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Different responses of soil element contents and their stoichiometry (C: N: P) to different grazing intensity on the Tibetan Plateau shrublands

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Potentilla fruticosa, a major alpine shrubland type, is widely distributed across the Tibetan Plateau, and grazing is the most common disturbance in the shrublands of *P. fruticosa*. However, soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and their stoichiometry under different grazing intensities were unclear. In our study, we explored SOC, STN, STP, their stoichiometry, and their controlling factors in the grazing disturbance of heavy grazing (HG), moderate grazing (MG), light grazing (LG), and no grazing (NG) conditions in the Tibetan Plateau *P. fruticosa* shrublands. The grazing intensities were mainly assessed by considering the shrublands' ground cover, the indicators of the road density, the distance between sampling sites and cowshed or sheep shed, the amounts of cow and sheep dung, and vegetation that had been gnawed and stampeded. Our results indicated that soil physical properties of soil temperature and bulk density have decreasing trends with decreasing grazing intensities from HG to NG. The SOC, STN, STP, and soil C:N and C:P ratios have increasing trends with decreasing grazing intensities from HG to NG, while the changes in soil N:P ratio were relatively stable along grazing intensities. Our results indicated that HG generally had stronger effects on SOC, STN, and soil C:N and C:P ratios than NG, indicating substantial effects of grazing disturbance on biogeochemical cycles of SOC and STN in the shrubland ecosystems. Therefore, for the alpine shrubland of *P. fruticosa*, the HG should be avoided for sustainable cycling of soil nutrients and the balance of soil nutrient stoichiometry. The grazing types can directly affect plant conditions, and plant conditions can directly affect soil physical and chemical properties and litter standing crops. Finally, soil physicochemical properties and litter standing crop resulting from different grazing intensities directly control SOC, STN, and STP. For the soil stoichiometry, the soil's physical and chemical properties resulting from different grazing intensities have direct impacts on soil C:P and N:P ratios.

KEYWORDS

soil element, soil stoichiometry, controlling factors, Tibetan plateau, alpine shrublands, grazing

1 Introduction

Carbon (C) can provide the structural basis for plants, and soil organic carbon (SOC), a major C pool for terrestrial C cycling, significantly regulates atmospheric CO_2 (Wang et al., 2015). Nitrogen (N), a bio-element, is responsible for litter decomposition, photosynthesis, and plant growth (Klausmeier et al., 2004), and soil N is derived from soil organic matter (Nie et al., 2022). Phosphorous (P), a component of DNA, RNA, and cell structure, has a significant coupled relationship with C and N for plant photosynthesis, SOC decomposition, N fixation, and assimilation of C:N (Bai et al., 2012). Ecological stoichiometry mainly includes the balance of C and nutrient elements, e.g., C:N, C:P, and N:P, in terrestrial ecosystems (Bai et al., 2019). Soil C:N, C:P, and N:P ratios were different in various plant communities because of different substrate inputs (Zechmeister-Boltenstern et al., 2015). Soil C:N:P ratio not only has been used to explore the intrinsic relationships between belowground and aboveground components in ecosystems but also can affect plant nutrient state, regulate plant growth, and reflect soil fertility (Zechmeister-Boltenstern et al., 2015).

Grazing occupies more than one-third of terrestrial land regions (Xun et al., 2018). Overgrazing, however, may be detrimental to habitat conservation status, and it is thus important to assess potential trade-offs between grazing and ecosystem systems. Grazing is an important anthropogenic disturbance and strongly affects the cycles of C, N, and P, and their stoichiometry (He et al., 2020). The disturbance of grazing has been demonstrated to induce changes in plant diversity in the steppe (Zhang et al., 2018), and the changes of plant can affect SOC (Nie et al., 2021), thus inevitably affecting soil stoichiometry. Overgrazing has caused considerable losses of soil C in the form of CO_2 from grasslands (Zhou et al., 2017). Grazing has had negative impacts on SOC, STN, and STP in the Tibetan Plateau alpine grasslands (Sun et al., 2019). Heavy grazing (HG) can negatively affect the accumulation of litter and soil coverage, and soil fertility and quality significantly decrease and substantially reduce production in ecosystems (Zhang et al., 2018). However, it was also demonstrated that grazing exclusion was not an effective option for SOC and STN sequestration, and the SOC and STN were relatively stable in the mountain meadow and typical steppe habitats in a mountain-basin ecosystem in an arid region of central China (Bi et al., 2018). On the Tibetan Plateau, grazing could reduce C emissions when alpine meadows suffer from droughts (Zhang Z. C et al., 2019). The rates of soil C changes increased linearly with those of N change, and soil C:N ratio was demonstrated to remain stable over the years of grazing exclusion (Yu et al., 2019). Among the 96 observations after grazing exclusion, 73% and 27% of the observations indicated an increase and decrease in soil C stock, respectively (Yu et al., 2019). Furthermore, the SOC has a significantly decreased trend with increasing grazing intensities in the Tibetan Plateau alpine meadow (Li et al., 2019). Grazing exclusion increased SOC, STN, and STP by 395 $g \cdot m^{-2}$ in the 0–15 cm soil depth, and 239 and 196 $g \cdot cm^{-2}$ in the 0–40 cm soil depth, respectively, for naturally restoring degraded grasslands in northern China (Wang N et al., 2019). In the grasslands of northern China, the enhancement of SOC with grazing exclusion is greater than the increase in STN, leading to an increase in the soil C:N ratio of 0.82 (Wang L et al., 2019). The deep understanding of soil C, N, P, and their stoichiometry variations to different grazing intensities is important for developing sustainable strategies for management and human-induced impacts on ecosystem functions.

Grazing has been demonstrated to affect C, N, and P, and their stoichiometry substantially varies among ecosystems and regions (Li et al., 2017; Zhou et al., 2017; He et al., 2020). Generally, no grazing (NG) fencing can sustain high SOC (Deng et al., 2017). However, other studies demonstrated that SOC was stable under the treatment of NG, light grazing (LG), moderate grazing (MG), and HG (Yang et al., 2018). Not only elements showed different responses to grazing treatments, but also the stoichiometry indicated various changes in grazing intensities. For example, HG can increase the soil C:N ratio, and LG decreases the soil C:N ratio in the alpine meadow (Yang et al., 2018). Different from the results in the alpine meadow, the soil C:N ratio was stable in the condition of LG in a sagebrush steppe (Shrestha and Stahl, 2008). In the desert steppe, typical steppe, and meadow steppe, both soil C:P and N:P ratios increased in HG (Bai et al., 2012), but in upland grasslands, the soil C:P and N:P ratios decreased in HG (Medina-Roldán et al., 2012). Therefore, the magnitude of grazing impacts on C, N, P, and their stoichiometry patterns depends on not only climatic conditions but also plant types and grazing intensity (McSherry and Ritchie, 2013). It was unclear how SOC, STN, STP, and their stoichiometry change in the different grazing intensities in the Tibetan Plateau alpine shrublands.

Soil stoichiometry, e.g., soil N:P ratio, has been explored in alpine shrublands, alpine wetlands, and alpine grasslands on the Tibetan Plateau (Yang et al., 2019; Nie et al., 2022; Nie et al., 2023). Grazing can stimulate soil C and N loss in the abiotic pathways (He et al., 2020). Specifically, livestock intensity can change soil structure through the surface crust and disrupt aggregates, resulting in increased soil susceptibility to wind and water erosions, finally leading to soil C and N losses (Neff et al., 2005). Climate, soil, and vegetation, including litter, characteristics can impact the biogeochemical cycles of SOC, STN, and STP, and thus control their stoichiometry. Microbes generally control the soil and plant feedback through nutrient mobilization and immobilization (Bai et al., 2012). Understanding the impacts of grazing intensity on the C:N:P stoichiometry in terrestrial ecosystems could contribute to predicting climate-biosphere feedback and improving management (Zhou et al., 2019a).

The alpine shrublands are important ecosystems across the Tibetan Plateau, and the *Potentilla fruticosa*, a major species in the alpine shrublands, is widely distributed and plays an important role in ecosystem security and C sequestration (Yashiro et al., 2010; Nie et al., 2022). Grazing animals in shrublands of *P. fruticosa* was the traditional way of life for the original residents of the Tibetan Plateau However, the unique conditions of high altitude and low temperature create a fragile alpine ecosystem, especially under the stress of overgrazing (Zhang T et al., 2019). A long history of grazing has existed across the Tibetan Plateau, and the degradation of shrublands can not only threaten herders' livelihoods but also damage the sustainability of ecosystem services. In this study, we aimed to explore SOC, STN, STP, and their stoichiometry under different grazing intensities. We hypothesized that 1) grazing intensities can significantly affect SOC, STN, and STP, thus controlling soil C:N, C:P, and N:P ratios; 2) grazing intensities can significantly affect soil physical properties; and 3) the

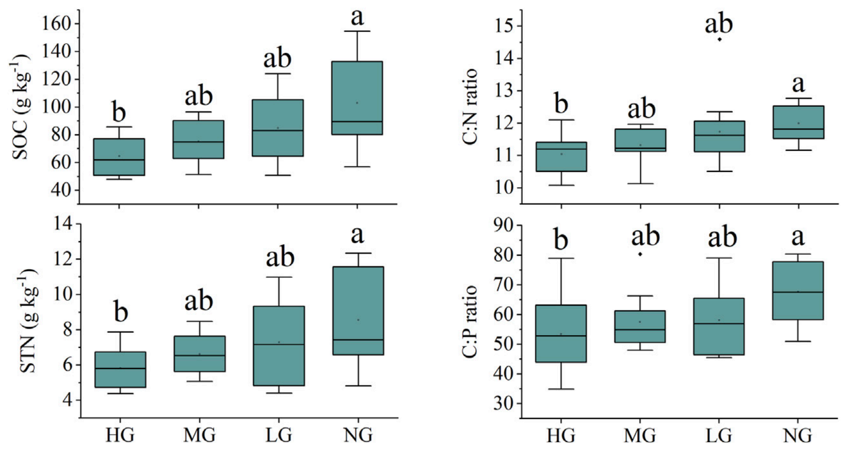

FIGURE 1
Soil organic carbon (SOC), soil total nitrogen (STN), and soil C:N and C:P ratios in the grazing intensity of heavy grazing (HG), moderate grazing (MG), light grazing (LG) and no grazing (NG) in *Potentilla fruticosa* shrublands on the Tibetan Plateau. Different low letters indicate a significant difference among the grazing intensities.

changing soil physicochemical properties and reduced litter resulting from different grazing intensities can change SOC, STN, STP, and their stoichiometry.

2 Material and methods

2.1 Study area

The study areas were mainly distributed in eastern Tibetan Plateau alpine shrublands, with latitude from 33°02′10.05″ to 38°09′39.09″ N, and longitude from 96°50′42.43″ to 102°13′28.55″ E. *P. fruticosa*, with a height of 25–150 cm, is an important shrubland type across the Tibetan Plateau. *P. fruticosa* is mainly located in the range of 2,300–4,000 m and can bear poor environments, e.g., snowy, cold, or windy conditions (Yashiro et al., 2010; Xu et al., 2019). The area of *P. fruticosa* is more than 100 km^2, and it plays an important role in water and heat balance for the Tibetan Plateau and its surrounding locations (Peng et al., 2020). Mesophytes are commonly distributed in the shrublands of *P. fruticosa*, e.g., *P. anserine*, *Dracocephalum heterophyllum*, and *Poa pratensis*. According to the soil classification system by the Food and Agriculture Organization (FAO) of the United Nations, the main soil types in the study area are mainly *Histosols* and *Kastanozems* (Nachtergaele et al., 2012).

2.2 Experimental design

To divide different grazing intensities, we referred to the methods employed in grasslands, which divide the grassland degradation as HG, MG, LG, and NG, with a ground cover of 0%–20%, 20%–70%, 70%–90%, and >90%, respectively. Therefore, we divided the grazing intensities as HG, MG, LG, and NG as having ground cover of <20%, 20%–70%, 70%–90%, and >90%, respectively. The distance of any two grazing intensities was less than 30 km to reduce the interference from the spatial heterogeneity (Dai et al., 2019). Besides the shrublands' ground cover, the road density, the distance between sampling sites and cowshed or sheep shed, the amount of cow and sheep dung, and vegetation that had been gnawed and stampeded were also assessed to decide the grazing intensity (Chen et al., 2018; Wang N et al., 2019; Huang et al., 2022). A total of 11 areas were chosen, and each area included HG, MG, LG, and NG; thus a total of 44 grazing sites (4 grazing sites/area × 11 areas) were found.

2.3 Sampling and measurement

Field sampling was carried out during the growing season in 2021. In each site, three plots of 5 m × 5 m were created, and the distance between any two plots for the same grazing intensity was less than 50 m and larger than 5 m (Technical manual writing group of ecosystem carbon sequestion project, 2015). An ecological investigation was conducted in each plot: specifically, the aboveground biomass of shrublands, the ground cover of shrublands, belowground biomass, litter of foliage, and litter of stem. Soil samples were collected at a soil depth of 0–20 cm, and three replicate soil samples in three plots were mixed. Gentle homogenization then took place, where the plant and stones were removed, and they were sieved using a mesh of 2 mm (Nie et al., 2022). In each site, the mixed soil samples were divided into two parts; one was air-dried to measure physical and chemical factors, and the other was stored at −20°C to measure soil microbial diversity.

Soil-state ^{13}C nuclear magnetic resonance (NMR) spectroscopy was used to estimate organic C functional groups, combing with the cross-polarization/total sideband suppression (CP/TOSS) technique (Zhang et al., 2015). Improving the signal-to-noise is necessary before NMR spectral analysis (Schmidt et al., 1997). The ^{13}C NMR ranges of chemical compositions of alkyl C, O-alkyl C, aromatic C, and carbonyl C, which were determined by chemical shift areas,

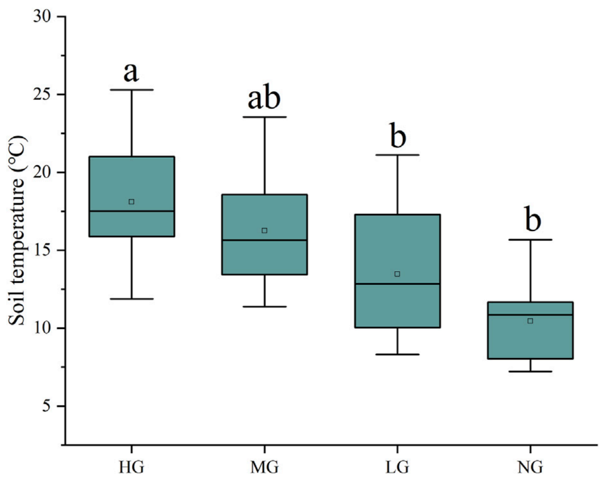

FIGURE 2
Soil temperature in the grazing intensity of heavy grazing (HG), moderate grazing (MG), light grazing (LG), and no grazing (NG) in *P. fruticosa* shrublands on the Tibetan Plateau. Different low letters indicate a significant difference among the grazing intensities.

were 0–45 ppm, 45–110 ppm, 110–165 ppm, and 165–210 ppm, respectively (Kögel-Knabner, 2002). The soil total C and STN were measured by an element analyzer (2400 Ⅱ CHNS/O, Perkin, Waltham, United States). Soil inorganic C was equivalent to carbonate values estimated by CO_2 evolution with a strong acid (Nelson and Sommers, 1982). SOC was determined by measuring the difference between soil total C and soil inorganic C. The STP was determined by the molybdate/ascorbic acid method with H_2SO_4-H_2O_2 digestion (Jones, 2001). Soil moisture and temperature were determined by a portable soil temperature and moisture probe (Testo 175H1, Huey Analytical Instrument, Qingdao, China). Soil pH was determined with a 2.5:1 ratio of water to soil. Soil sample of bulk density was collected in a container of 100 cm^3 (50 mm height and 50.46 mm diameter), then dried in an oven (105°C). The bulk density was measured using soil dry mass by volume. The litter of foliage, litter of branches, belowground biomass, and aboveground biomass were dried at 65°C for 48 h to obtain their dry weight and weighed until they reached a constant value.

To explore microbial factors in different grazing intensities, molecular analyses were conducted to extract DNA from soil samples. Specifically, frozen soil (10 g) was freeze-dried for 72 h (ALPHA 1-2 LD plus, Christ, Germany). Then, DNA from the freeze-dried soils (0.5 g) was extracted using a Power Soil DNA Isolation Kit (Qiagen, Hilden, Germany). The DNA was tested for its content and quality by 1% agarose gel electrophoresis and a spectrophotometer (ND-1000, NanoDrop Technologies, Wilmington, United States), respectively. The V4-V5 hypervariable regions of 907R (5′-CCGTCAATTCCTTTGAGT TT-3′) and 515F (5′-GTGCCAGCMGCCGCGTAA-3′) were amplified for 16S rRNA gene. The amplified fungal ITS 1 regions were ITS2-2043R (5′-GCTGCGTTCTTCATCGATGC-3′) and ITS5-1737F (5′-GGAAGTAAAAGTCGTAACAAGG-3′). The paired-end reads were merged by using FLASH (http://ccb.jhu.edu/software/FLASH/). The bacteria and fungi were determined by the silva reference database (http://www.arb-silva.de) and the BLAST tool in QIIME (http://qiime.org/index.html), respectively. Community diversity indicators, Shannon, and PD whole tree estimator for bacteria and fungi were determined by 40,800 and 73,250 reads per sample, respectively.

2.4 Statistical analysis

One-way analysis of variance was conducted to determine the effects of the grazing intensity on SOC, STN, STP, and soil C:N, C:P, and N:P ratios, followed by the Games-Howell test. The significance was determined by SPSS 22.0 (SPSS Incorporation, United States). The ordinary least squares method was employed to explore the relationships among SOC, STN, STP, their stoichiometry on soil (bulk density, soil pH, soil temperature, soil moisture), plant (aboveground biomass, belowground biomass, ground cover of shrublands), litter (litter foliage, litter stem, total litter), and microbes (16s Shannon, 16s PD whole tree, IT Shannon, and IT PD whole tree).

The relative importance of the direct and indirect effects of soil, plant, litter, and microbe factors affecting SOC, STN, STP, and soil C:N, C:P, and N:P ratios was assessed using structural equation modeling (SEM). A prior conceptual model of hypothetical relationships was established before SEM analysis (Supplementary Figure S1). If Fisher's C is statistically non-significant, a good model fit is necessary ($p > 0.05$). The package of "PIECEWISE" was used to estimate SEM analysis in the statistical R software (R Development Core Team, 2012).

3 Results

3.1 SOC, STN, STP and their stoichiometry under different grazing intensity

The SOC, STN, and STP have increasing trends with decreasing grazing intensities from HG to NG. Specifically, SOC and STN in the HG, MG, LG, and NG were 64.57 ± 14.03 and 5.83 ± 1.13, 75.13 ± 14.55, and 6.62 ± 1.14, 84.92 ± 25.06 and 7.29 ± 2.26, and 103.03 ± 33.82 and 8.57 ± 2.72 g·kg^{-1}, respectively. In addition, both SOC and STN were significantly lower in HG than in NG ($p < 0.05$) (Figure 1). STP in the HG, MG, LG, and NG were 1.23 ± 0.15, 1.32 ± 0.26, 1.46 ± 0.34, and 1.50 ± 0.34 g·kg^{-1}, respectively. There was no significant difference in STP among different grazing intensities (Supplementary Figure S2).

Soil C:N and C:P ratios have increasing trends with decreasing grazing intensities from HG to NG, while the change in soil N:P ratio was relatively stable along grazing intensities. Soil C:N and C:P ratios in HG, MG, LG, and NG were 11.04 ± 0.62 and 53.41 ± 13.45, 11.31 ± 0.53 and 57.61 ± 9.31, 11.73 ± 1.09 and 58.19 ± 11.61, and 12.00 ± 0.54 and 67.66 ± 10.16, respectively (Figure 1). Soil N:P ratios in HG, MG, LG, and NG were 4.83 ± 1.15, 5.09 ± 0.76, 4.99 ± 1.05, and 5.64 ± 0.82, respectively (Supplementary Figure S2). Soil C:N ratio and N:P ratio in the NG were significantly larger than that in the HG, while the soil N:P ratio was not significantly different among different grazing intensities. The grazing intensities can significantly affect SOC and STN, thus controlling soil C:N and

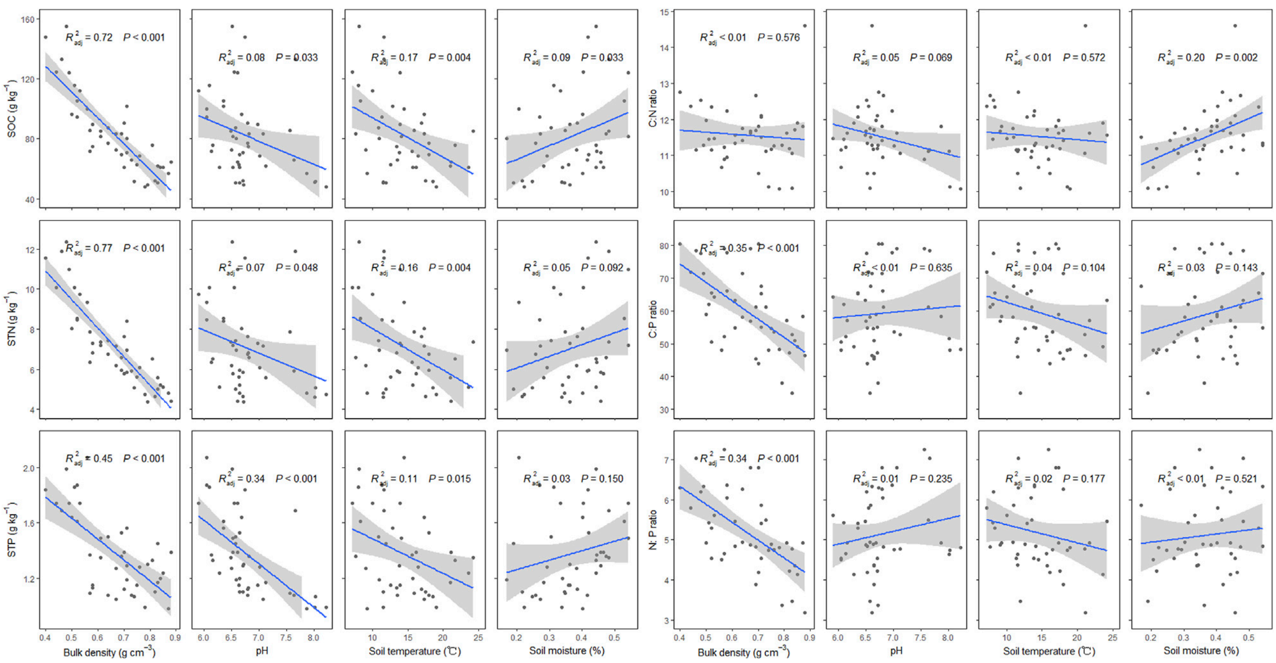

FIGURE 3
Effects of bulk density, soil pH, soil temperature, and soil moisture on soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and soil C:N, C:P, and N:P ratios in *P. fruticosa* shrublands on the Tibetan Plateau. The gray areas correspond to 95% confidence intervals.

C:P ratios, and the significantly lower SOC, STN, soil C:N, and C:P ratios in HG than in NG partly supported the first hypothesis.

Furthermore, soil temperature has a decreasing trend with decreasing grazing intensities from HG to NG. The soil temperature of 18.10°C ± 4.09°C in HG is significantly larger than that in LG (13.46°C ± 4.01°C) and NG (10.46°C ± 2.76°C) (Figure 2). Although the bulk density also has a decreasing trend with grazing intensities from HG to NG, differences were not significant. The soil moisture was relatively stable in different grazing intensities (Supplementary Figure S3). Thus, these results supported the second hypothesis.

3.2 Effects of soil, plant, litter, and microbes on SOC, STN, STP, and their stoichiometry

Soil physical and chemical properties have significant effects on SOC, STN, STP, and stoichiometry. Specifically, with increasing bulk density, soil pH, and soil temperature, SOC, STN, and STP have significantly decreasing trends. However, with increasing soil moisture, SOC has a significantly increasing trend, and both STN and STP have weak increasing trends with increasing soil moisture (p = 0.09 for STN, and p = 0.15 for STP). Soil C:N ratio has an increasing trend with increasing soil moisture, and soil C:P and N:P ratios have decreasing trends with increasing bulk density (Figure 3).

Plant factors have significant effects on SOC, STN, STP, and their stoichiometry. Specifically, with increasing aboveground biomass, belowground biomass, and ground cover of shrublands, SOC, STN, and STP have increasing trends ($p < 0.05$), while the increasing trend of STP along the ground cover of shrublands was not significant (p = 0.065). Soil C:N ratio and C:P ratio have increasing trends along increasing aboveground biomass and ground cover of shrublands ($p < 0.05$), but the increasing trends of soil N:P ratio along soil aboveground biomass and ground cover of shrublands were not significant (p = 0.137 for aboveground biomass, p = 0.131 for ground cover of shrublands). Soil C:N, C:P, and N:P ratios have increasing trends along increasing belowground biomass, but their relationships were not significant ($p > 0.05$) (Figure 4).

Litter standing crop has significant effects on SOC, STN, STP, and their stoichiometry. Specifically, with increasing litter standing crop foliage, litter standing crop stem and total litter standing crop, SOC, STN, and STP have increasing trends ($p < 0.05$). Although soil C:N, C:P, and N:P ratios have increasing trends with litter factors, only soil C:P ratio has increasing trends with increasing both litter standing crop stem and total litter standing crop ($p > 0.05$) (Figure 5).

Microbes have significant effects on SOC, STN, STP, and their stoichiometry. The 16s Shannon, rather than IT Shannon, has significant effects on SOC, STN, and STP ($p < 0.05$). The SOC and STN have decreasing trends with increasing 16s PD whole tree ($p < 0.05$), while the decreasing trend of STP was not significant along the 16s PD whole tree (p = 0.248). The SOC, STN, and STP have significant and increasing trends along IT PD whole tree ($p < 0.05$). Soil C:P and N:P ratios have significant decreasing trends with increasing 16s PD whole tree ($p < 0.05$). In addition, soil C:P ratio has an increasing trend with IT PD whole tree ($p < 0.05$) (Figure 6).

The SOC chemical compositions have significant effects on SOC and STP, and their C:N ratio. Specifically, with increasing carbonyl C, SOC and STP have decreasing trends. STP has an increasing trend

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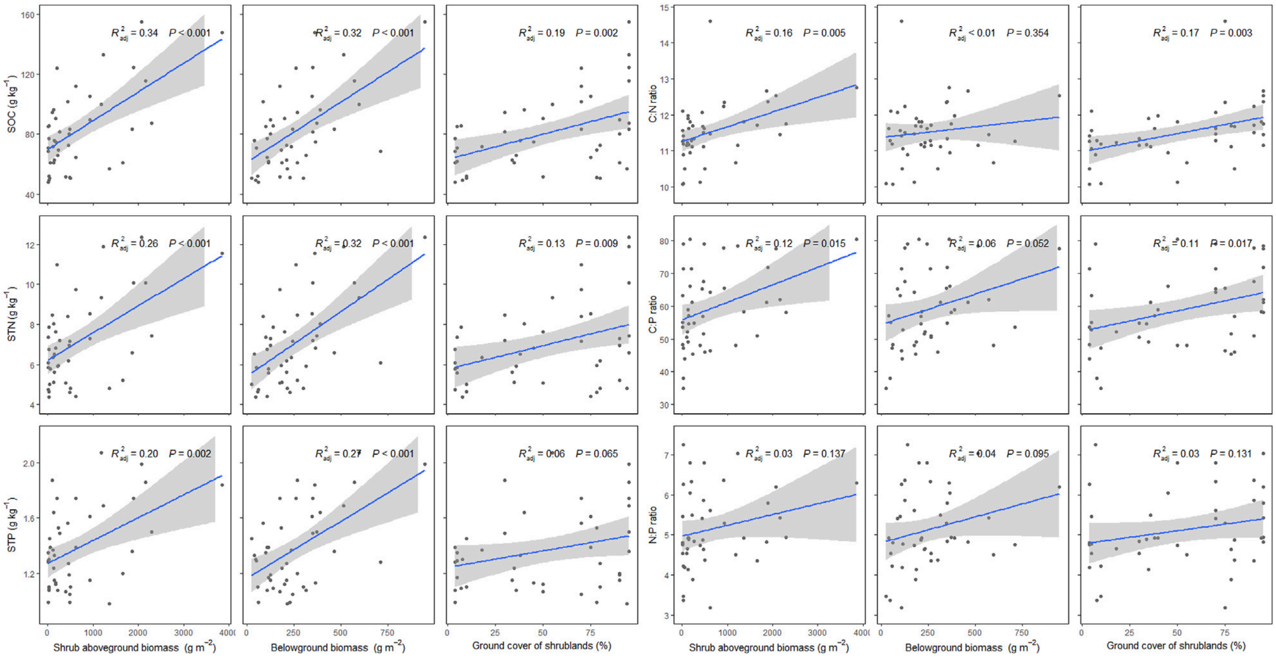

FIGURE 4
Effects of shrubland aboveground biomass, belowground biomass, and ground cover of shrublands on soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and soil C:N, C:P, and N:P ratios in *P. fruticosa* shrublands on the Tibetan Plateau. The gray areas correspond to 95% confidence intervals.

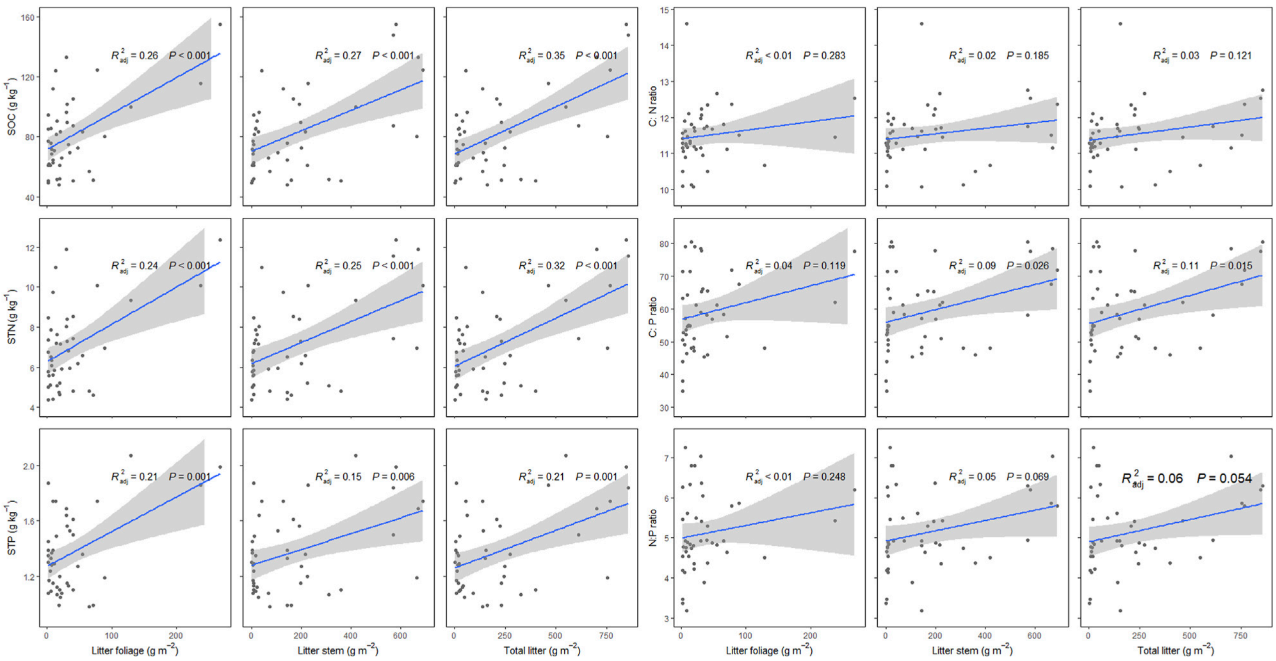

FIGURE 5
Effects of litter foliage, litter stem, total litter on soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and soil C:N, C:P, and N:P ratios in *P. fruticosa* shrublands on the Tibetan Plateau. The gray areas correspond to 95% confidence intervals.

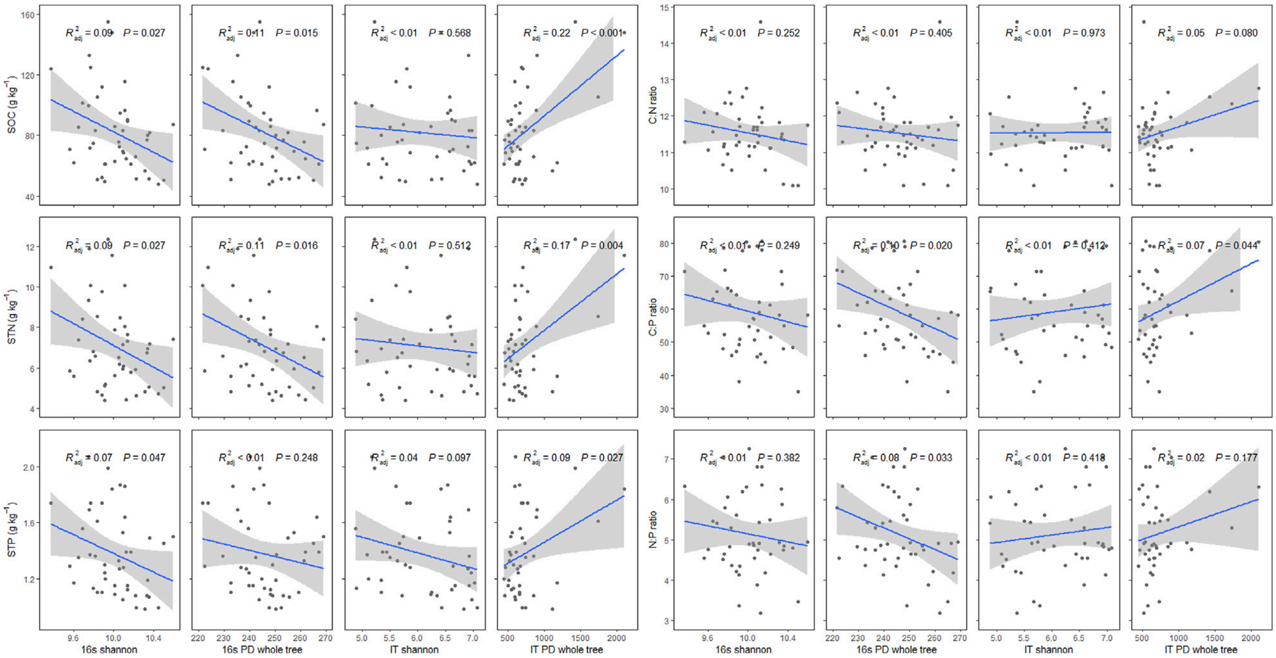

FIGURE 6
Effects of 16s Shannon, 16s PD whole tree, IT Shannon, and IT PD whole tree on soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and soil C:N, C:P, and N:P ratios in *P. fruticosa* shrublands on the Tibetan Plateau. The gray areas correspond to 95% confidence intervals.

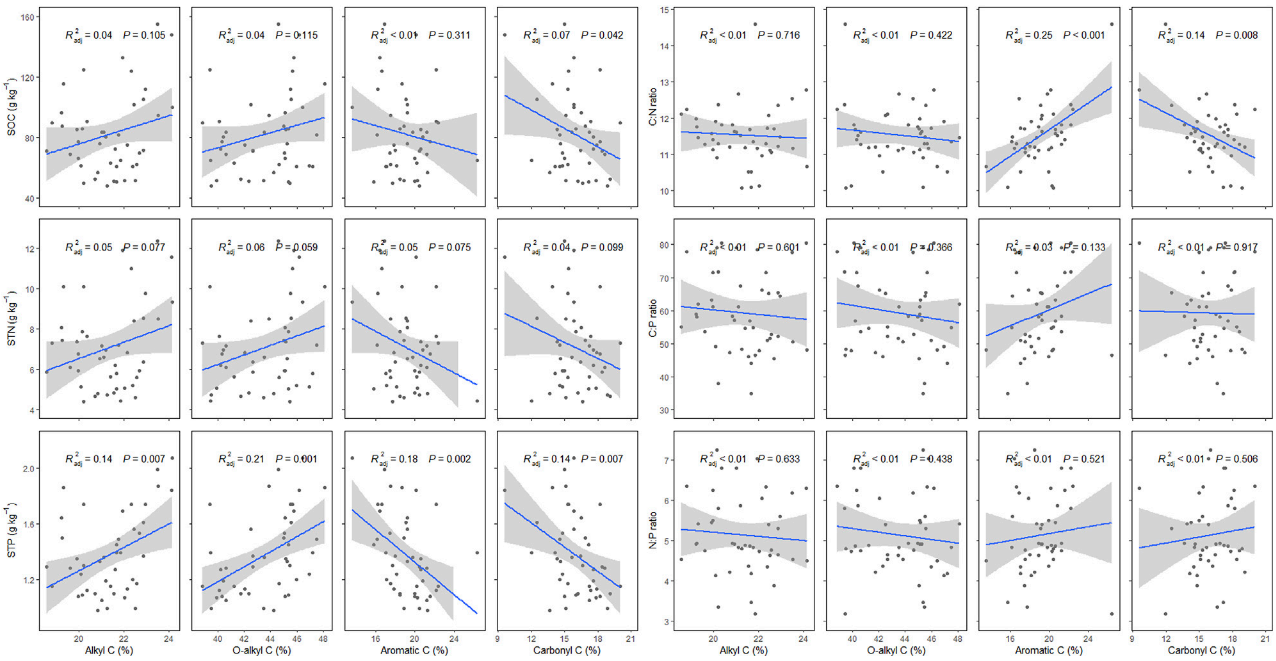

FIGURE 7
Effects of alkyl C, O-alkyl C, aromatic C, and carbonyl C on soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and soil C:N, C:P, and N:P ratios in *P. fruticosa* shrublands on the Tibetan Plateau. The gray areas correspond to 95% confidence intervals.

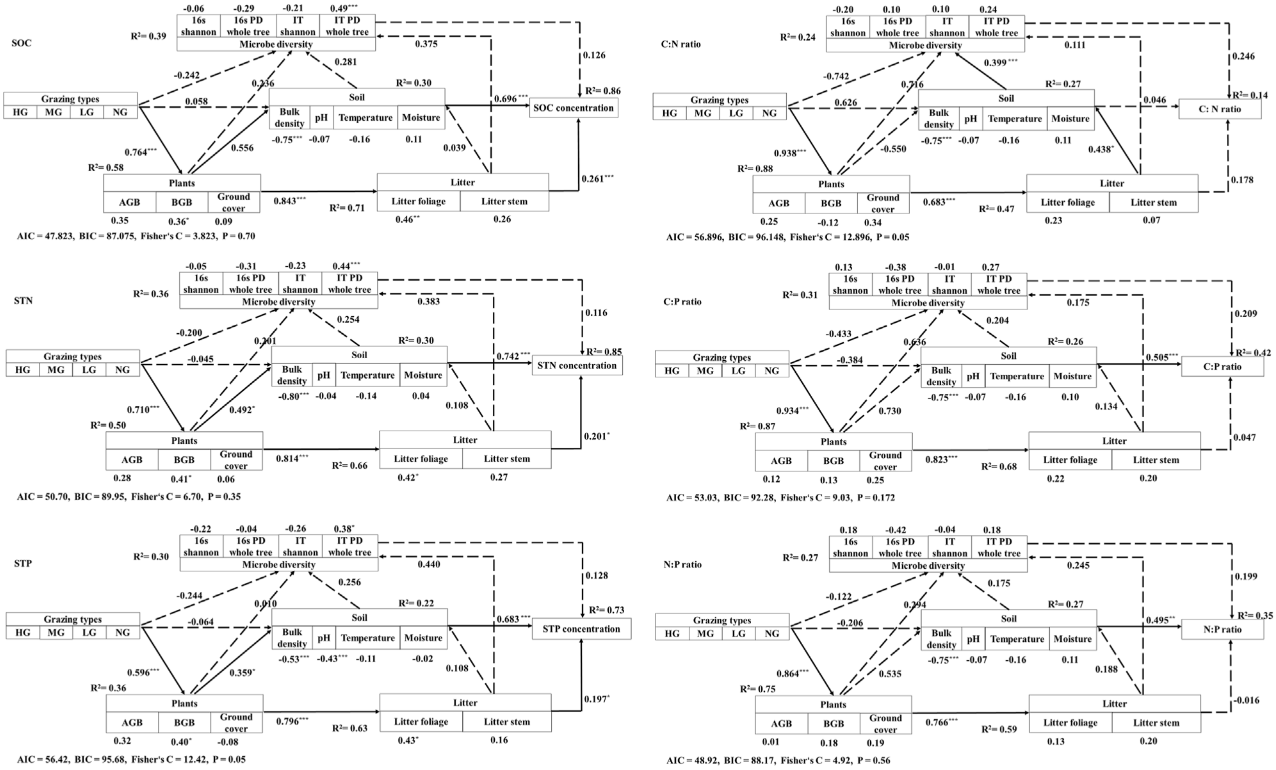

FIGURE 8
Structural equation models depicting direct and indirect drivers of soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and soil C:N, C:P, and N:P ratios in *P. fruticosa* shrublands on the Tibetan Plateau. The dashed arrows show non-significant effects. The solid lines represent significant effects. HG, heavy grazing; MG, moderate grazing; LG, light grazing; NG, no grazing; AGB, aboveground biomass of shrublands; BGB, belowground biomass of shrublands.

with increasing alkyl C and O-alkyl C, and a decreasing trend with aromatic C ($p < 0.05$). Soil C:N ratio has a decreasing trend with increasing aromatic C, while it has an increasing trend with increasing carbonyl C ($p < 0.05$) (Figure 7).

Results from SEM indicated that grazing intensity can directly affect plant conditions, and plant conditions can directly affect soil physical and chemical properties and litter standing crops. Finally, soil physicochemical properties and litter-standing crop resulting from different grazing intensities also directly control SOC, STN, and STP. For the soil stoichiometry, the soil's physical and chemical properties resulting from different grazing intensities have direct effects on soil C:P and N:P ratios (Figure 8). Thus, these results supported the third hypothesis.

4 Discussion

Grazing, a significant anthropogenic activity, affects the biogeochemical cycles of C, N, and P and their stoichiometry in the terrestrial ecosystem (Knops et al., 2002; He et al., 2020). The SOC in different grazing intensities was from 64.57 g·kg^{-1} to 103.03 g·kg^{-1}, which was in the range of SOC (0.04–126.12 g·kg^{-1}) across the Tibetan Plateau (Nie et al., 2021). The aboveground biomass and litter are principal C inputs (Ding et al., 2017; Leal et al., 2019). The aboveground biomass and total litter in NG were significantly higher than that in HG, which results in a significantly lower SOC in HG than that in NG. It has also been shown that the disturbed soil surface crust and structure by grazing contribute to accelerate soil C loss because of enhanced soil susceptibility to water and wind erosion (McSherry & Ritchie, 2013). At a global scale, grazing can decrease soil C pool by 3.1% in grasslands (Zhou et al., 2017). Soil organic matter is the principal soil N resource (Nie et al., 2022), and the STN shift in different grazing intensities is similar to SOC, and STN was higher in NG than that in HG. Similarly, a meta-analysis at a global scale showed that soil N losses under HG and HG significantly decreased soil N by 13.04% (Zhou et al., 2017). However, STP was stable in different grazing intensities. This is because the parent materials instead of plant conditions can play a significant role in regulating STP (Lin et al., 2009; Zhang Z. C et al., 2019).

In our studies, soil C:N and C:P ratios, rather than soil N:P ratio, were affected by grazing intensities. This is because the decreasing level was larger in SOC (37%) than in STN (31%), while STP was relatively stable from HG to NG. Similarly, the enhancement of soil C sequestration with grazing exclusion is greater than the increase in soil N, leading to an increase in the soil C:N ratio of 0.82 units across the grasslands in northern China (Wang L et al., 2019). Other results were different from our results, and grazing can reduce about 22.4% of the SOC and 30.9% of STN than that in un-grazed regions (Zhang et al., 2018). Their difference may result from various ecological environments, types of grazing animals or plants, and grazing time of year (Li et al., 2017; Zhang et al., 2018; Yu et al., 2019). The increased SOC, on the one hand, might be attributed to the increased biomass induced by reducing livestock grazing intensities (Zhou et al., 2019b). On the other hand, increasing vegetation recovery, resulting from decreasing grazing intensities, could prevent soil C loss caused by wind erosion by improving vegetation cover, which mitigates the exposure of the bare soil surface to wind erosion (Mekuria et al., 2007). The increasing SOC along with decreasing grazing intensities indicated soil C accumulation after decreasing grazing intensities in the Tibetan Plateau alpine shrublands of *P. fruticosa*. In grasslands, grazing was also demonstrated to change the soil C:N and C:P ratios (Zhou et al., 2007; Yang et al., 2019), while grazing did not affect the soil N:P ratio in a semi-arid pasture in Brazil (Filho et al., 2019; Yang et al., 2019). The responses of SOC, STN, and STP and their stoichiometry to grazing intensities have significant applications for the strategy of sustainable development in terrestrial management (He et al., 2020). Therefore, for the alpine shrubland of *P. fruticosa*, HG should be avoided for sustainable cycling of soil nutrients and the balance of soil nutrient stoichiometry.

Grazing can modify the distribution of significant environmental predictors of soil pH (Fierer et al., 2007). Soil pH has negative relationships with SOC, STN, and STP. It has been demonstrated that soil pH can indicate various gradients of soil characteristics and is closely linked to biological processes (Hong et al., 2018; Rasmussen et al., 2018). With increasing soil pH, the available minerals, e.g., iron, manganese, and zinc, can decrease, limiting the growth of the plant. Thus, in the condition of increasing soil alkalinity, the SOC accumulation is limited, due to decreasing plant biomass input (Davidson and Janssens, 2006). Soil pH was found to be important in microbial activities and dynamics of soil C and N (Aciego Pietri and Brookes, 2008). In acidic soils, bacteria diversity was less, consequently limiting soil C and N decomposition (Shen et al., 2013; Tashi et al., 2016).

Grazing reduces leaf areas and exposes more soil surfaces. Lower plant cover caused by grazing would also increase soil temperature, which can stimulate microbe activity, limit SOC accumulation (Davidson and Janssens, 2006), and create a negative relationship with SOC. Soil temperature in HG was significantly higher than that in LG across the Tibetan Plateau alpine shrublands of *P. fruticosa*. Similarly, soil temperature was demonstrated to be increased exponentially with increasing grazing intensity in the warm season, and the increased temperature was 2.6°C in a Eurasian Steppe, due to the removal of aboveground biomass (Yan et al., 2018). However, increasing soil moisture can contribute to plant growth and lead to a high production of plants and more plant litter, which contribute to soil organic matter input (Wynn et al., 2006) and, eventually, shape its positive relationship with SOC. Similarly, precipitation also played a major role in the soil C change following grazing exclusion, with faster accumulation under wetter conditions (Yu et al., 2019). The positive relationship between soil C:N ratio and soil moisture existed in our study, which indicated that soil moisture can contribute to SOC accumulation.

Grazing is a major driver of the composition of microbial communities, which play significant roles in soil functioning (Eldridge et al., 2020). Grazing has been demonstrated to shift microbial communities from fungi dominated and slow growing to bacteria-dominated and fast-growing (Xun et al., 2018). Microbes have significant effects on SOC decomposition (Yang et al., 2008). In our study, with increasing 16s Shannon instead of IT Shannon, SOC, STN, and STP have decreasing trends, which indicated that bacteria rather than fungi have more significant effects on controlling soil nutrient element decomposition. Plant removal by grazing reduces leaves, leading to reduce litter input and shifts in soil bacterial communities and soil C processes (Zhou et al., 2017). Trampling of vegetation can lead to reductions in plant cover, changes in litter distribution, and reductions in resource connectivity (Eldridge et al., 2017), which might also alter microbial community composition (Eldridge et al., 2020). It should be noted that 16s PD whole tree and IT PD whole tree also can significantly affect SOC and STN. Our results were consistent with the previous result that microbial robustness can significantly affect soil stability (Griffiths and Philippot, 2013). Bacteria rather than fungi are more important in labile-SOC turnover (Xun et al., 2018), and with increasing 16s Shannon and 16s PD whole tree, the more labile-soil organic matter was decomposed, thus creating a negative relationship between 16s Shannon and 16s PD whole tree and SOC, STN, and STP.

Results from SEM indicated that SOC, STN, and STP in different grazing intensities can be directly controlled by soil physicochemical properties and litter standing crops. The effects of grazing types on soil nutrient elements were through their effects on plant conditions, and plant conditions can directly affect soil physical and chemical properties and litter standing crops. Livestock grazing usually inhibits leaf photosynthesis and primary production (Zhou et al., 2017). For the soil stoichiometry, the soil's physical and chemical properties have direct effects on soil C:P and N:P ratios. Therefore, a certain amount of litter standing crop and healthy soil physicochemical properties should exist to avoid unbalanced nutrition in the Tibetan Plateau *P. fruticosa* shrublands.

5 Conclusion

In our study, we explored SOC, STN, STP, their stoichiometry, and their controlling factors in the grazing disturbance of HG, MG, LG, and NG in the Tibetan Plateau *P. fruticosa* shrublands. Our results indicated that SOC, STN, STP, and soil C:N, C:P, and N:P ratios were quantified, respectively. The SOC, STN, and C:N and C:P ratios were significantly higher in NG than that in HG; hence, for the alpine shrubland of *P. fruticosa*, HG should be avoided for sustainable cycling of soil nutrients and the balance of soil nutrient stoichiometry. The grazing types can directly affect plant conditions, and plant conditions can directly affect soil physical and chemical properties and litter standing crops. In addition, healthy soil physicochemical properties and a certain amount of litter standing crop are necessary to allow C sequestrations and soil nutrient balance in the *P. fruticosa* shrublands across the Tibetan Plateau. Although the effects of grazing intensities on SOC, STN, STP, and their stoichiometry have been explored, the grazing types of NG, LG, MG, and HG are only roughly defined. More specific grazing conditions quantified in the grazing regions are necessary to provide a more accurate estimation of soil element stoichiometry and nutrient balance for sustainable development across the Tibetan Plateau.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

XN, YD, and GZ conceived the study and designed the methodology; XN, YD, GZ, LR, DW, CL, YC, and XL collected the data, XN analyzed the data; XN led the writing of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1170507/full#supplementary-material

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