

Article

Changes in Soil Nutrient Storage and Their Controlling Variables Under Different Treatments Across Northern China's Meadow Grassland

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Abstract

Meadow grasslands are characterized by high primary productivity and are an important ecological barrier against sandstorms and desertification in northern China. The dynamic changes in reserves of soil organic carbon stocks (SOCSs), total nitrogen (TNS), and total phosphorus (TPS) in grassland ecosystems are easily disturbed by human activities. However, the effects of different treatments on the relationships among soil nutrient reserves (SOCS, TNS, and TPS) and the mechanisms underlying the effects of various key variables on changes in soil nutrient reserves remain unclear. This study investigated the changes in soil nutrient reserves in meadow grasslands in northern China after mowing (M), burning (F), and grazing (G) treatments than without any anthropogenic interference (E, control) from 2020 to 2023, as well as the vegetation and soil variables that may affect them. The results showed that compared with the control treatment, once-a-year mowing and burning significantly increased SOCS (M: 12.75%, F: 23.72%), TNS (M: 15.6%, F: 26.8%), TPS (12.4%, 27.2%) and strengthened the correlations between SOCS and TNS and between SOCS and TPS, while grazing treatments significantly reduced soil nutrient reserves (13.0%, 11.8%, 10.1%) and the correlation between soil nutrient reserves. In general, under different treatments, soil temperature was the important control variable affecting each reserve. Vegetation was also a key control variable affecting SOCS, while TNS and TPS were mainly regulated by soil factors. It should be pointed out that owing to different treatments, the key vegetation variables affecting SOCS differed notably from those affecting TNS and TPS. This study emphasized the impact of different treatments on soil nutrient reserves and their main controlling variables, providing an important theoretical basis for further optimizing and improving the scientific management strategy of grassland ecosystems.

Keywords: meadow grassland; grassland management; nutrient stocks; vegetation restoration



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1. Introduction

Grasslands cover over one-third of Earth's land area and contribute approximately 40% to the global gross agricultural product, making them the largest coupled human–nature system on the planet. They provide essential ecosystem services to both human populations

and wildlife [1,2]. However, long-term unsustainable human activities have degraded ecosystem functions [3], leading to severe soil erosion and grassland degradation globally. These environmental issues pose significant challenges to the management and utilization of semi-arid grassland ecosystems, highlighting the urgent need for effective strategies to restore degraded grasslands [4]. Appropriate grassland treatments have become very effective in restoring degraded grasslands by improving vegetation production and nutrient storage [5]. Therefore, understanding the effects of different treatments on vegetation and soil nutrient stocks is essential for maintaining the functionality and sustainability of grasslands.

Changes in soil organic carbon stock (SOCS), total nitrogen stock (TNS), total phosphorus stock (TPS), and their cycling processes are important aspects of sustainable soil quality and grassland ecosystem function. Current treatments commonly applied to grasslands include grazing [3], fencing [6], mowing [7], and fire [8]. These treatments are universal and not limited to specific climates, cultures, or economic conditions. These treatments directly affect the distribution of soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP), and have complex effects on soil nutrient cycling [9]. However, there is considerable debate regarding the responses of grassland SOCS, TNS, and TPS to these treatments. Some studies have reported decreases in SOCS, TNS, and TPS following grazing, fencing, and mowing [10,11] while others have reported increases [12], or no effects [13]. These inconsistencies are attributed to differences in grassland type, treatment intensity, and treatment age, all of which affect nutrient cycling in grassland ecosystems. Given the limited understanding of how these treatments affect nutrient stocks over time, this study aims to elucidate the responses of SOCS, TNS, and TPS to various treatments as well as the mechanisms driving these changes, with the goal of identifying strategies for enhancing grassland management and ecological function.

Different treatments affect the distribution of SOC, TN, and TP in grassland ecosystems. The persistence and stability of SOCS, TNS, and TPS are influenced by both biotic and abiotic factors, including vegetation characteristics and soil physical properties [14]. In general, higher vegetation productivity is associated with greater root surface area, which in turn increases TNS and SOCS [15]. Previous studies have largely focused on the effects of biotic and abiotic factors on TNS and SOCS in grassland ecosystems, particularly in relation to treatment types [16], age, vegetation characteristics [15], and soil physicochemical properties [12]. However, most of these studies have only compared the effects of single treatments to the enclosure treatment (the control group) at a certain age, without considering the combined effects of biotic and abiotic factors on SOCS, TNS, and TPS. Therefore, this study aims to clarify the relative contributions of vegetation and soil variables to SOCS, TNS, and TPS and to provide insights into how grassland management strategies can improve ecological functioning of grasslands through different treatments.

Different treatments influence the formation and stabilization of soil organic matter by altering the quantity and quality of litter and root secretions, thereby indirectly altering the dynamics of SOC, TN, and TP [12]. While most studies have focused on comparing the dynamics of organic carbon stock in enclosure and grazing treatments [17], few have examined TNS and TPS. Additionally, soil TPS primarily originates from rock weathering [18], while TNS is influenced by nitrogen fixation, deposition, and leaching of inorganic nitrogen [19]. In their study of mountain ecosystems in East Africa, Njeru et al. [20] found that most changes in TN reserves were related to SOC reserves. However, few studies have systematically investigated the relationships between TNS and TPS following different treatments, and few studies have paid close attention to the associations between SOCS, TNS, and TPS to different treatments in meadow grasslands. Thus, it is necessary to evaluate the response of carbon and nutrient stocks to different treatments in meadow grasslands.

To restore ecosystem function in semi-arid regions, the Chinese government has initiated the ‘Returning Grazing Land to Grassland’ project [21]. Grazing exclusion may alter soil properties, favoring the accumulation of SOC and TN rather than an increase in TP, and ultimately decoupling SOC and TN reserves from TP reserves [19]. The research of [22] investigated different grazing gradients in the Inner Mongolia grassland and found that soil organic carbon, total nitrogen, and total phosphorus storage increased only at a grazing intensity of 0.34 AU ha^{-1} . Pellegrini et al. [23] found that different mowing heights have varying effects on soil carbon sequestration, with lower mowing heights potentially increasing soil carbon pools. Research on fire has mainly focused on the effects of fire location and frequency on soil carbon storage [23]. In summary, we found that the effects of different treatments on soil nutrient reserves primarily influence the pattern of reserve changes. However, there is limited information on the effects of different treatments on the relationship between SOCS, TNS, and TPS. In addition, there is limited information on which vegetation and soil variables affect SOCS, TNS, and TPS. To address these knowledge gaps, this study was conducted to sample the vegetation and soil of grazing (G), mowing (M), and fire (F) treatments compared to E (control group), evaluated over four consecutive years (2020–2023) in the meadow grasslands of the Horqin Sandland, Inner Mongolia, China. This study aimed to (1) evaluate changes in SOCS, TNS, and TPS across mowing, burning, and grazing treatments compared with the control group; (2) investigate the relationships between SOCS, TNS, and TPS under mowing, burning, and grazing treatments compared with the control group; and (3) identify the key plant and soil variables that influence SOCS, TNS, and TPS in meadow grasslands subjected to different treatments.

2. Materials and Methods

2.1. Overview of the Study Area

The study area is located in Horqin Sandland, China ($122^{\circ}33'00''\sim 122^{\circ}41'00'' \text{ E}$, $43^{\circ}18'48''\sim 43^{\circ}21'24'' \text{ N}$). The region experiences a temperate continental monsoon climate, with the vegetation growing season spanning from early May to late September. The average annual precipitation is 389 mm, with approximately 80% occurring between May and September. The average annual temperature is 6.6°C , while the average annual evaporation is 1412 mm. More than ten landform types exist in the study area, including moving sand dunes, semi-mowing sand dunes, transition zone dunes, meadow farmland, meadow grassland, and lakes. This distribution of landforms creates an area in which dunes and meadows are interspersed. The meadow (investigated) grassland is flat and the main soil type is chestnut–calcium soil, which is thick and fertile. The dominant vegetation species include reeds (*Phragmites australis*), goat grass (*Leymus chinensis*), and oxalis (*Eleusine indica*). The location of the study area site within the meadowland is depicted in Figure 1.

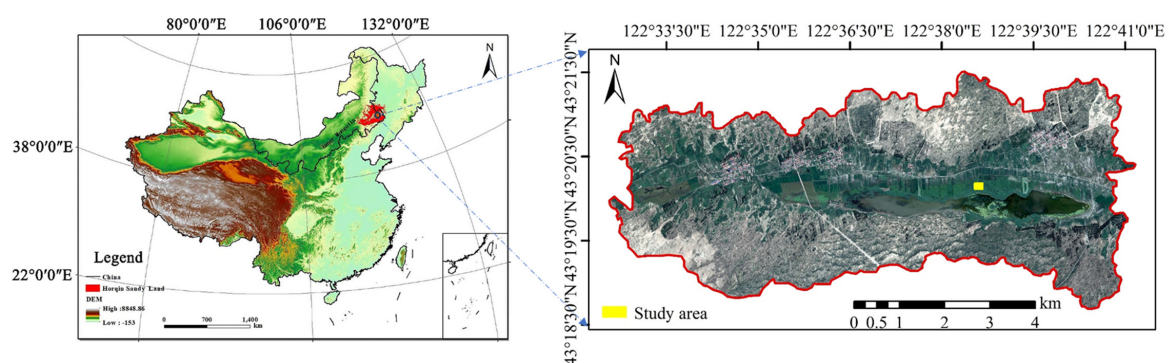


Figure 1. Schematic layout of test sites within the study area. Note: The left picture is a map of China, and the right picture is our research area in Horqin Sandland; the experimental area is located in the representative meadow area in the right picture.

2.2. Experimental Design

As shown in Figure 2, a meadow grassland with flat terrain and uniform vegetation growth was selected in the study area in 2010. Within this area, 400 m² (20 × 20 m) of grassland was fenced and allowed to remain without any human interference; the vegetation grew naturally within the enclosed area. Outside the fence was a grazing area, where local herders allowed their sheep to graze twice a day, with no grazing rest period throughout the year. The sheep grazed freely throughout the year. The grazing intensity design of this study follows the agricultural industry standard, using a 50 kg sheep as the standard sheep unit, with approximately 10 sheep units per hectare. The stocking rate remained consistent throughout the year, without seasonal variation. The frequency of grassland utilization was high. First, in August 2019, half of the grassland within the fence of the sample plot was mowed, and the harvested aboveground biomass was collected and taken away, leaving a stubble height of 7 cm, which was determined as the mowing area (M). Then, in April 2020, 1/4 of the fenced area was burned, which was determined as the burned area (F). Finally, the remaining 1/4 area was left without any human interference, and the vegetation grew naturally, which was determined as the enclosure area (E), which was also the control group. From 2019 to 2023, the treatment duration and intensity of mowing, burning, and enclosure remained consistent each year. All treatment areas had the same soil type and geographic characteristics, and a buffer area of 1 m was maintained for each treatment area. After each fire treatment, each treatment area was evenly divided into four small replicate blocks; at the beginning of April each year from 2020 to 2023, three (1 m × 1 m) vegetation sample squares and three soil sampling points were evenly distributed inside each repeated block. In total, there were 12 vegetation sample squares and 12 soil sampling points in each treatment area.

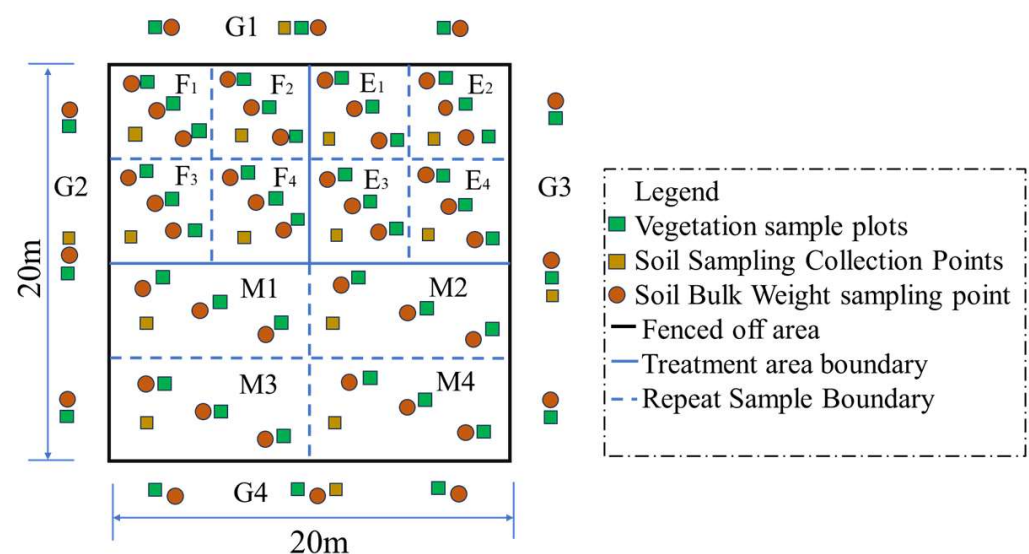


Figure 2. The distribution of different treatments in the experimental area, along with the layout of sampling points for vegetation and soil in each treatment area, is shown. Note: E, control group; M, mowing; F, burning; G, grazing.

2.3. Survey Items and Methods

2.3.1. Vegetation Survey

The vegetation survey was conducted when the vegetation was mature every year (i.e., in August) from 2020 to 2023. Vegetation types and species in the sample plots were recorded. For each species, 20 representative plants were selected, and the average vegetation height (H) was calculated. Fractional vegetation cover (FVC) within the sample plots was estimated using vertical aerial images captured by an unmanned aerial vehicle

(DJI Phantom 4 Pro V2.0, DJI Technology, Shenzhen, China) and a visual estimation method. Vegetation biomass was determined by cutting the vegetation within the sample plots and green-killing at 105 °C for about 30 min, followed by drying at 65 °C for 48 h to a constant weight. Aboveground biomass (AGB) was then calculated. Vegetation richness (R) was assessed as the number of plant species in the replicate plots.

2.3.2. Collection and Determination of Soil Samples

Soil samples were collected immediately after each vegetation survey. Before soil collection, the surface layer was cleared of withered material. Soil samples were collected at depths of 0–5 cm, 5–10 cm, 10–15 cm, and 15–20 cm using a soil auger. In all, 3 replicate soil samples were taken from each soil sampling point. The soil samples from the same soil layer depth in each replicate block in the same treatment method were mixed, placed into pre-marked sealed bags, and air-dried in a cool indoor environment. They were subsequently ground (2 mm) and sieved for further analysis. Soil temperature and moisture content at depths of 5, 10, 15, and 20 cm were measured at each soil sampling point at 7:00, 10:00, 13:00, and 16:00 on the day of sampling using a TDR150 instrument (Spectrum Technologies, Aurora, CO, USA). The average of these readings was taken to represent the daily soil moisture and temperature values for that day. After the collection of soil physical and chemical samples was completed, three soil profiles measuring 60 cm in length × 60 cm in width × 100 cm in depth were dug in each treatment area, and ring cutters (100 cm³) were vertically pressed into the 0–5 cm, 5–10 cm, 10–15 cm, and 15–20 cm soil layers. Three ring cutters were pressed into each soil layer so that the soil sample filled the ring cutters. This was done to calculate the dry bulk density of the soil sample per unit volume.

Soil pH and conductivity were measured by using a pH potentiometer (PHS-2F, Shanghai, China) and conductivity analyzer (DDJ-308F, Shanghai, China) in air-dried soil samples (soil/water = 1:2.5). Soil organic carbon was determined using the potassium dichromate oxidation–external heating method, soil TN was determined using a Kjeldahl nitrogen analyzer (K9860, Jinan, China), and soil TP was determined using sulfuric acid soluble molybdenum antimony perchlorate colorimetry.

2.4. Estimation of SOCS, TNS, and TPS

SOCS, TNS, and TPS were calculated using the following equations [19]:

$$SOC_{stock} = \sum_{i=1}^n 0.1 \times SOC_i \times BD_i \times D_i$$

$$TN_{stock} = \sum_{i=1}^n 0.1 \times TN_i \times BD_i \times D_i$$

$$TP_{stock} = \sum_{i=1}^n 0.1 \times TP_i \times BD_i \times D_i$$

where SOC_{stock} , TN_{stock} , and TP_{stock} represent the reserves of SOC, TN, and TP, and the unit is Mg/ha; $\sum_{i=1}^n$ refers to summing the reserves from the 1st layer to the nth layer to obtain the total reserves for the entire section. SOC_i , TN_i , and TP_i denote the content of SOC, TN and TP at depth i in units of g kg^{−1}, respectively; N is the number of soil layers, four of which (0–5 cm, 5–10 cm, 10–15 cm, and 15–20 cm) were included in this study; BD_i denotes the bulk density of the soil at depth i , representing the weight of dried soil per unit volume of soil in its natural field state, expressed in units of g cm^{−3}; D_i denotes the depth of the layer (cm) (in this study, the soil depths of “0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm” were 5 cm each); and the parameter 0.1 is the conversion factor of the unit.

2.5. Statistical Analysis

Origin 2021 software was used to examine the effects of different treatments on nutrient storage. For interactions among SOCS, TNS, and TPS, a linear mixed effects model (LMM) was used, with treatment as a fixed factor and the sampling time and sampling block as random factors. Redundancy analysis (RDA) was employed to evaluate the effects of vegetation and soil variables on SOCS, TNS, and TPS. Multivariate linear regression analysis (MLRA) was used to determine the relative importance of vegetation and soil variables to SOCS, TNS, and TPS. Prior to the analysis, variables with high variance inflation factors ($VIF > 20$) were excluded to prevent covariance. A structural equation modeling (SEM) framework was used to reveal the direct and indirect effects of key driving variables on SOCS, TNS, and TPS in Amos 27.0.

3. Results

3.1. Changes in SOCS, TNS, and TPS Under Different Treatments

Compared with the enclosed plots, nutrient reserves under burning treatments exhibited significant increases across different years and soil depths ($p < 0.05$). In contrast, grazing treatments yielded distinct results: soil organic carbon stocks (SOCSs) decreased significantly ($p < 0.05$) (Figure 3a–c), while total nitrogen stocks (TNSs) and total phosphorus stocks (TPSs) showed an overall downward trend, with their variation patterns being regulated by both year and soil depth. Specifically, TNS decreased significantly in the 0–20 cm soil layer during 2020–2022 and in the 0–15 cm soil layer in 2023 ($p < 0.05$), whereas no significant difference was observed in the 15–20 cm soil layer in 2023 ($p > 0.05$) (Figure 3b). For TPS, significant reductions primarily occurred in the 0–20 cm soil layer during 2020–2021 and in the 0–10 cm soil layer during 2022–2023 ($p < 0.05$), with no significant difference detected in the 10–15 cm soil layer ($p > 0.05$) (Figure 3c). Mowing treatments generally led to an increasing trend in nutrient reserves, though this effect varied with year and soil depth. In 2020, all reserves in the 0–5 cm soil layer decreased significantly ($p < 0.05$); in 2021, no significant difference was found in the 0–5 cm soil layer ($p > 0.05$). However, significant increases were observed in the 5–20 cm soil layer during 2020–2021 and across all soil depths during 2022–2023 (Figure 3a–c).

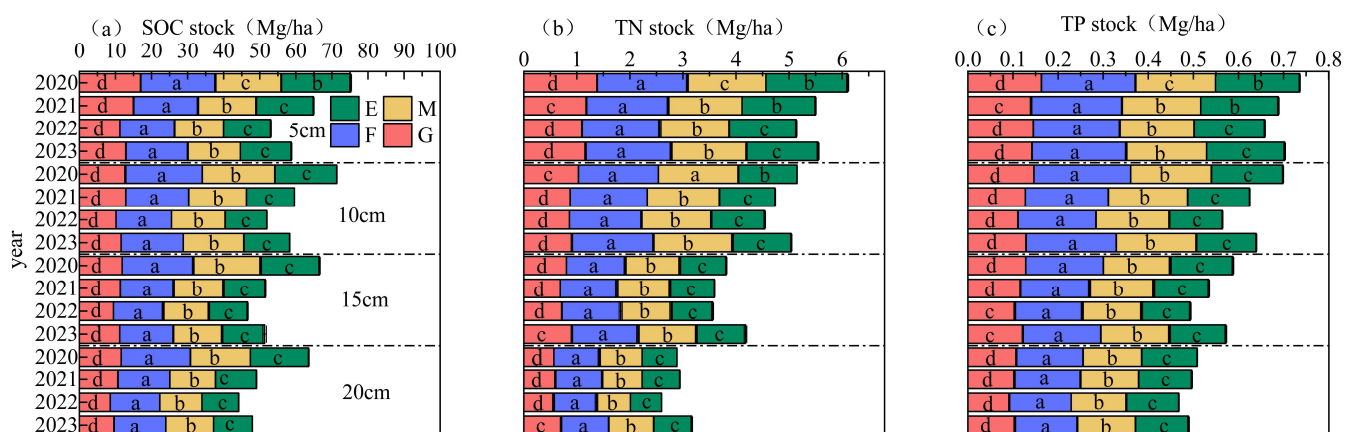


Figure 3. Effects of different treatments on soil organic carbon, total nitrogen, and total phosphorus reserves. Note: E, control group; M, mowing; F, burning; G, grazing. Different lowercase letters (a, b, c, d) in the figure indicate that the average values of nutrient reserves differ significantly over the years at the 0.05 level.

3.2. Relationships Among SOCS, TNS, and TPS Under Different Treatments

SOC, TN, and TP contents were positively correlated with the treatments (Figure 4a–c).

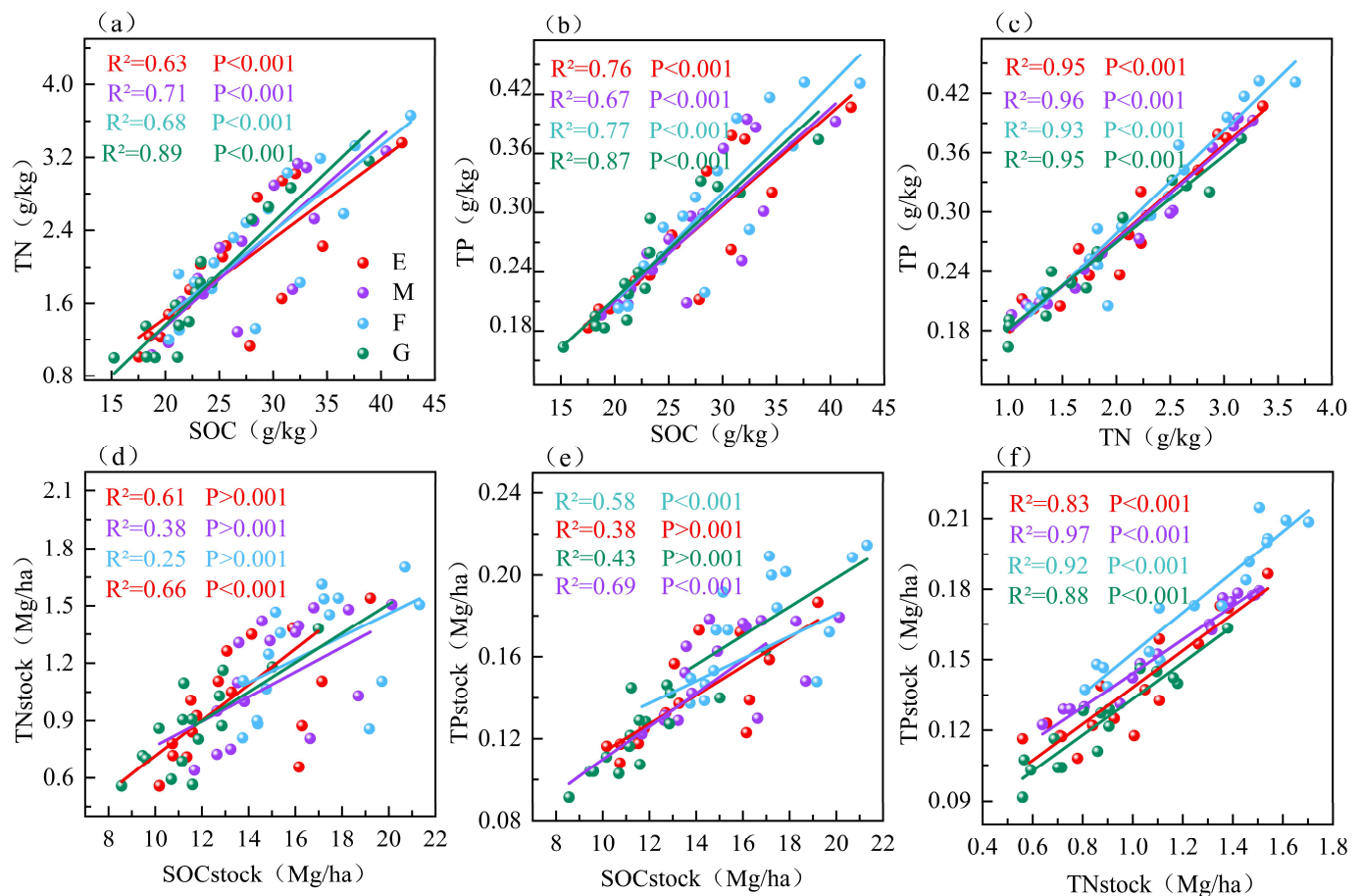


Figure 4. Regression relationships of soil organic carbon, total nitrogen, and total phosphorus stocks under different treatments. Note: E, control group; M, mowing; F, burning; G, grazing. Figures (a–c) represent the relationships between SOC and TN, SOC and TP, and TN and TP contents under different treatments, respectively. Figures (d–f) illustrate the relationships between SOCS and TNS, SOCS and TPS, and TNS and TPS under different treatments, respectively.

Under different treatments, soil TNS and TPS showed strong correlations, all of which were extremely significant (E: $R^2 = 0.83$, $p < 0.001$; M: $R^2 = 0.97$, $p < 0.001$; F: $R^2 = 0.92$, $p < 0.001$; G: $R^2 = 0.88$, $p < 0.001$; Figure 4f). However, the relationships between SOCS and TNS and between SOCS and TPS showed different variation trends. Compared with group E, the correlations between SOCS and TNS and between SOCS and TPS were weakened in treatments M and F (SOCS and TNS: E: $R^2 = 0.61$, $p > 0.001$; M: $R^2 = 0.38$, $p > 0.001$; F: $R^2 = 0.25$, $p > 0.001$; Figure 4d) (SOCS and TPS: E: $R^2 = 0.58$, $p < 0.001$; M: $R^2 = 0.38$, $p > 0.001$; F: $R^2 = 0.43$, $p > 0.001$; Figure 4e). However, compared with treatment E, the relationships between SOCS and TNS ($R^2 = 0.66$, $p < 0.001$, Figure 4d), as well as between SOCS and TPS, were both strengthened in treatment G ($R^2 = 0.69$, $p < 0.001$, Figure 4e).

3.3. Key Factors Affecting SOCS, TNS, and TPS Under Different Treatment Methods

As shown in Figure 5, the RDA explained 99.5%, 98.7%, 97.1%, and 98.6% of the variability in SOCS, TNS, and TPS for the E, M, F, and G treatments, respectively. SOCS, TNS, and TPS were positively correlated with most vegetation and soil factors (Figure 6).

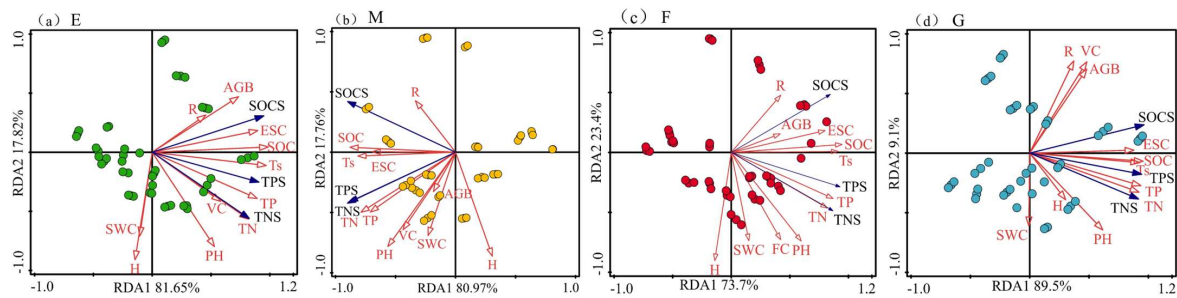


Figure 5. Redundancy analysis (RDA) of the effects of different treatments on soil organic carbon, total nitrogen, and total phosphorus stocks. Note: Figures (a–d) represent the redundancy analyses of environmental variables on nutrient storage under different treatments (E, M, F, and G). E, control group; M, mowing; F, burning; G, grazing; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; H, plant height; VC, vegetation cover; AGB, aboveground biomass; R, plant richness index; SWC, soil water content; Ts, soil temperature; PH, soil pH; ESC, soil electrical conductivity.

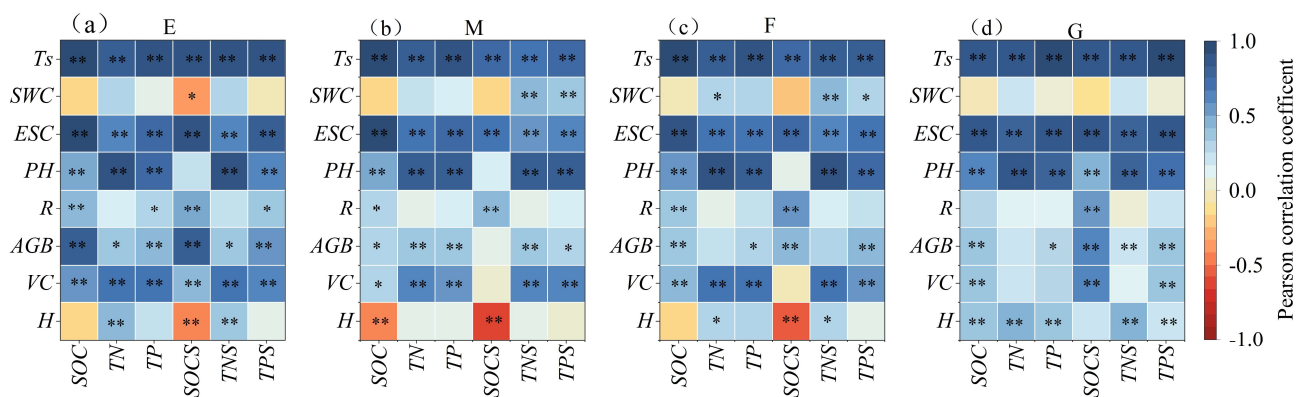


Figure 6. Correlation heatmap of the effects of different treatments on soil organic carbon, total nitrogen, and total phosphorus stocks. Note: Figures (a–d) show the correlation analysis between environmental variables and nutrient reserves under different treatments (E, M, F, and G). E, control group; M, mowing; F, burning; G, grazing; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; H, plant height; VC, vegetation cover; AGB, aboveground biomass; R, plant richness index; SWC, soil water content; Ts, soil temperature; PH, soil pH; ESC, soil electrical conductivity. In Pearson correlation matrix analysis, blue indicates a positive correlation with an environmental variable, and red indicates a negative correlation, the stronger the correlation. “****” “***” indicates significant correlation at 0.01, 0.05 levels.

The MLRM results (Figure 7) showed that environmental factors explained 98.3%, 97.7%, 94.8%, and 94.1% of the variation in SOCS under the E, M, F, and G treatments, respectively. Similarly, environmental factors explained 99.1%, 96.1%, 96.8%, and 98.3% of the variation in TNS, and 94.4%, 93.2%, 92.7%, and 94.2% of the variation in TPS under the E, M, F, and G treatments, respectively.

The results in Figure 7 show that soil temperature is an important control factor for each reserve under different treatments ($R^2 = 15\text{--}29\%$). Soil salinity can also explain the changes in SOCS under treatments E, F, and G ($R^2 = 20\text{--}27\%$), but it can only explain 10.1% of the changes in SOCS in treatment M. Vegetation is also an important control variable affecting SOCS, but the vegetation variables affecting SOCS are different in different treatments. In treatments E, M, F, and G, the controlling vegetation variables are aboveground biomass ($R^2 = 20\%$), vegetation height ($R^2 = 34.5\%$) and richness index ($R^2 = 16.7\%$), vegetation height ($R^2 = 17\%$), and vegetation richness ($R^2 = 14.2\%$), respectively. Soil pH and salinity were important control variables affecting TNS and TPS in treatments E and F ($R^2 = 14.2\text{--}16.7\%$), while in treatment M, they were soil moisture and pH ($R^2 = 13.0\%, 24.8\%$), and in treatment G, they were soil organic carbon and salinity ($R^2 = 19.0\text{--}23.0\%$).

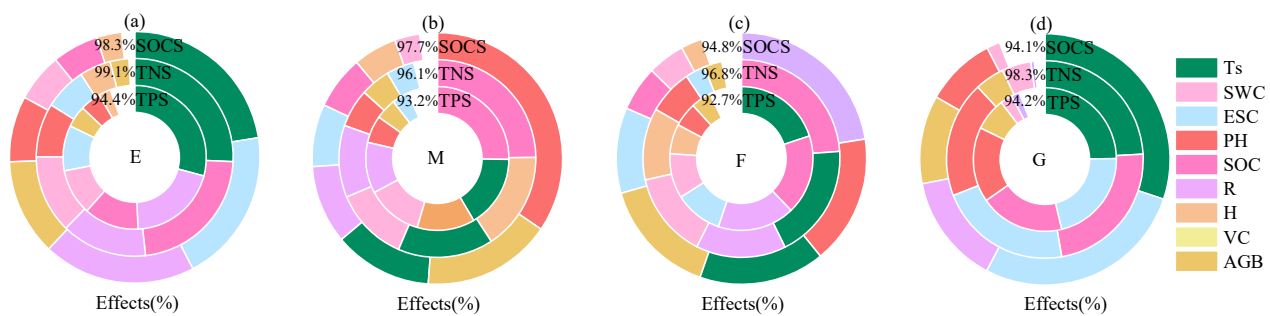


Figure 7. Multivariate linear regression models (MLRMs) explaining the relationship between soil stocks and environmental variables. Note: Figures (a–d) illustrate the explanation of environmental variables affecting nutrient storage under different treatments (E, M, F, and G). E, control; M, mowing; F, burning; G, grazing; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; H, plant height; VC, vegetation cover; AGB, aboveground biomass; R, plant richness index; SWC, soil water content; T_s , soil temperature; PH, soil pH; ESC, soil electrical conductivity.

The SEM model (Figure 8) showed that the key factors explained the changes in SOCS, TNS, and TPS under different treatments. The key factors in treatments E, M, F, and G explained 91%, 73%, 82%, and 90% of the changes in SOCS (Figure 8a–d); 97%, 86%, 90%, and 87% of the changes in TNS (Figure 8e–h); and 89%, 86%, 83%, and 87% of the changes in TPS (Figure 8i–l), respectively. The study showed that soil temperature under different treatments had a positive impact on each reserve indirectly or directly by first affecting vegetation factors and soil factors, with a total standardized effect of 0.715–0.926. This made soil temperature the most critical driving factor affecting each reserve (Figure 8).

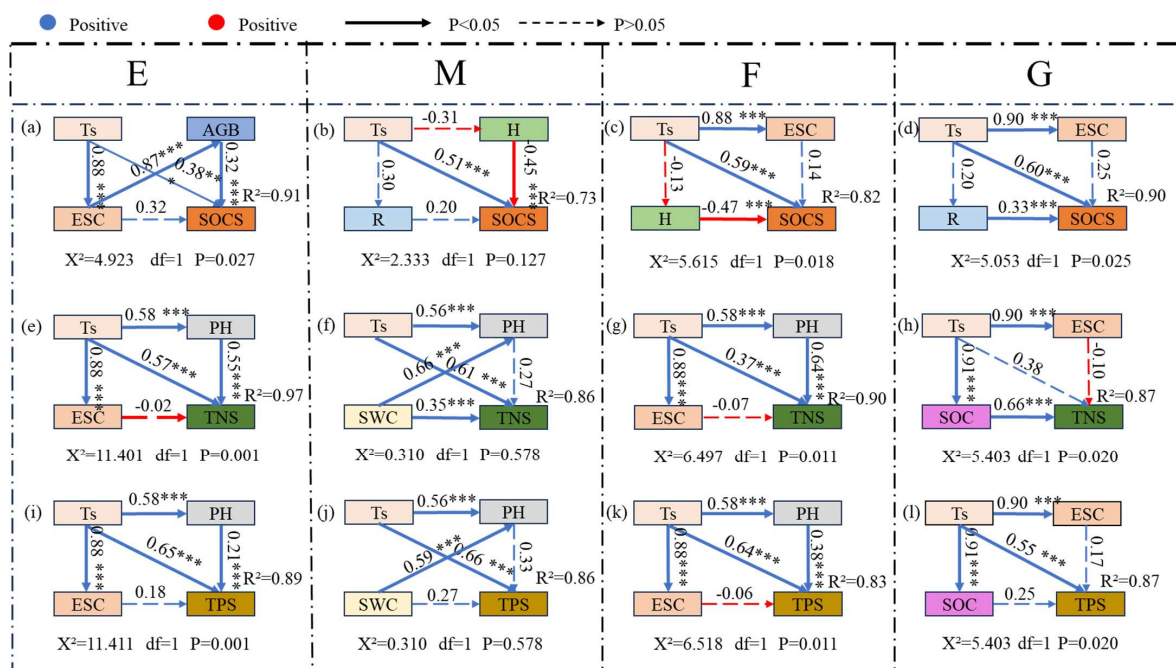


Figure 8. Contribution of key factors to direct and indirect regulatory pathways of soil organic carbon, total nitrogen, and total phosphorus stocks using structural equation modeling. Note: Figures (a–d), (e–h), and (i–l) represent the path analysis of the impact of key variables in different treatments (E, M, F, and G) on SOCS, TNS, and TPS, respectively. E, control group; M, mowing; F, burning; G, grazing; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; H, plant height; VC, vegetation cover; AGB, aboveground biomass; R, plant richness index; SWC, soil water content; T_s , soil temperature; PH, soil pH; ESC, soil electrical conductivity. Across all the models, solid line arrows represent positive effects, and dotted line arrows represent negative effects. R^2 indicates the proportion of variance explained for each dependent variable in the model. *** $p < 0.001$.

Different treatments showed that soil temperature could directly promote SOCS ($\beta = 0.38\text{--}0.60$, $p < 0.05$) (Figure 8a–d). In the E treatment, soil temperature could also significantly positively affect soil salinity ($\beta = 0.88$, $p < 0.05$). Soil salinity could significantly affect aboveground biomass ($\beta = 0.87$, $p < 0.05$), and aboveground biomass was an important factor significantly affecting SOCS ($\beta = 0.32$, $p < 0.05$). Vegetation height in the M and F treatments was significantly negatively correlated with SOCS ($\beta = 0.45\text{--}0.47$, $p < 0.05$) (Figure 8b,c). Vegetation richness in the G treatment was significantly positively correlated with SOCS ($\beta = 0.33$, $p < 0.05$) (Figure 8d).

Soil temperature in treatments E, M, and F had a significant positive effect on soil TNS and TPS ($\beta = 0.37\text{--}0.66$, $p < 0.05$) (Figure 8e–g,i–l), with soil temperature in treatments E, M, and F being found to significantly promote soil pH ($\beta = 0.55\text{--}0.64$, $p < 0.05$). Soil pH in treatments E and F could directly and significantly positively affect soil TNS and TPS ($\beta = 0.21\text{--}0.64$, $p < 0.05$) (Figure 8e,g,i,k), while the effect in treatment M was not significant. In treatment M, soil moisture could directly and significantly promote soil TNS ($\beta = 0.35\text{--}0.61$, $p < 0.05$) (Figure 8f), while in treatment G, soil temperature promoted TNS and TPS by significantly promoting soil SOC content ($\beta = 0.66$, $p < 0.05$).

4. Discussion

4.1. Effects of Different Treatments on SOCS, TNS, and TPS Compared to Control Treatment

Changes in SOCS, TNS, and TPS after different treatments are critical for evaluating the recovery of degraded grasslands [24], and have important implications for predicting the effects of grassland restoration on global climate [25]. However, the dynamics of SOCS, TNS, and TPS across treatments are highly complex.

Compared to the control treatment, grazing significantly reduced SOCS, TNS, and TPS (Figure 3), which aligns with the findings of previous studies [26]. However, some researchers have reported that grazing can enhance soil nutrient accumulation [27,28]. The differing results are due to plant species subjected to grazing compensating for growth through adaptive physiological processes that allow them to maintain or even increase their biomass, and the degree of this tolerance (regenerative capacity) depends on the intensity of livestock disturbance. Light and moderate grazing typically cause less damage to the soil, create favorable conditions for vegetation growth, and increase aboveground biomass; moderate grazing also improves soil nutrient content through livestock dung [29]. However, the study area is located in a pastoral area and experiences year-round high-intensity grazing, which severely depletes vegetation and soil resources. Livestock trampling and foraging reduce root biomass and root exudates, leading to significant declines in all three nutrient stocks. However, at deeper soil layers, disparities in nitrogen (N) and phosphorus (P) reserves may be attenuated due to the disturbance resistance exhibited by grazed grasslands.

The relationship between fire and nutrients in the soil is complex due to the interaction among several factors. The research of Rai et al. [30] has shown that soil nutrient availability can change significantly after severe wildfires; however, low-intensity fires generally have less impact on soil properties. However, in their study of savannas in northeastern South Africa, Strydom et al. [31] found that fire had a negative impact on soil properties. Dean et al. [32] found that controlled fires increased soil nutrient concentrations two weeks after the fire. These studies have shown that the impact of fire on grassland soil nutrients depends mainly on the intensity of the fire and the time of sampling after the fire. Our results showed that the soil nutrient reserves of meadow grasslands increased significantly after fires. This is most likely due to the lush vegetation growth of meadow grasslands and the use of low-intensity fires once a year, with a sampling interval of four months. In this

case, low-intensity fires promote the transfer of nutrients from aboveground biomass to the soil surface, thereby promoting a rapid increase in soil nutrient reserves.

As an important grassland management measure, mowing can drive the redistribution of soil nutrient resources by affecting litter decomposition rate, light intensity, and aboveground biomass and biodiversity [33]. A previous study by Hassan et al. [34] has shown that regular high-frequency mowing will reduce the accumulation of aboveground biomass and plant litter as well as the transport of organic nutrients into the soil system. In contrast, the studies of Cui et al. [35] in coastal wetlands and Chen et al. [36] in semi-arid grasslands have shown that mowing can promote the accumulation of soil nutrients. They believe that moderate mowing management can effectively improve light conditions and soil ventilation, thereby significantly improving the germination rate of vegetation, enhancing photosynthetic efficiency, and effectively promoting the improvement of vegetation productivity. As vegetation productivity increases, root secretions increase, ultimately increasing soil nutrient input. Chai et al. [37] also found that reasonable mowing can actively promote the growth and development of vegetation roots, increase the turnover rate of the root system, and thus promote an increase in soil nutrient reserves. However, excessive mowing causes the loss of soil nutrients. These research results reveal that the impact of mowing on grassland nutrients is mainly related to the intensity of mowing. The results of this study show that compared with the control treatment, the annual mowing of meadow grassland significantly increased soil nutrient reserves. This is potentially attributable to the fact that the intensity of the annual mowing falls within the range that the meadow grassland can withstand and is beneficial to its ecological cycle. However, in the 0–5 cm soil layer, nutrient reserves exhibited a significant decrease in 2020 and no significant difference in 2021, respectively. This phenomenon may be attributed to the buffering effect of mowing on grassland nutrient reserves.

4.2. Interaction of SOCS, TNS, and TPS Under Different Treatments

The interactions among soil SOCS, TNS, and TPS play a key role in terrestrial ecosystems [15]. Different treatments promote vegetation succession and recolonization, leading to the redistribution of SOC, TN, and TP. In this study, we observed that the SOC, TN, and TP contents were positively correlated across different treatments, consistent with previous findings [14].

Compared with the control group, mowing and burning treatments weakened the correlation between SOCS and TNS as well as between SOCS and TPS. In the fire treatment, the apomictic material entered the soil as ash, which rapidly increased soil fertility and promoted root growth and root exudation, thereby increasing SOCS rapidly [9]. However, both mowing and fire treatments excluded livestock feces and urine, which reduced the input of nitrogen, thereby limiting the changes in the soil TNS. Soil P is mainly derived from the weathering of soil rock matrices, which is a very slow process, resulting in relatively stable soil P stocks [18]. Consequently, TNS and TPS could not adapt to the rapid increase in SOCS. As the nitrogen and phosphorus resources in the soil became depleted, vegetation and soil microorganisms may have competed for soil nitrogen and phosphorus to support their growth. More importantly, N and P deficiencies in the soil may have intensified the competition between vegetation and soil microorganisms under high moisture conditions.

Several studies have shown that grazing has complex and compound effects on soil SOC, TN, and TP storage through direct and indirect pathways [38]. On the one hand, livestock mainly affect the input of nutrients into the soil through selective foraging, which in turn influences feed intake and excrement, the quantity and quality of vegetation litter, community structure, and root secretions [39]. On the other hand, grazing can also affect the output of soil nutrients by affecting soil geochemistry as well as microbial community

structure and activity [38]. Furthermore, nitrogen storage in soils is influenced by nitrogen fixation, sedimentary inputs, and leaching of inorganic nitrogen, whereas phosphorus storage is greatly influenced by weathering of primary rock minerals [38]. The results of this study indicated that there was a coupling relationship between grazing treatments and SOCS, TNS, and TPS, which is consistent with the results of Peri et al. [40]. Livestock feces and urine contain sufficient water and nitrogen [41]. Their deposition in the soil accelerates the effectiveness of nutrients, stimulates the activity of soil microorganisms, and promotes plant growth, which has a positive impact on the accumulation of carbon in the soil [42]. In addition, the reduction in soil nitrogen input during grazing may be due to the removal of biomass by livestock grazing and trampling, which in turn causes the reduction of carbon input from litter [43]. Moreover, because nitrogen and phosphorus affect the decomposition process of soil organic matter. Therefore, the relationship between soil carbon storage and nitrogen/phosphorus storage was strengthened compared with the control treatment.

4.3. Key Factors Controlling SOCS, TNS, and TPS in Different Treatments

Changes in both vegetation and soil factors under different treatments affect soil nutrient inputs and outputs. Our results showed that SOCS, TNS, and TPS were correlated with most vegetation and soil factors, indicating that these stocks are sensitive to environmental changes across treatments (Figure 6). This is consistent with the results of Li et al. [19] in temperate grasslands and Lu et al. [44] in desert–steppe transition zones, which also demonstrates that soil nutrients are highly sensitive to changes in soil and vegetation environments. However, the formation process of soil nutrients varies under different treatments, resulting in changes in the relationship between driving factors and various reserves.

Our results indicate that soil temperature plays a key role in influencing the dynamic changes in soil nutrient reserves. It can have a direct positive impact on soil nutrient reserves, and can also indirectly affect soil nutrient reserves by acting on vegetation or other soil variables (Figure 8). This fully reveals the interdependence between soil temperature and soil nutrients. A large number of studies, such as that of Kumar et al. [45], have shown that within a suitable temperature range, temperature increases mainly promote the accumulation and circulation of soil nutrients through a series of physiological processes. On the one hand, temperature increases can significantly promote the metabolic activity of plant root cells, enhance their ability to absorb nutrients, and improve the photosynthetic efficiency of plants, thereby promoting root growth and lateral root development. These temperature increases can also increase root secretions. On the other hand, as the temperature rises, the decomposition process of litter is accelerated [46]. Soil microbial activity increases, and soil respiration increases accordingly [47]. These changes have had a significant impact on soil nutrient reserves.

Vegetation root exudates are the main source of soil carbon accumulation, so the state of vegetation plays a vital role in soil carbon accumulation. A previous study by Yuan et al. [48] recognized that plant diversity, primary productivity, and the ecosystem carbon cycle are positively correlated. Under the enclosure treatment, aboveground biomass had a significant promoting effect on organic carbon storage (Figure 8a). Grazing and trampling reduce competitive exclusion within plant communities, which can maximize plant diversity [49]. Han et al. [50] found that the higher the plant diversity, the more diverse the organic matter composition of litter and root exudates, and the higher the diversity of soil microbial communities. Vegetation diversity may increase soil organic carbon by promoting the growth of soil microorganisms, thereby increasing microbial biomass. We also found that under mowing and burning treatments, vegetation height had an inhibitory effect on SOCS (Figure 8b,c). This may be because mowing and burning significantly reduce

vegetation height, which in turn causes a decrease in litter. Vegetation and litter can cover the soil surface and reduce solar radiation. The increase in soil temperature will increase the mineralization rate of the soil [51], thereby enhancing soil SOCS.

The main controlling variables of soil TNS and TPS are soil variables, indicating that the soil environment plays a key role in the accumulation of TN and TP. Soil temperature during enclosure, mowing, and burning promote the solubility and escape rate of carbon dioxide in the soil. The decomposition of a large amount of carbonic acid leads to a decrease in the hydrogen ion concentration in the soil and an increase in pH (Figure 8e–g). In turn, soil pH affects nitrogen content by affecting the growth and reproduction of soil microorganisms or by affecting the nitrogen cycle process [52]. It can also promote the solubility of soil phosphorus by changing the solubility and adsorption process of phosphorus minerals [53], significantly increasing TNS and TPS during enclosure and burning processes. However, during the mowing process, soil pH had no significant effect on TNS and TPS. This may be because after the grassland was mowed, a large amount of aboveground biomass and litter was removed, which inhibited the growth of microorganisms, making the mowing process less significant for TNS and TPS. Mowing reduces soil moisture and exacerbates the moisture limitation of the grassland. In semi-arid areas, soil water availability has a positive impact on soil nitrogen transformation and availability [54], which is consistent with our research results. Soil organic carbon is positively correlated with temperature [55], and fresh livestock manure contains organic matter (10–20%) and microorganisms. Warming has a substantial promoting effect on the accumulation of soil carbon in grassland ecosystems [27]. In addition, since the nitrogen cycle is closely related to the carbon cycle, the decrease in soil TN may be due to the reduction in plant litter input after grazing animals remove aboveground biomass.

5. Conclusions

In comparison to the control treatment, mowing and fire significantly increased the SOCS, TNS, and TPS. This indicates that semi-arid meadow grasslands exhibit the potential to sequester C, N, and P reserves under mowing and fire treatment. Conversely, the grazing treatment resulted in a decrease in these reserves. In addition, compared with the control group, mowing and burning treatments weakened the correlation between SOCS and TNS and between SOCS and TPS, while grazing treatment strengthened them. Under different treatments, soil temperature was the control variable with the greatest effect on all stocks. Plant community characteristics also played an important role in SOCS accumulation, while TNS and TPS were mainly regulated by soil factors. The key vegetation variables affecting SOCS as well as the key soil variables affecting TNS and TPS showed significant differences among treatments. This study is significant because it enhances our understanding of the relationship between soil nutrient storage and vegetation variables and soil variables under different treatments and their driving processes. Additionally, it provides a scientific basis for ecological restoration and construction of meadow grasslands in semi-arid regions. However, we also recognize that this study has limitations. Many factors, such as the effects of soil microbes and root decomposition on soil nutrient storage, as well as other comprehensive analyses of meadow ecological ecosystems, have not yet been studied in the long term. To promote ecological restoration in semi-arid grasslands, we can mitigate the impact of grazing by adjusting grazing intensity, timing, and seasonal management, and strategically planning grazing areas. Additionally, grassland resilience can be strengthened through fertilization management and the diversification of plant species. These aspects need to be further explored and validated in future studies.

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