the actual import and export of livestock pens are about 50 m away from the 0 m grazing gradient set in this study. According to the author's observations, the livestock is essentially concentrated at the same time, waiting to go back to their pens at the 0 m grazing gradient. We are also selected and marked with stone each grazing gradient (GG) to facilitate revisiting for soil and herbage sampling. For each grazing gradient, three 1 m × 1 m plots were randomly selected near the stone. Using a soil auger and sampling to 40 cm depth in 10 cm steps, soil samples for four soil depths (0–10, 10–20, 20–30, and 30–40 cm) were collected in every plot. In this way, we randomly selected two soil cores and mixed the same soil depth in a composite sample in each plot in August 1999 and August 2019.

2.3. *Laboratory analyses*

Soil bulk density (SBD, g cm^{-3}) was measured using a stainless-steel cutting ring (5 cm diameter and 5 cm high) after the ground-level plants were removed. Soil water content (SW,%) was surveyed by the oven dried method before air drying. The soil samples were first passed through a 2 mm sieve and handpicked to remove plant detritus, and then air–dried to chemical analysis. The soil pH was measured by weighing 10 g of dry soil and extracting it with 50 ml of distilled water. The organic carbon concentration (OC, g kg^{-1}) of soil was determined according to the Walkley-Black method (Nelson and Sommers, 1983). The soil available nitrogen concentration (AN, mg kg^{-1}) was measured with the alkali-hydrolysis and diffusion methods (Wang et al., 2013). Olsen-P concentration (AP, mg kg^{-1}) was measured using the molybdo-vanado phosphatase method with 0.5 M $NaHCO_3$ at pH 8.5 (Olsen et al., 1954). Total nitrogen concentration (TN, g kg^{-1}) in soil was measured using the Kjeldahl method (Bremner and Mulvaney, 1982). Total phosphorus concentration (TP, g kg^{-1}) in soil was analyzed using the molybdenum blue colorimetric method (Anderson and Ingram, 1989).

2.4. *Calculations and statistical analysis*

Soil nutrient density (SND) was calculated by.

$$SND = SNC \times SBD \times H \times 10^{-2} \tag{1}$$

where *SND* and soil nutrient concentration (*SNC*) are the *SND* (kg/m^{-2} or g/m^{-2}) and *SNC* (g kg^{-1} or mg kg^{-1}), respectively; and *SBD* and *H* are the soil bulk density (g cm^{-3}) and the soil sampling depth (cm), respectively.

Soil moisture (SM) was calculated by.

$$SM = SW \times SBD \times H \times 10 \tag{2}$$

where *SM* is the soil moisture (mm); and *SW* is the soil water concentration (SW, %).

Coefficient of variation (CV) was calculated by.

$$CV = SD \div SE \tag{3}$$

where *SD* is the standard deviation; and *SE* is the mean of the data.

To assess the effects of time of grazing and grazing gradients on the soil moisture and SBD, two-factor analyses of variance (ANOVAs) were conducted in SPSS 17.0 software. The soil nutrient index at each soil depth along the grazing gradients were analyzed by one-factor ANOVAs with SAS 8.0 (USA) software. Change effect size (Hedges'g) and 95 % confidence intervals were calculated by JASP version 0.16.1 software. SPSS was used for the statistical analysis as well as data fitting to a linear model. The normalized effect (standardized coefficient) of grazing time, grazing gradients, year, and their interaction on different indexes in the 0–10 cm soil layer was analyzed using an SPSS multiple linear regression model. The normality and homogeneity of variances for all the parameters were tested using the Shapiro–Wilk test and Levene's test, respectively. For all tests, significance was determined at $\alpha = 0.05$ level, unless otherwise stated.

3. Results

3.1. Effects of seasonal grazing on soil bulk density and soil moisture

The SBD was highest in the first 300 m soil along the grazing gradient and in the 20–40 cm soil depth. Grazing increased the SBD (Table 1).

The soil moisture was high in the 0–20 cm soil depth. Long-term grazing in non-growing season increased soil moisture significantly in the 0–20 cm soil depth, while it decreased in the 20–40 cm soil depth of SAP. Furthermore, growing season grazing decreased soil moisture significantly in the first 300 m soil (Table 2).

3.2. Effects of seasonal grazing on soil available nutrient density

With the increase of the soil depth, SAND and SAPD decreased gradually. In the first 300 m of the two pastures, SAND was higher, while SAPD exhibited the opposite trend. Similar nutrient distribution was found in the 0–40 cm soil depth of SAP but only in the 0–20 cm soil depth of WP (Fig. 2A and B). The SAPD:STPD ratio and the SAND:STND ratio exhibited significant differences in SAP and WP grazing gradients (Fig. 2C and D). Long-term grazing improved SAPD and SAND in the 0–20 cm soil of the two pastures but had little influence on the SAND:STND ratio or SAPD:STPD ratio (Fig. 2E, F, G, and H). Grazing in 2019 had a positive effect on SAND, SAPD, and the SAND:STND ratio compared with 1999, but a negative effect on the SAPD:STPD ratio. Non-growing season grazing had a positive effect on SAND and a negative effect on SAPD, whereas grazing along grazing gradients had the opposite effects. GS*GY and GG*GY had positive effects on SAND and SAPD, respectively. GS*GY had a positive effect on the SAND:STND ratio and the SAPD:STPD ratio. GS*GG and GS*GG*GY had negative effects on the SAND:STND ratio (Fig. S1A, B, C, and D).

3.3. Effects of seasonal grazing on soil total C, N and P density

Soil total C, N, and P density decreased gradually with increasing soil depth and was high in the first 300 m soil of SAP but not in WP (Fig. 3A, B, and C). Long-term growing season grazing had a positive effect on the soil total C, N, and P density in the 0–10 cm soil depth but a negative or no effect in the 10–40 cm soil depth. Long-term grazing had no significant effect in the first 300 m soil of WP but a positive effect in the 0–40 cm soil depth at distance (>600 m) (Fig. 3D, E, and F). Non-growing

Table 1

Soil bulk density and change effect size of different soil depths at different grazing gradients in two pastures.

Grazing season	Grazing gradient (m)	Soil Bulk Density (g cm^{-3})				Change effect size			
		0–10 cm	10–20 cm	20–30 cm	30–40 cm	0–10 cm	10–20 cm	20–30 cm	30–40 cm
SAP	0	1.44 ± 0.04Ab	1.43 ± 0.03Aab	1.46 ± 0.03Aa	1.41 ± 0.03Aab	7.05 (2.13, 12.0)*	6.22 (1.80, 10.6)*	4.51 (1.08, 7.87)*	2.11 (-0.09, 4.18)*
	300	1.57 ± 0.03Aa	1.50 ± 0.03ABa	1.41 ± 0.04BCabc	1.38 ± 0.04Cb	11.7 (3.86, 19.7)*	7.77 (2.40, 13.2)*	5.00 (1.29, 8.64)*	1.55 (-0.42, 3.39)*
	600	1.46 ± 0.03Aab	1.41 ± 0.03Abc	1.45 ± 0.04Aab	1.51 ± 0.04Aa	9.54 (3.07, 16.1)*	7.57 (2.33, 12.9)*	5.53 (1.51, 9.51)*	3.25 (0.51, 5.89)*
	900	1.52 ± 0.03Aab	1.32 ± 0.02Bc	1.36 ± 0.03Bbc	1.36 ± 0.03Bb	13.1 (4.38, 22.0)*	6.12 (1.75, 10.5)*	5.03 (1.31, 8.71)*	3.37 (0.56, 6.08)*
	1200	1.31 ± 0.04Ac	1.16 ± 0.03Bd	1.36 ± 0.03Abc	1.36 ± 0.04Ab	9.52 (3.06, 16.1)*	4.33 (1.00, 7.59)*	6.90 (2.06, 11.7)*	3.56 (0.66, 6.38)*
	1500	1.32 ± 0.03Ac	1.09 ± 0.03Bd	1.33 ± 0.03Ac	1.32 ± 0.04Ab	12.0 (3.99, 20.2)*	4.62 (1.13, 8.05)*	6.35 (1.85, 10.9)*	4.28 (0.98, 7.50)*
WP	0	1.68 ± 0.04Aa	1.61 ± 0.02ABa	1.68 ± 0.03Aa	1.53 ± 0.04Bd	9.24 (2.96, 15.6)*	6.70 (1.99, 11.4)*	6.38 (1.86, 10.9)*	4.37 (1.02, 7.65)*
	300	1.58 ± 0.03Bab	1.60 ± 0.03Bab	1.70 ± 0.02Aa	1.59 ± 0.02Bcd	10.1 (3.28, 17.0)*	8.67 (2.74, 14.7)*	11.1 (3.63, 18.6)*	6.73 (2.00, 11.5)*
	600	1.51 ± 0.03Bbc	1.62 ± 0.03Aa	1.70 ± 0.03Aa	1.71 ± 0.03Aab	9.27 (2.97, 15.7)*	14.0 (4.70, 23.5)*	12.0 (3.97, 20.1)*	9.87 (3.19, 16.6)*
	900	1.46 ± 0.03Cc	1.58 ± 0.04Babc	1.71 ± 0.04Aa	1.73 ± 0.03Aa	10.6 (3.46, 17.8)*	10.1 (3.41, 17.6)*	12.7 (4.23, 21.3)*	11.6 (3.82, 19.4)*
	1200	1.43 ± 0.03Bc	1.52 ± 0.03Bbc	1.62 ± 0.03Aa	1.69 ± 0.03Aab	10.7 (3.50, 18.0)*	9.12 (2.91, 15.4)*	11.1 (3.66, 18.7)*	12.2 (4.07, 20.6)*
	1500	1.43 ± 0.03Bc	1.50 ± 0.03Bc	1.52 ± 0.03Bb	1.63 ± 0.03Abc	10.9 (3.56, 18.3)*	12.0 (3.97, 20.1)*	9.75 (3.15, 16.4)*	9.42 (3.03, 15.9)*
Source of variation									
Grazing season (GS)		**	***	***	***				
Grazing gradient (GG)		***	***	***	**				
GS*GG		**	***	NS	**				

Note: for each grazing season (GS), means ± SE in a column followed by different lowercase and capital letters are significantly different in grazing gradient and soil depth, respectively, according to Duncan's test at $P < 0.05$. Change effect size presented as Hedges' g and their 95 % confidence intervals. Positive values of change effect size indexed improvements in the 2019 from 1999. Negative values of change effect size are the opposite. Significant change effects are indicated with an *. Soil bulk density (SBD), spring and autumn pasture (SAP), winter pasture (WP).

Table 2
The soil moisture and change effect size of different soil depths at different grazing gradients in two pastures.

Grazing Season	Grazing gradient (m)	Soil Moisture (mm)				Change effect size			
		0–10 cm	10–20 cm	20–30 cm	30–40 cm	0–10 cm	10–20 cm	20–30 cm	30–40 cm
SAP	0	349.1 ± 36.7Ad	336.6 ± 25.6ABd	326.8 ± 28.1ABd	258.8 ± 8.85Bd	−2.90 (-5.36, −0.33)*	−7.48 (-12.7, −2.29)*	−8.20 (-13.9, −2.57)*	−6.29 (-10.8, −1.82)*
	300	456.1 ± 5.12Ad	381.2 ± 24.5Bd	289.1 ± 31.7Cd	274.7 ± 19.0Cd	−5.81 (-10.0, −1.63)*	−6.38 (-10.9, −1.86)*	−6.00 (-10.3, −1.71)*	−6.35 (-10.9, −1.85)*
	600	1751 ± 136Ab	1440 ± 86.7ABa	1208 ± 85.1Bb	1458 ± 118ABb	4.96 (1.28, 8.60)*	4.51 (1.08, 7.87)*	0.77 (-0.96, 2.41)	0.49 (-1.17, 2.10)
	900	1334 ± 21.7Ac	857.1 ± 44.3Bc	615.9 ± 19.5Cc	828.7 ± 9.60Bc	15.3 (5.17, 25.7)*	−0.12 (-1.71, 1.49)	−2.61 (-4.91, −0.18)*	−3.22 (-5.84, −0.49)*
	1200	2216 ± 145Aa	1655 ± 144Ba	1626 ± 164Ba	1889 ± 190ABa	7.26 (2.20, 12.3)*	2.83 (0.30, 5.25)*	1.21 (-0.64, 2.95)	0.94 (-0.83, 2.61)*
	1500	1704 ± 34.3Ab	1154 ± 35.0Cb	1079 ± 43.8Cb	1328 ± 33.5Bb	12.3 (4.10, 20.7)*	0.87 (-0.88, 2.53)	−1.41 (-3.21, 0.51)	−1.47 (-3.29, 0.47)*
WP	0	936.3 ± 12Ac	722.5 ± 30Bc	436.6 ± 43Cc	416.3 ± 31Cc	23.7 (8.14, 38.7)*	1.50 (-0.45, 3.33)*	2.18 (-0.05, 4.28)*	−3.95 (-6.99, −0.84)*
	300	1082 ± 33Ab	922.7 ± 38Bb	724.7 ± 44Cb	655.9 ± 36Cb	6.72 (1.99, 11.4)*	0.39 (-1.26, 1.99)*	0.59 (-1.09, 2.20)	−11.5 (-19.4, −3.80)*
	600	1400 ± 38Aa	1145 ± 28Ba	868.0 ± 33 Da	966.9 ± 19Ca	0.47 (-1.19, 2.08)*	13.0 (4.32, 21.7)*	0.72 (-0.99, 2.36)*	−6.62 (-11.3, −1.96)
	900	988.4 ± 39Ac	843.2 ± 24Bb	723.6 ± 38Cb	682.8 ± 29Cb	1.53 (-0.43, 3.37)*	11.3 (3.73, 19.0)*	−0.04 (-1.64, 1.56)	−4.59 (-8.00, −1.12)
	1200	549.8 ± 31Ad	465.2 ± 28ABd	378.6 ± 37Bcd	266.7 ± 20Cd	12.5 (4.17, 21.1)*	5.27 (1.41, 9.09)	−2.25 (-4.38, 0.01)*	−6.06 (-10.4, −1.73)*
	1500	469.9 ± 6.2Ad	390.4 ± 18Bd	281.1 ± 18Cd	175.7 ± 3.6De	9.56 (3.08, 16.1)*	11.4 (3.76, 19.2)*	−3.79 (-6.73, −0.76)*	−4.85 (-8.42, −1.23)*
Source of variation									
Grazing season (GS)		***	***	***	***				
Grazing gradient (GG)		***	***	***	***				
GS*GG		***	***	***	***				

Note: for each grazing season (GS), means ± SE in a column followed by different lowercase and capital letters are significantly different in grazing gradient and soil depth, respectively, according to Duncan's test at $P < 0.05$. Change effect size presented as Hedges' g and their 95 % confidence intervals. Positive values of change effect size indexed improvements in the 2019 from 1999. Negative values of change effect size are the opposite. Significant change effects are indicated with an *. Soil moisture (SM), spring and autumn pasture (SAP), winter pasture (WP).

season grazing had a negative effect on SOCD and STND relative to growing season grazing, while grazing along grazing gradients had a negative effect on SOCD and STPD. Grazing in 2019 relative to 1999 and GS*GG*GY had positive effects on the soil total C, N, and P density. GS*GG and GG*GY had positive effects on SOCD and STPD, respectively. GS*GY had a negative effect on SOCD and STND (Fig. S2A, B, and C).

3.4. *Effects of seasonal grazing on soil total C, N and P density ratio*

Grazing increased the SOCD:STND ratio in the first 300 m soil while decreasing the STND:STPD ratio. Growing season grazing also increased the soil SOCD:STPD ratio, while non-growing season grazing decreased the soil SOCD:STPD ratio (Fig. 4A, B, and C). Long-term growing season grazing had a negative effect on the SOCD:STND ratio and the SOCD:STPD ratio in the 20–40 cm soil depth but non-growing season grazing had no effect in the 0–40 cm soil depth (Fig. 4D, E, and F). Non-growing season grazing and GS*GG had negative effects on the soil total C, N, and P density ratio, whereas GS*GY*GG had the opposite effects. In the first 300 m soil, grazing in 2019 relative to 1999 and GY*GG had negative effects on the SOCD:STPD ratio and the STND:STPD ratio but positive effects on the SOCD:STND ratio. GS*GY had a positive effect on the SOCD:STPD ratio and the STND:STPD ratio (Fig. S3A, B, and C).

3.5. *Coefficient of variation (CV) analysis with different nutrient density*

CV values of various indexes showed no discernible trend along the soil depth of SAP, whereas they increased gradually in WP soil (Fig. 5A). CV values of various indexes have no discernible trend along grazing gradients in two pastures (Fig. 5B). Other than STND and SAND:STND ratio, the CV of other indexes decreased across soil depth (Fig. 5C). Long-term grazing increased the CV of soil total C, N and P density in the first 300 m soil (Fig. 5D).

3.6. *Correlation analysis between C, N and P density*

The available and total C, N, and P density had a significant positive correlation. The grazing season had an effect on the slope of available and total C, N, and P density (Fig. 6).

4. Discussion

4.1. *Effects of long-term seasonal grazing on soil physical and chemical properties*

Livestock grazing and trampling can reduce plant height, number, causing a decline in grass transpiration, whereas the evaporation is enhanced because of greater exposure to radiation (Ebrahimi et al., 2016; Penner et al., 2019; Zhang et al., 2019; Li et al., 2021a; Li et al., 2021b). As a result of the vegetation is less disturbed by grazing, which may decrease soil moisture by transpiration in WP, especially deep soil moisture (Table 2). The soil retains a certain amount of water, and compaction becomes more intense with increased livestock trampling (Chai et al., 2019), which may cause the SBD of WP to be higher than that of SAP (Table 1).

Normally, livestock modify the distribution of soil nutrients through hotspots of nutrient enrichment (Meglioli et al., 2017). However, plant roots and soil processes control the mobilization of different soil elements, such as direct physicochemical mobilization processes for P and indirect microbial-dominated mobilizing processes for N (Wen et al., 2021). Intensive grazing may be due to the stimulating impact of urine and dung deposition, which significantly increased the functional gene alpha diversity, changed the overall functional community structure, and increased nitrogen mineralization and denitrification genes (Tang et al., 2019). At the same time, P availability is usually related to fine root growth and higher soil water content (Zhou et al., 2021), while

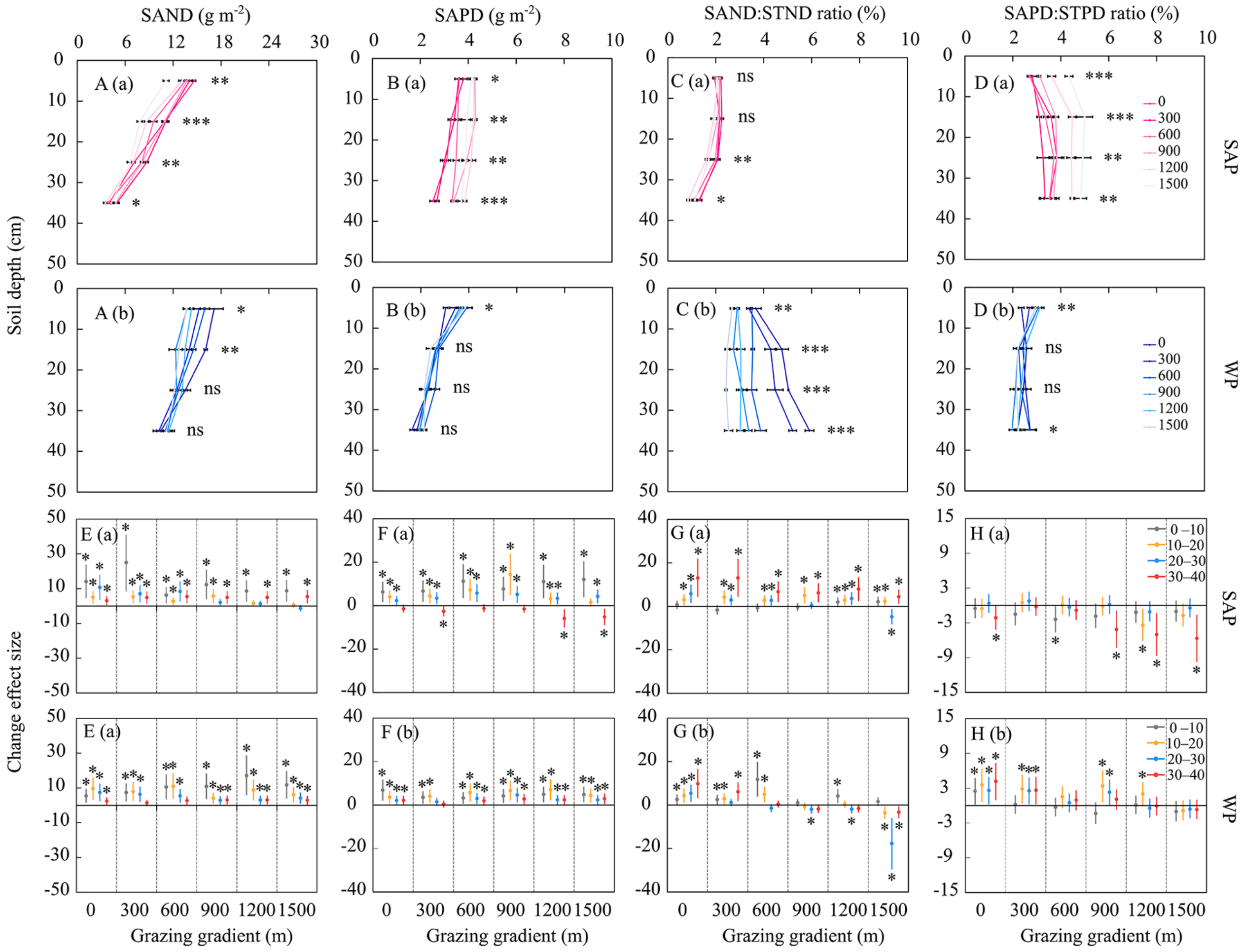

Fig. 2. The distribution and change effect size (Hedges' g) of SAND (A and E), SAPD (B and F), the SAND:STND ratio (C and G), and the SAPD:STPD ratio (D and H) in different soil depths on different grazing gradients (GG). Spring and autumn pasture (SAP) and winter pasture (WP) are represented by "a" and "b", respectively. Change effect size presented as Hedges' g and their 95% confidence intervals. Positive values of change effect size indexed improvements in the 2019 from 1999. Negative values of change effect size are the opposite. Significant change effects are indicated with an *. Note: soil available nitrogen density (SAND), soil available phosphorus density (SAPD), soil available nitrogen density:soil total nitrogen density (SAND:STND ratio), soil available phosphorus density:soil total phosphorus density (SAPD:STPD ratio).

intensive grazing leads to drier and denser soil (Gass and Binkley, 2011). The above reasons may explain why SAND is higher and SAPD is lower in the first 300 m soil. (Fig. 2A and B). The results indicate that along grazing gradients has a negative effect on SAND and a slight positive effect on SAPD in the topsoil. Furthermore, GG*GY has a positive effect on SAPD, implying that it contributes to the accumulation of soil-available P over a wide gradient in a warming and humidifying climate (Fig. S1 B and D). The ratio of soil-available nutrients to soil total nutrients can be used to characterize the strength of a potential soil nutrient availability mechanism (Liang et al., 2021). P is derived primarily from rock weathering rather than organic matter decomposition, and its movement in soil is primarily influenced by soil moisture (Penuelas et al., 2013). Plants can increase P availability by integrating dynamic root interactions (Wen et al., 2021). Livestock, through feeding and excreta, can affect the plant roots and soil moisture, respectively, potentially weakening the P mineralization in the first 300 m soil (Fig. 2D). However, the N mineralization is higher in the first 300 m soil, which could be related to soil temperature, soil moisture, and microbial activity (Liu et al., 2011; Wen et al., 2021). Therefore, the availability of soil nutrients may be directly influenced by the response of vegetation.

Livestock need to empty their digestive tracts for feeding when they enter the pasture and wait return to the pens in the first 300 m, which may increase the number of dung and urine return activities, thereby increasing the soil nutrients (Hou et al., 2003). However, when grazing occurs during the growing season, the plants may absorb more nutrients from the soil by increasing the input of root carbon to reconstruct their photosynthetic tissue (Wu et al., 2016). Increased root allocation increases soil carbon inputs as well as nitrogen retention (Sun et al., 2017; Fig. 6A, and D). However, plants were unable to achieve timely photosynthetic organ reconstruction and root growth in the non-growing season, resulting in soil nutrient accumulation in the first 300 m soil (Fig. 3A, B, and C). To optimize the benefits of the ecosystem, that is, to not only promote the increase of storage nutrients but also to maintain a stable community, grazing should be altered as needed in conjunction with the reaction of the vegetation.

The more severe the mechanical crushing of vegetation, the more the broken litter was buried in the shallow soil, which accelerated litter decomposition (Li et al., 2019), increasing the SOCD:STND ratio in the first 300 m soil (Fig. 4A). The STND:STPD ratio decreased in the first 300 m soil (Fig. 4C), indicating N limitation in this area. Furthermore, livestock activities may alter soil structure by disrupting aggregates and the surface crust, increasing soil susceptibility to water and wind erosion and stimulating soil C and N losses (Li et al., 2019). Growing season grazing increased the SOCD:STPD ratio in the first 300 m soil, whereas non-growing season grazing decreased it (Fig. 4B; 6E), which may be caused by disproportionate amount of the dung and urine return in different grazing time. Grazing time significantly affects the soil stoichiometric ratio, and periodic pasture exchange in SAP and WP may be

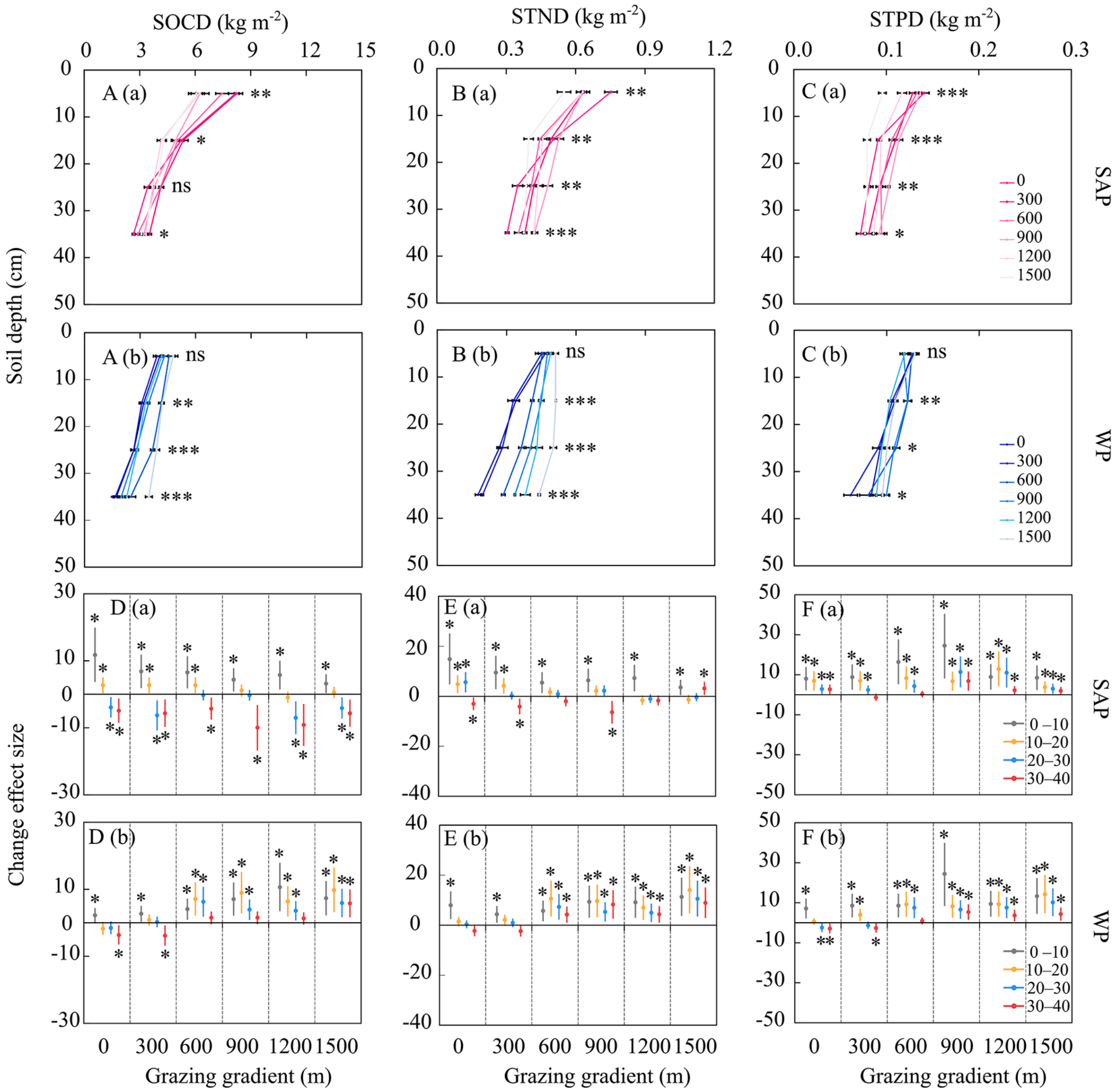

Fig. 3. The distribution and change effect size (Hedges' g) of SOCD (A and D), STND (B and E), and STPD (C and F) in different soil depths on different grazing gradients (GG). Spring and autumn pasture (SAP) and winter pasture (WP) are represented by "a" and "b", respectively. Change effect size presented as Hedges' g and their 95% confidence intervals. Positive values of change effect size indexed improvements in the 2019 from 1999. Negative values of change effect size are the opposite. Significant change effects are indicated with an *. Note: soil organic carbon density (SOCD), soil total nitrogen density (STND), soil total phosphorus density (STPD).

an effective measure to balance soil nutrients.

4.2. *Changes in soil physical and chemical properties under long-term seasonal grazing*

Under long-term grazing, SBD increased and soil moisture was higher in topsoil, which may be related to precipitation and grazing (Liu et al., 2021). In addition, grazing during the growing season destroys the vegetation canopy (Ebrahimi et al., 2016; Penner and Frank, 2019), causing a positive effect on soil moisture of SAP but not on the first 300 m soil of WP (Table 1).

The availability of N and P is typically linked to plant rhizosphere processes and soil moisture (Gourley et al., 2015; Lu et al., 2015; Wen et al., 2021). For alpine grassland, precipitation has a much greater influence than grazing on controlling the dynamics of grassland net primary production (Li et al., 2021a; Li et al., 2021b), and the response of linked aboveground vegetation with underground roots is slow to climate and grazing (Zhang et al., 2022; Xu et al., 2022). For instance, compared to grazing exclusion, long-term continuous grazing increases the distribution of biomass to roots (Sun et al., 2014). The influence of climate and roots may be the main reason for promoting the increase of soil available nutrients. The findings of the present study showed that the topsoil moisture also increased slightly (Table 2). Meanwhile, climate warming may increase soil inorganic N mobilization (Kuster et al., 2016) and P assimilation in topsoil (Zhou et al., 2021), contributing to an increase in soil-available nutrient density in the 0–20 cm soil depth of two pastures (Fig. 2E and F). In addition, grazing may strongly influence the soil microbial community and regulate the nutrient turnover, thereby promoting soil productivity (Xun et al., 2018). Plants can respond to nutrient resource gradients by strengthening different nutrient acquisition capabilities of their root systems (such as changing root morphology, and exuding organic acids and enzymes), and these

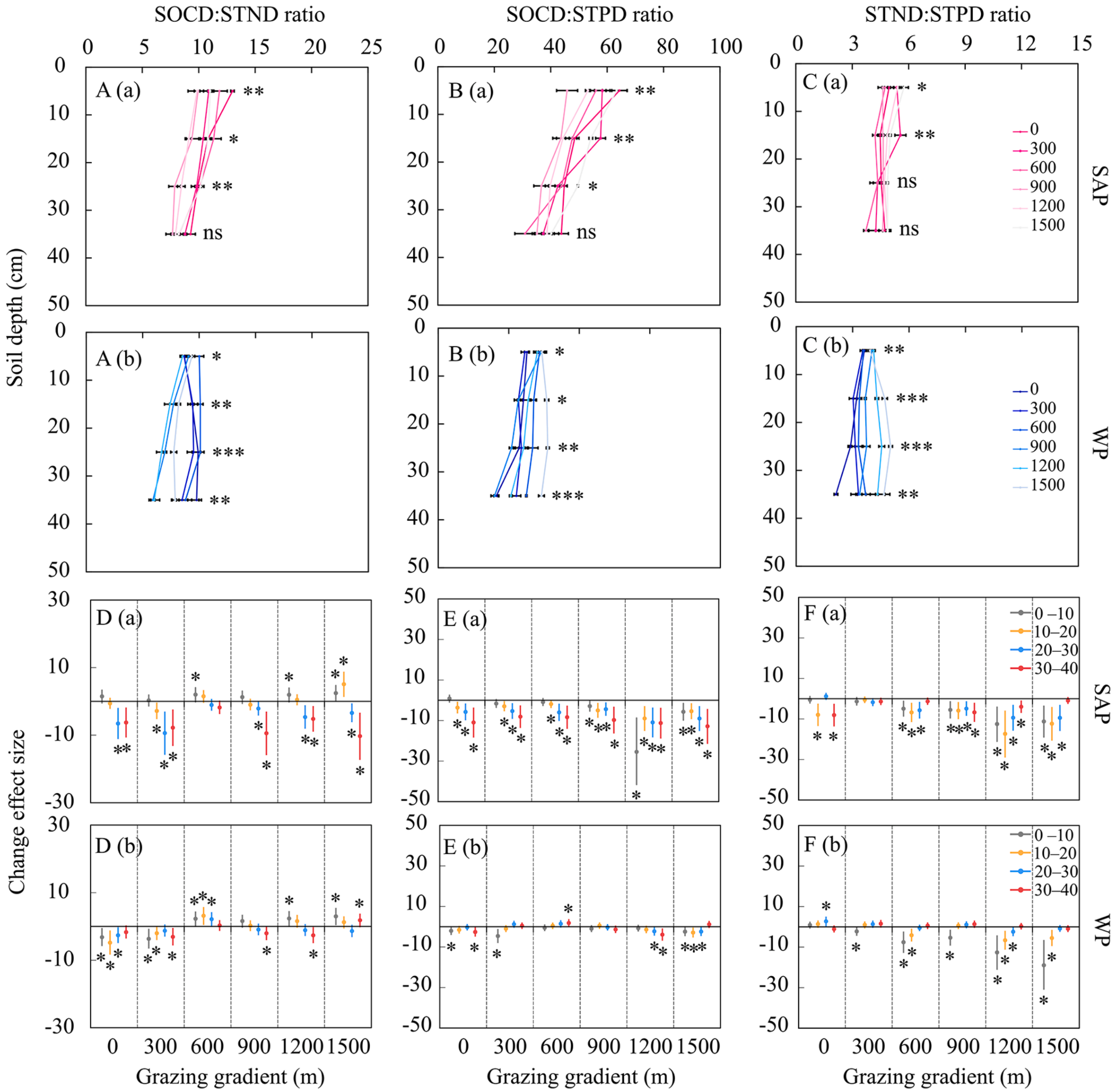

Fig. 4. The distribution and change effect size (Hedges' g) of the SOCD:STND ratio (A and D), The SOCD:STPD ratio (B and E) and STND:STPD ratio (C and F) in different soil depths on different grazing gradients (GG). Spring and autumn pasture (SAP) and winter pasture (WP) are represented by "a" and "b", respectively. Change effect size presented as Hedges' g and their 95% confidence intervals. Positive values of change effect size indexed improvements in the 2019 from 1999. Negative values of change effect size are the opposite. Significant change effects are indicated with an *. Note: soil organic carbon density:soil total nitrogen density ratio (SOCD:STND ratio), soil organic carbon density:soil total phosphorus density ratio (SOCD:STPD ratio), soil total nitrogen density:soil total phosphorus density ratio (STND:STPD ratio).

changes may significantly increase the nitrogen fixation rate and phosphorus mineralization rate (Herben et al., 2022; Wen et al., 2021; Liu et al., 2021). Long-term grazing had no effect on the SAND:STND ratio or the SAPD:STPD ratio (Fig. 2G and H). This implies that intensive grazing activities in grasslands limit the capacity of diverse soil microbial communities to sustain ecosystem function and physicochemical mobilizing processes (Wang et al., 2020; Wen et al., 2021). The different SAND:STND, SAPD:STPD ratio in topsoil between two grazing pastures, along grazing gradients, and grazing in 2019 relative to 1999, provided further evidence for different mechanisms regulating soil N and P availability (Fig. S1 C and D). Consequently, it is important to research the various elements's response mechanisms in order to encourage the ecosystem's healthy development.

Normally, the vertical distribution of soil nutrients is attributed to the roots in the soil and the related soil processes (Liu et al., 2014; Wen et al., 2021). The root turnover is rapid in topsoil in alpine meadow ecosystems and plays an important role in nutrient storage and turnover (Wu et al., 2011). This could help explain why grazing during the growing season promotes the accumulation of soil nutrients in the topsoil. The WP has no grazing during the growing season, which causes the downward transport of root production, increases the depth of soil nutrients (Wu et al., 2016) (Fig. 3D, E, and F). Growing season grazing had a positive effect on the soil total nutrient density, indicating that it may have had a root excitation effect that promoted more nutrient accumulation (Fig. 6A). GS*GG*GY had a positive effect on total nutrient density (Fig. S2 A, B, and C), indicating that grazing contributed to the soil nutrient accumulation during the warming and humidifying process (Li et al., 2021a; Li et al., 2021b). As a result, SAP and WP exchange periodically to maintain the sustainability of the ecosystem.

Long term growing grazing had a negative effect on the SOCD:STND

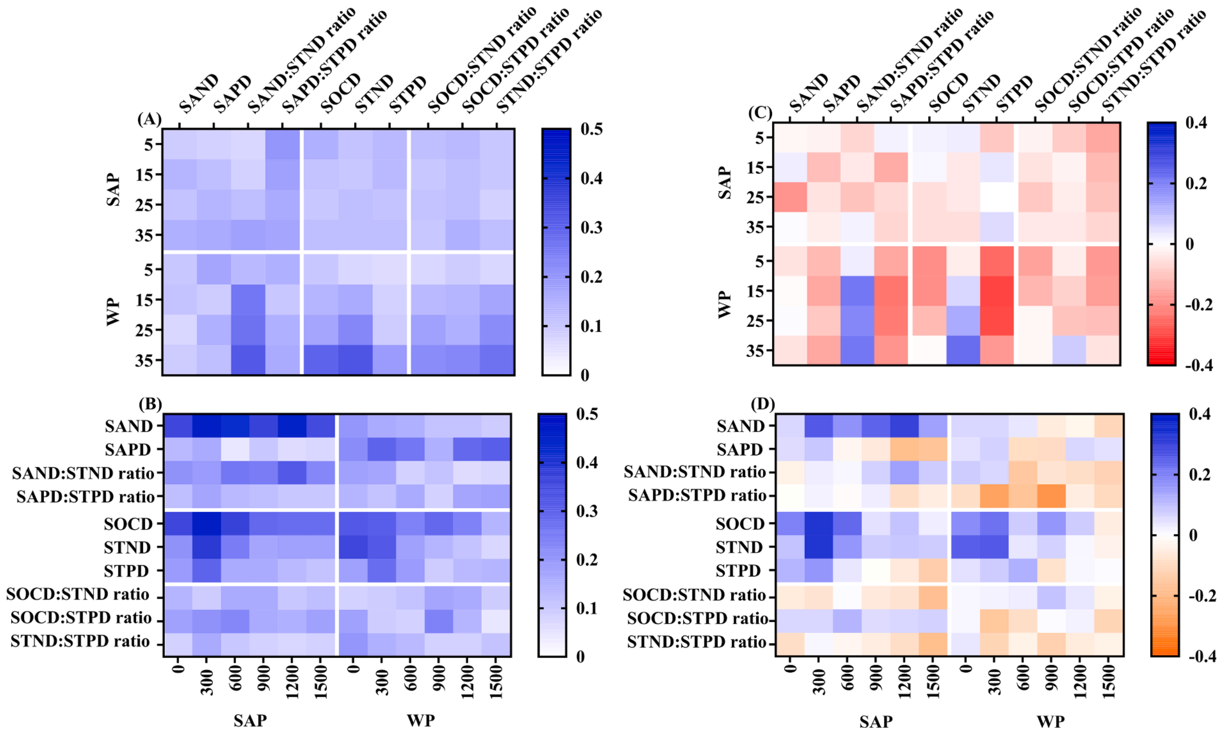

Fig. 5. Heat map estimated different index heterogeneity in terms of the coefficient of variation along the soil depth in 2019 (A) and the CV difference (C), and the CV along grazing gradients in 2019 (B) and the CV difference (D).

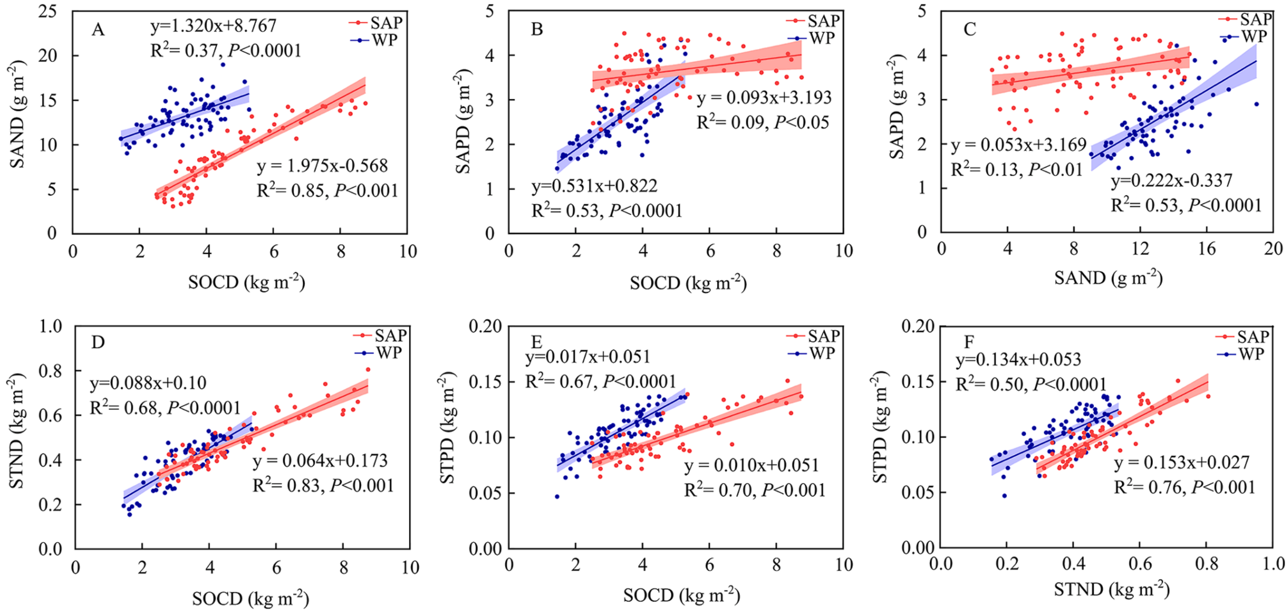

Fig. 6. Relationships between SOCD and SAND (A), SOCD and SAPD (B), SAND and SAPD (C), SOCD and STND (D), SOCD and STPD (E), and STND and STPD (F). Note: soil available nitrogen density (SAND), soil available phosphorus density (SAPD), soil organic carbon density (SOCD), soil total nitrogen density (STND), soil total phosphorus density (STPD).

ratio and the SOCD:STPD ratio in the 20–40 cm soil depth (Fig. 4D and E). This could be due to a changed in carbon storage in the deep soil (Fig. 6A, B, D, and E). With increasing grazing pressure, more root biomass was allocated to the topsoil than the deep soil (Burke et al., 1999), which may have promoted carbon accumulation in the topsoil. In addition, grazing had a negative effect on the STND:STPD ratio in the 0–20 cm soil depth of two pastures. This implies that grazing may hasten N limitation in topsoil (Yu et al., 2021; Yang et al., 2019). No significant effects were observed in the first 300 m soil (Fig. 4F), which was caused by a large amount of excreta return that weakened the effect of N limitation. Briefly, Non-growing season grazing converted litter into excreta, but the temperature sensitivity of dung mass loss was approximately-three times that of the litter mass loss, resulting in nutrient loss over time (Wu et al., 2012; Wu et al., 2016). Along grazing gradients had a positive effect on the SOCD:STND ratio but a negative effect on the SOCD:STPD ratio and the STND:STPD ratio, which may have been due to C and P accumulation in the first 300 m topsoil (He et al., 2019). Furthermore, GS*GG*GY had a positive effect on the soil nutrient density ratio, implying that long-term seasonal grazing contributed to increase soil C, N, and P absorption (Fig. S3 A, B, and C). Therefore, for different gradients, especially the first 300 m, regular soil nutrient monitoring and human intervention (such as fertilization) should be carried out to eliminate potential element restrictions.

5. Conclusions

In this study, it was found that long-term (1999–2019) grazing had an overall positive effect on soil C, N, and P accumulation in soil. The current study demonstrated that grazing had a negative effect on P availability and a positive effect on N availability in the first 300 m soil along the grazing gradient. At the grazing gradient level, there was a positive effect on soil total C and N accumulation during the growing season grazing in the first 300 m soil, while there was no significant effect during the non-growing season grazing. At the soil depth level, growing season grazing have a positive effect on soil total C, N, and P accumulation in the 0–10 cm soil, but non-growing season grazing had a positive effect throughout the profile (0–40 cm). In the context of warm and humid climate change in the future, grazing can contribute to the accumulation of soil nutrients, especially carbon sequestration of deep soil by grazing in the non-growing season. It can help to explain some of the missing carbon sinks in the global carbon cycle, help to slow global warming, and provide new ideas for designing peak carbon dioxide emissions and carbon neutrality policies. However, we have to consider whether the diversity and stability of vegetation communities meet our expectations. If the community system over a certain threshold and then collapses, the impact on the ecosystem may be irreversible. Therefore, we suggest that periodic pasture exchange in SAP and WP and human intervention (such as fertilization) should be carried out to increase the sustainability of the system.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2022.116111.

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