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Grazing Decreases Soil Aggregation and Has Different Effects on Soil Organic Carbon Storage across Different Grassland Types in Northern Xinjiang, China

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Abstract: Soil aggregates, as the basic component of soil, make great contributions to the stability of soil structure and soil carbon (C) sequestration. Recently, grasslands have been experiencing continuous grazing, which has had a significant impact on soil aggregation and soil C storage. However, how soil aggregates and soil C in different grasslands respond to grazing remains unclear. Therefore, three national fenced grassland-monitoring sites that represented mountain meadow (MM), temperate steppe (TS), and temperate steppe desert (TSD) were selected to investigate the differences in the responses of soil aggregates and soil C among grazing of different types of grasslands. Soil samples of 0–10 cm was collected from both inside and outside the fence of each site to analyze soil properties and soil aggregate characteristics. The results showed that soil nutrients varied greatly among the three grassland types, with the highest values in MM. At each site, grazing increased the content of sand and decreased the contents of silt and clay compared to fenced plots. Soil aggregate composition showed significant responses to both grassland type and grazing, especially the proportions of soil aggregates >2 mm, which significantly decreased by 51.7% on average in grazing plots compared with fenced plots. A significant decrease (on average, 25.1%) in the mean weight diameter (MWD) of soil aggregates under grazing was detected across all grassland types. The effect of grazing on nutrients in macroaggregates (>0.25 mm) was greater than that in microaggregates (<0.25 mm). Aggregate-associated SOC concentration decreased under grazing in MM and TS. However, grazing had no significant influence on the SOC density of MM, while it led to a significant decrease in TS and an increase in TSD. The magnitude of grazing effect size on aggregate-associated SOC varied with different soil particle sizes, with greater responses in aggregates >2 mm and the biggest value in TDS. In addition, the results of the correlation analysis and redundancy analysis (PDA) indicated that soil bulk density and nutrients made the main contribution to soil composition and stability of soil aggregates. Overall, grazing had a significant influence on soil aggregation, stability, and SOC, playing a crucial role in grassland soil stability and the accumulation of SOC.

Keywords: grazing; grassland type; soil aggregates; aggregates stability; nutrients

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Citation: Fan, L.; Liang, Y.; Li, X.; Mao, J.; Wang, G.; Ma, X.; Li, Y. Grazing Decreases Soil Aggregation and Has Different Effects on Soil Organic Carbon Storage across Different Grassland Types in Northern Xinjiang, China. *Land* **2023**, *12*, 1575. https://doi.org/10.3390/land12081575

Academic Editors: Ligang Xu, Pavel Krasilnikov and Lúcia Helena Cunha dos Anjos

Received: 19 June 2023
Revised: 2 August 2023
Accepted: 2 August 2023
Published: 9 August 2023

1. Introduction

Grassland is one of the major ecosystems, covering up to 30–40% of the Earth's land surface and storing 28–37% of the carbon in the terrestrial ecosystem, which plays an indispensable role in the global carbon cycle [1–3]. However, global change and excessive utilization of grassland (especially overgrazing) have led to continuous land degradation and further decline in soil quality [3].

Grassland soil dominates the function and dynamics of a grassland ecosystem [4]. Soil aggregates are formed by soil particles under the interaction of organic and inorganic cementing materials, which are the basic units of soil structure and the carriers of soil nutrients [5]. On the one hand, distribution characteristics of soil aggregates affect soil porosity, permeability, water retention, and material circulation and energy flow in soil [5]. On the other hand, soil aggregates not only dominate the changes in soil nutrients, but also affect soil nutrient retention capacity [6]. Soil aggregates provide physical protection for SOC, where SOC can act as a cementing material to promote the formation and stabilization of soil aggregates in turn [7]. The stability of soil aggregates represents the carbon sequestration capacity and erosion resistance of soil, which determines the stability of soil and can be used as a basic index for evaluating the quality of grassland soil in arid zones [8]. Therefore, the response of soil aggregates to grazing can profoundly affect the physical and chemical properties of grassland soil.

Grazing is one of the main utilizations for grassland, significantly affecting the physical and chemical properties of soil [9]. Studies have shown that grazing affected the function and dynamics of ecosystems by altering the storage and flow of matter and energy in soil through the feeding, trampling, and excretion of livestock [10]. Therefore, research on grassland degradation should focus on the changes in soil properties and their responses to grazing [11]. Previous studies investigating the impacts of grazing on soil aggregate formation and stabilization in grasslands have produced significant findings. Several studies have shown that grazing, especially overgrazing, destroys soil water-stable aggregates, reduces the stability of aggregates and the soil organic carbon (SOC) concentration, and undermines soil erosion resistance [4,12,13]. Some researchers have reported the opposite results, finding that grazing can result in an increase in the percentages of large aggregates and SOC concentration [14,15]. In addition, some researchers have noted that grazing has no effect on soil aggregates and SOC concentration [16,17]. Thus, there is inconclusive evidence to explain how grazing affects grassland soil aggregates.

Northern Xinjiang, a part of the arid region of central Asia, is one of the key pastoral areas in Xinjiang. An alternating distribution of mountains and basins is the basic geomorphic feature of this area [18]. Grassland is the main type of vegetation, with obvious vertical zonality as the altitude increases [19]. There are 10 grassland types distributed in this region, with significant differences in climatic factors (including temperature and precipitation), plant communities, growth conditions, soil microbial biomass, and soil microbial activities [19]. These differences may cause spatial heterogeneity of grassland soil grain size composition and nutrient distribution [20]. For example, studies have shown that differences in biomass lead to differences in the composition and stability of soil aggregates [21,22]. Soil depth may also cause different distributions of aggregates [21]. In addition, different grassland types may respond differentially to grazing. However, most studies on grassland ecosystems in China have only assessed the characteristics of soil aggregates for specific grassland types individually [12,14,23,24]. In addition, most of those studies have concerned the grasslands of Loess Plateau, Inner Mongolia Steppe, and Qinghai–Tibet Plateau [4,13,24–26]. Studies on soil aggregates in northern Xinjiang are rarely documented, especially considering the combined effects of grassland type and grazing.

In order to better understand the influences of grassland type and grazing on grassland soil quality in northern Xinjiang, three national fixed grassland-monitoring field stations (representing mountain meadow, temperate steppe, and temperate steppe desert) are selected according to vertical zonality, and soil samples inside and outside of the fences are collected to explore the effects of grazing on the composition, stability, and nutrients of soil aggregates. Our experimental results can bring some new insights into grassland management and help policy formulation by local governments, which serve as a global database of soil quality research. Our objectives for this study, therefore, are set to (1) quantify the characteristics of the distribution, stability, and nutrients changes of soil aggregates for different grassland types and (2) analyze the differences and the reasons for the responses of soil aggregates to grazing for different types of grasslands.

2. Materials and Methods

2.1. Study Area

The study area was situated at the north of the Xinjiang Uygur Autonomous Region, China (34°34′–40°47′ N, 110°14′–116°34′ E), bordered by Mongolia, Russia, and Kazakhstan. The study region is characterized by a continental cold temperate climate, with an average annual temperature of 4 °C (2001–2020) and an average annual precipitation of 200 mm (2001–2020). The dominant soil types in the study area are chernozems and kastanozems under the World Reference Base soil classification system [27]. Grassland is the main type of vegetation in the study region, where it covers more than 70% of the area. In addition, owing to the impacts of geographical conditions, grassland types change with obvious vertical zonality as the altitude increases [28].

In this area, the distribution of mountain meadow (MM), temperate steppe (TS), and temperate steppe desert (TSD) descends as the altitude decreases. MM is mainly distributed in the mid-mountain belt from 1700 to 2900 m a.s.l., with a humid climate and high rainfall. MM has the highest layer height and vegetation coverage compared to the other two grassland types. Climate conditions in TSD are the harshest among these three grasslands. Furthermore, owing to the impacts of geographical conditions and climate changes, the area of TSD has gradually increased in the study area [29].

2.2. Experimental Design and Soil Sampling

The experiment was conducted in MM, TS, and TSD grassland areas, each with a fenced grassland (non-grazing treatment, NG) plot and a neighboring grazing grassland (grazing treatment, G) plot. The grazing exclusion areas of the three grasslands were fenced for 8–10 years by the local government. Livestock grazing has been completely excluded from the fenced grasslands since the establishment of the fencing, while the area outside the fences has had continuous free grazing with sheep, goats, and cows from local herdsmen. MM, TS, and TSD are summer pastures, spring/autumn pastures, and winter pastures, respectively. Since the beginning of the 21st century, the grasslands in the Altay Prefecture, where the study area belongs, have been facing increasing levels of overloading. According to a local grassland inspection report, the number of livestock in the Altay Prefecture reached 4.28 million in 2012, resulting in an overload rate of 75% [30]. Moreover, the grazing pressure on summer pastures was particularly high due to the scarcity of grass in spring/autumn pastures and winter pastures. The details of the sampling plots are shown in Table 1. The soil type, soil texture, and plant species composition were found to be similar both inside and outside the fence at each site. As shown in Figure 1, the sand, silt, and clay contents of the soil in both the fenced grassland and grazing grassland of each site were similar.

From May to July 2021, an experimental plot (10 m × 10 m) was set up at each site. For each plot, we randomly selected three quadrats (1 m × 1 m) using a diagonal method to collect soil samples. After removing the aboveground parts of the plant and litter entirely in the quadrats, three subsamples (0–10 cm depth) were collected using a soil auger with a diameter of 10 cm and a length of 10 cm, which were then mixed into a single soil sample. A total of 18 mixed soil samples inside and outside the fences were collected from the three grassland types. Then, soil samples were air-dried in a laboratory for the further determination of soil nutrients and soil aggregates.

Table 1. Details of the sampling plots.

Item	MM	TS	TSD
Lon (°)	85.71	89.75	86.21
Lat (°)	47.22	46.98	47.29
Alt (m)	2045.00	1450.00	1127.00
MAP (mm)	397.16	276.447	256.17
MAT (°C)	−1.21	4.57	7.52
Grazing season	Summer	Spring/Autumn	Winter
Zonal soil	Chernozems	Kastanozems	Kastanozems
Dominant species	*Carex stenocarpa; Polygonum viviparum*	*Festuca rupicola*	*Seriphidium gracilescens; Stipa glareosa*

Note: Lon, longitude; Lat, latitude; Alt, altitude; MAP, mean annual precipitation; MAT, mean annual temperature; MM, mountain meadow; TS, temperate steppe; TSD, temperate steppe desert.

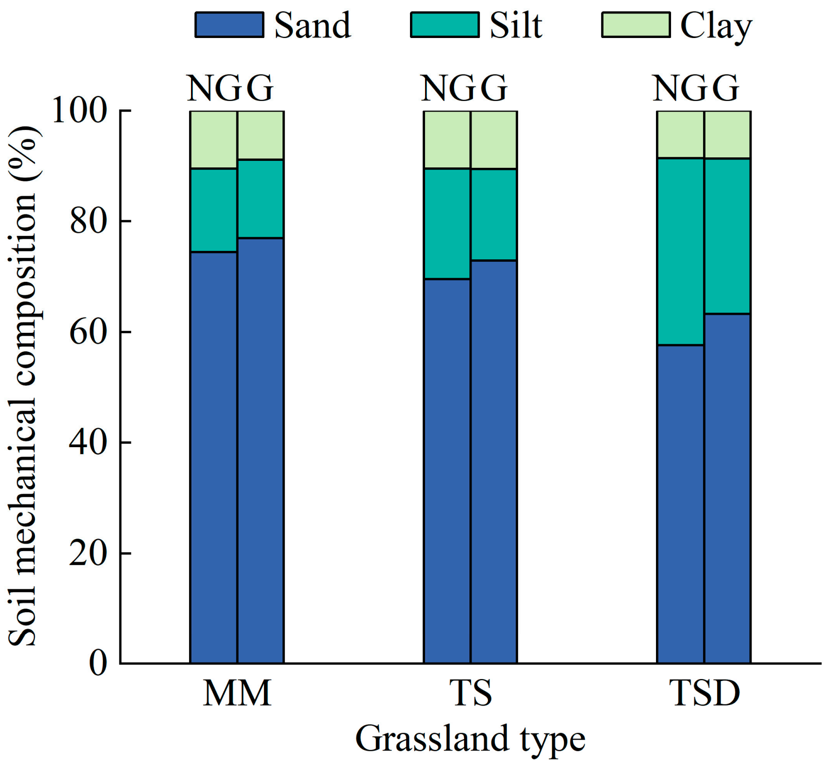


Figure 1. Soil texture characteries of three grassland types under grazing and non-grazing conditions. Note: NG, non-grazing treatment; G, grazing treatment; MM, mountain meadow; TS, temperate steppe; TSD, temperate steppe desert. Sand, 0.02–2 mm; silt, 0.002–0.02 mm; clay, <0.002 mm.

2.3. Soil Aggregate Size Distribution and Analysis

A wet-sieving method was used to quantify water-stable aggregates (WSAs) [31]. The air-dried soil samples were processed via passing through 2 mm, 0.25 mm, and 0.053 mm sieves to determine weight by particle size. Approximately 50 soil samples were evenly spread on the top sieve (2 mm) and then submerged in a bucket of distilled water for 10 min. The sieve was shaken vertically for 15 min at a frequency of 30 times/min^{-1} and an amplitude of 5 cm to achieve the grading of aggregate size. Then, the water-stable aggregates retained on each sieve were transferred into containers and weighed after drying at 60 °C until reaching a constant weight. The amounts of true aggregates were calculated by subtracting the weight of plant residues and stones from the total weight. Finally, a total of four aggregate classifications with different diameters were clarified, including >2 mm, 0.25–2 mm, 0.053–0.25 mm, and <0.053 mm. Meanwhile, >0.25 mm particles were named as macroaggregates, and 0.053–0.25 mm particles were named as microaggregates.

The mean weight diameter (MWD) of the soil aggregates was used to evaluate the water stability of soil aggregates using Equation (1) [5]:

$$\mathrm{MWD} = \frac{\sum_{i=1}^{n}(X_i W_i)}{\sum_{i-1}^{n} W_i} \quad (1)$$

where X_i is the mean diameter of the aggregate fraction *i*, and W_i is the mass proportion of the aggregate fraction *i*.

2.4. Measurement of Soil Physico-Chemical Properties

The soil particle composition was analyzed using a hydrometer method. Soil organic carbon (SOC) concentration was determined with a potassium dichromate oxidation method; soil total nitrogen (TN) concentration was determined with the Kjeldahl method; and soil total phosphorus (TP) was determined with an ammonium molybdate colorimetric method. Available nitrogen (AN) was determined using a method of alkaline hydrolysis diffusion; soil available phosphorus (AP) was determined using sodium bicarbonate extraction and a molybdenum antimony colorimetric method. Soil bulk density of the 0–10 cm soil layer was determined using a soil wreath knife with a volume of 60 cm^3 (3.1 cm in height and 5 cm in diameter) [32].

2.5. Calculation of SOC Density of Bulk Soil and Grazing Effect Size on Aggregate-Associated SOC

Soil organic carbon density (SOCD) (kg m^{-2}) of the bulk soil was calculated using Equation (2) [33]:

$$\mathrm{SOCD} = C \times D \times E/100 \quad (2)$$

where *C* is the organic carbon concentration (g kg^{-1}) in the soil layer of 0–10 cm, *D* is the soil bulk density (g cm^{-3}) in the soil layer of 0–10 cm, and *E* is the soil depth (cm).

The grazing effect size on aggregate-associated SOC was calculated with Equation (3):

$$\text{Effect size} = \frac{C_{NGi} \times W_{NGi}}{C_{Gi} \times W_{Gi}} \quad (3)$$

where C_{NGi} is the aggregate-associated SOC of fraction *i* in the NG treatment, W_{NGi} is the proportion of aggregate fraction *i* in the NG treatment, C_{Gi} is the aggregate-associated SOC of fraction *i* in the G treatment, and W_{Gi} is the proportion of aggregate fraction *i* in the G treatment.

2.6. Statistical Analysis

A two-way analysis of variation (ANOVA) and multiple comparisons were used to evaluate the effects of grazing and grassland type on bulk soil and aggregates. A least significant difference (LSD) test following a one-way analysis of variance was used to compare the differences of mean values at $p < 0.05$. Pearson's correlation analysis was used to explore the relationship between soil nutrients and soil MWD. A redundancy analysis (RDA) was used for the relationship between the characteristics of soil aggregates and the properties of bulk soil. The RDA was performed using Canoco 5. Origin Pro 2023 was used to prepare all of the figures.

3. Results

3.1. Soil Properties

The soil textures of the three grasslands belonged to sandy-type soil. In the three grasslands, grazing resulted in an increase in the content of sand and a decrease in the content of silt (Figure 1). The soil bulk density showed significant differences among the grassland types ($p < 0.05$, Figure 2a, Table S1), especially under the grazing treatment, where the soil bulk density in TSD exhibited an obviously higher value than the other two grassland types ($p < 0.05$, Figure 2a). The SOC, TN, TP, AN, and AP concentrations of bulk soil varied significantly among the different grassland types, with the highest values in MM ($p < 0.05$, Figure 2b–f, Table S1). Grazing significantly decreased the SOC concentrations in MM and TS; however, it had no significant effect on TN, TP, and AN concentrations of the three grassland types (Figure 2b–e, Table S1). Compared to the NG treatment, grazing increased AP concentrations in TS and TSD, but it was not statistically significant (Figure 2f). Grassland type and grazing had significant interactive effects on soil bulk density, SOC, and AP concentration ($p < 0.05$, Table S1).

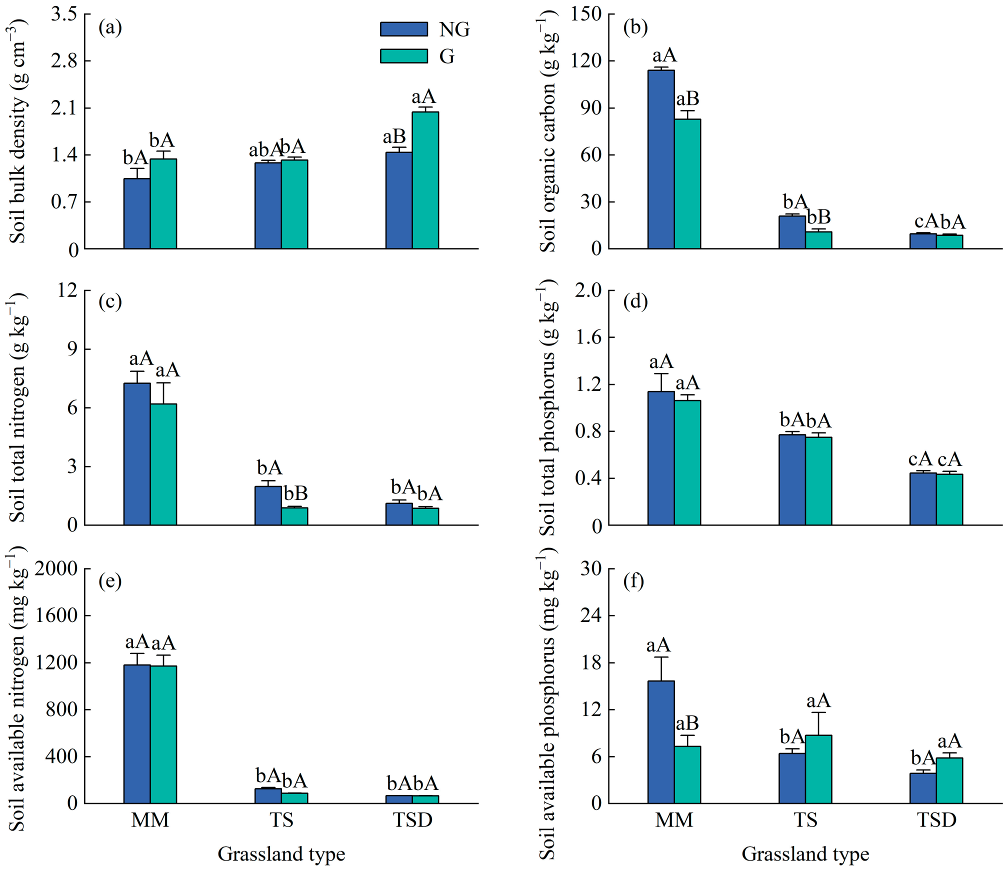


Figure 2. Responses of soil physical and chemical properties to grazing in different grassland types: (**a**) soil bulk density, (**b**) soil organic carbon, (**c**) soil total nitrogen, (**d**) soil total phosphorus, (**e**) soil available nitrogen, and (**f**) soil available phosphorus. Note: NG, non-grazing treatment; G, grazing treatment; MM, mountain meadow; TS, temperate steppe; TSD, temperate steppe desert. Different lowercase letters indicate significant differences ($p < 0.05$) between different grassland types, and different uppercase letters indicate significant differences ($p < 0.05$) between grazing and non-grazing treatments.

3.2. Aggregate Particle Distribution and Stability

The soil aggregate distribution and MWD of different grassland types were significantly influenced by grazing ($p < 0.05$, Figure 3, Table S2). Grazing significantly decreased the proportion of aggregates >2 mm of MM, TS, and TSD by 51.3%, 31.6%, and 71.9%, respectively, and also reduced the MWD values. On the contrary, grazing significantly increased the proportion of aggregates of 0.25–2 mm in MM and TSD and the proportion of aggregates of 0.053–0.25 mm in TS ($p < 0.05$, Figure 3a). Under the influence of grazing, the proportion of aggregates <0.053 mm in the three grasslands decreased to some extent. Grassland type had a significant effect on aggregate distribution and MWD ($p < 0.05$) (Figure 3, Table S2). The proportion of aggregates >2 mm and the MWD decreased in the order of MM, TS, and TSD ($p < 0.05$, Figure 3). In addition, grassland type and grazing had significant interactive effects on the proportion of aggregates >2 mm ($p < 0.05$, Table S2).

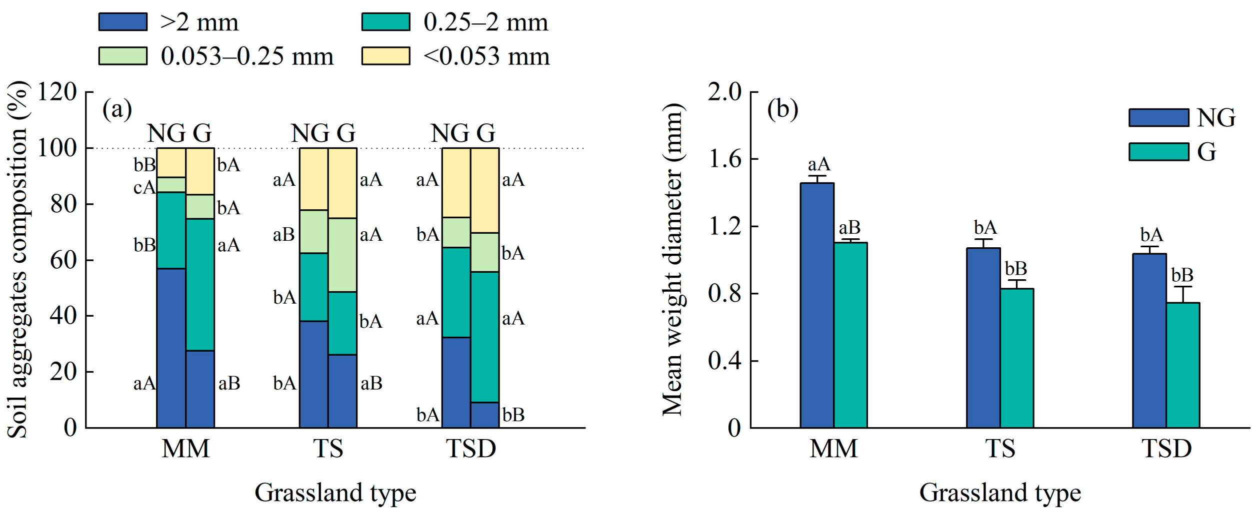


Figure 3. Responses of the composition and stability of soil aggregates to grazing: (**a**) soil aggregates composition, and (**b**) mean weight diameter. Note: NG, non-grazing treatment; G, grazing treatment; MM, mountain meadow; TS, temperate steppe; TSD, temperate steppe desert. Different lowercase letters indicate significant differences ($p < 0.05$) between different grassland types, and different uppercase letters indicate significant differences ($p < 0.05$) between grazing and non-grazing treatments.

3.3. Characteristics of Nutrients in Soil Aggregates

Nutrients in soil aggregates showed obvious differences among the three grassland types and responded differently to grazing ($p < 0.05$, Figure 4, Table S3). Where MM was concerned, grazing significantly reduced SOC, TN, TP, AN, and AP concentrations in aggregates >2 mm from 127.77 to 71.43 g kg^{-1}, 8.22 to 5.31 g kg^{-1}, 0.81 to 0.52 g kg^{-1}, 623.11 to 233.25 mg kg^{-1}, and 11.85 to 8.89 mg kg^{-1}, respectively ($p < 0.05$, Figure 4). Grazing significantly decreased the SOC and AN concentrations in aggregates of TS ($p < 0.05$, Figure 4a,d). In general, grazing had no significant effect on the aggregate-associated nutrients of TSD (Figure 4a). Grazing decreased the AN concentrations of three size of aggregates in TS and TSD but increased the AP concentrations to some extent (Figure 4d,e). According to the results of the two-way analysis of variance, the main influence of grazing on aggregate nutrients was in the size of >2 mm (Table S3). Aggregate-associated nutrients showed significant differences among the three grassland types ($p < 0.05$, Figure 4, Table S3). MM grassland had higher SOC, TN, TP, AN, and AP values in aggregates compared with the other two grassland types ($p < 0.05$). For example, the SOC concentration of MM was 5–15 times greater than those of the other grassland types, the TN concentration was 3–6 times greater, and the TP concentration was 1–3 times higher. The TP concentration of each aggregate size in TS was significantly higher than that of TSD ($p < 0.05$, Figure 4c). Grassland type and grazing had a significant interactive effect on aggregate nutrients, which was also mainly reflected in aggregates >2 mm ($p < 0.05$, Table S3).

Compared to the NG treatment, the SOCD of bulk soil in TS was significantly reduced by grazing but increased in TSD ($p < 0.05$, Figure 5a). However, grazing had no significant effect on the SOC density of MM (Figure 5a). The grazing effect size on aggregate-associated SOC was significantly different among the three grassland types in aggregates >2 mm. The effect size was TSD, MM, and TS in descending order ($p < 0.05$, Figure 5b).

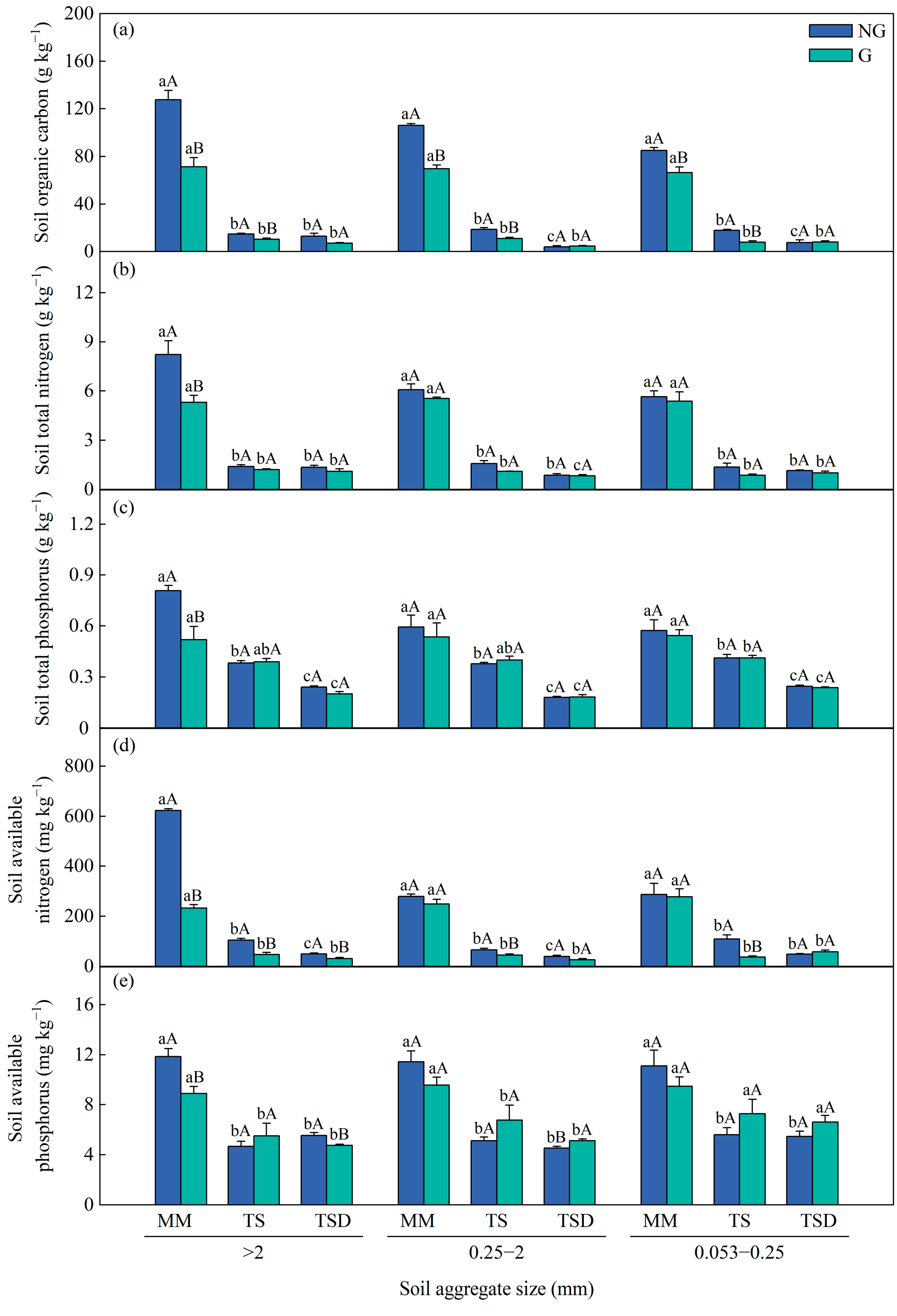


Figure 4. Responses of soil nutrients in aggregates to grazing: (**a**) soil organic carbon, (**b**) soil total nitrogen, (**c**) soil total phosphorus, (**d**) soil available nitrogen, and (**e**) soil available phosphorus. Note: NG, non-grazing; G, grazing; MM, mountain meadow; TS, temperate desert steppe; TSD, temperate steppe desert. Different lowercase letters indicate significant differences ($p < 0.05$) between different grassland types, and different uppercase letters indicate significant differences ($p < 0.05$) between grazing and non-grazing treatments.

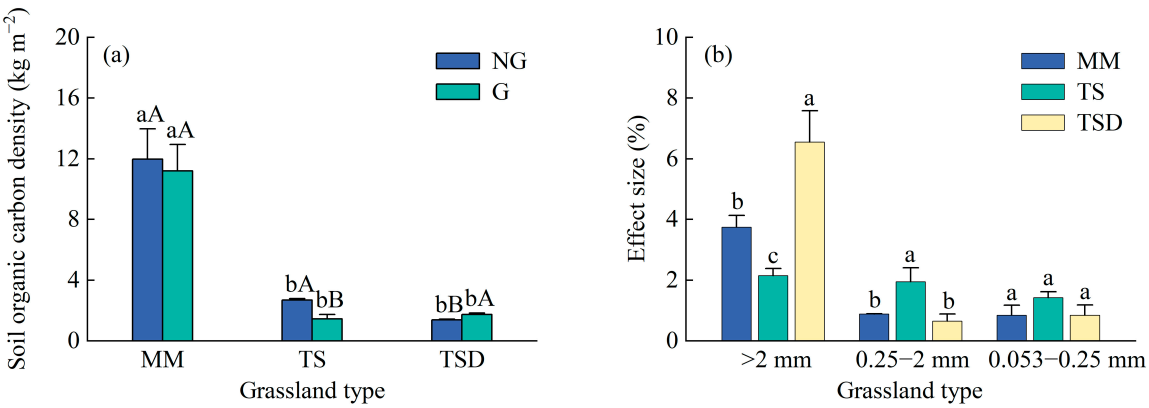


Figure 5. Organic carbon density in the soil layer of 0–10 cm (**a**) and grazing effect size on aggregate-associated SOC varied in different sizes of soil aggregates (**b**). Note: NG, non-grazing; G, grazing; MM, mountain meadow; TS, temperate steppe; TSD, temperate steppe desert. Different lowercase letters indicate significant differences ($p < 0.05$) between different grassland types, and different uppercase letters indicate significant differences ($p < 0.05$) between grazing and non-grazing treatments.

3.4. Influence of Soil Variables on Soil Aggregates

Through an RDA analysis and Pearson's correlation coefficient, the relationships between aggregate characteristics and soil properties were analyzed. The RDA analysis showed that the environmental properties of axes one and two represented 60.21% and 17.88% of the total variance, respectively (Figure 6). The soil bulk density, SOC, and AN were significantly correlated with soil aggregate composition and stability, with soil bulk density being the primary environmental factor, followed by SOC. MWD and the proportion of aggregates >2 mm were positively regulated by soil nutrients and negatively regulated by soil bulk density. The proportions of aggregates of 0.053–0.25 and <0.053 mm were positively regulated by BD (Figure 6, Table 2). MWD was significantly positively correlated with the concentrations of soil SOC, TN, TP, AN, and AP and negatively correlated with soil bulk density ($p < 0.05$, Figure 6). There were significant positive correlations between soil nutrients; however, soil nutrients were negatively correlated with soil bulk density (Figure 7). The proportion of aggregates >2 mm was significantly positively correlated with soil nutrients and significantly negatively correlated with soil bulk density, while the proportions of aggregates of 0.053–0.25 and <0.053 mm were contrary to this.

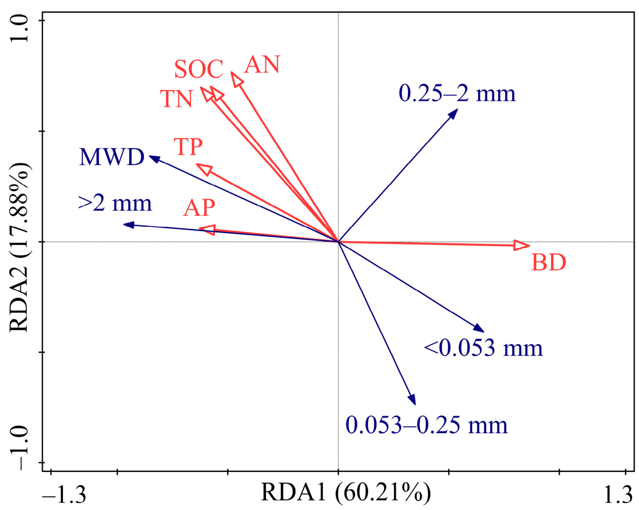
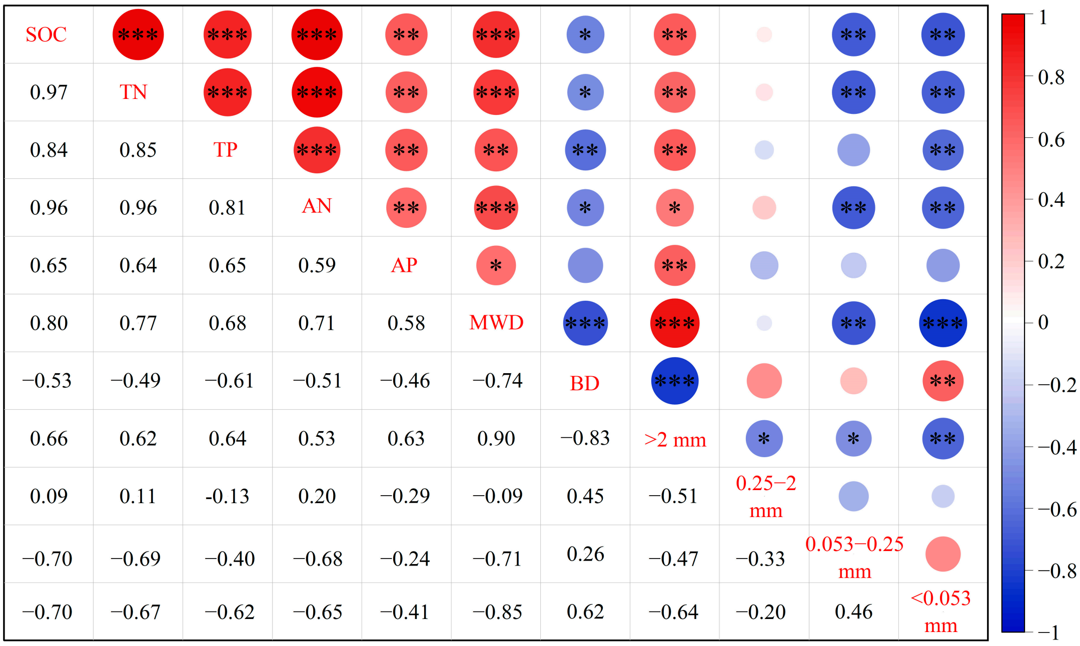


Figure 6. Redundancy analysis (RDA) for relationships between characteristics of soil aggregates and properties of bulk soil. BD, soil bulk density; SOC, soil organic carbon; TN, soil total nitrogen; TP, soil total phosphorus; AN, soil available nitrogen; AP, soil available phosphorus; MWD, mean weight diameter.

Table 2. The goodness of fit (R^2), adjusted goodness of fit (R^2), explained fitted variation (contribution), *F*, and *p*-values of BD, SOC, TN, TP, AN, and AP from the RDA.

Explanatory Variable	R^2	Adjusted R^2	Contribution (%)	*F*	*p*-value
BD	0.45	0.38	57.10	13.00	<0.01 **
SOC	0.14	0.12	17.80	5.10	<0.01 **
AN	0.13	0.11	16.80	6.60	<0.01 **
AP	0.04	0.03	4.50	1.90	0.19
TN	0.02	0.01	2.00	0.80	0.55
TP	0.01	0.01	1.70	0.70	0.47
First Axis				16.60	<0.01 **
All Axes	0.79	0.67		6.70	<0.01 **

Note: BD, soil bulk density; SOC, soil organic carbon; TN, soil total nitrogen; TP, soil total phosphorus; AN, soil available nitrogen; AP, soil available phosphorus. ** indicates significant difference at $p < 0.01$.



The correlation analysis of soil aggregates and soil properties.

Figure 7. Correlation analysis of aggregate characteristics and soil properties. Note: SOC, soil organic carbon; TN, soil total nitrogen; TP, soil total phosphorus; AN, soil available nitrogen; AP, soil available phosphorus; BD, soil bulk density. *, **, and *** indicate significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

4. Discussion

4.1. Effects of Grazing and Grassland Type on Soil Aggregate Size Distribution and Stability

As the physical structure of soil, the compositions of aggregates with different particle sizes are influenced by environmental factors [5]. In this study, under grazing, aggregates >2 mm of MM, TS, and TSD changed to aggregates <2 mm, accompanied by a decrease in aggregate MWD (Figure 3). Residues both from aboveground and underground parts of plants, as well as soil silt and clay contents, are all crucial factors that influence the formation and stability of soil aggregates [4,34–37]. The precipitation conditions in MM and TS are better than those in TDS, leading to higher vegetation coverage and biomass. MM, in particular, exhibits the highest biomass and endures the most severe grazing pressure as summer pastures, resulting in the most severe overload phenomenon [32]. Under significant grazing pressure, the vegetation in MM and TSD do not have enough recovery time after being grazed by livestock. This leads to a reduction in vegetation coverage and an increase in exposed soil. Additionally, the soil experiences erosion, leading to losses of silt and clay [4,32,38]. Our analysis of soil mechanical composition also revealed that grazing in grasslands led to decreases in the contents of silt and clay and an increase in sand, as compared to fenced plots. The absence of the support of plants to the soil, the feedback of litter to soil C, and the absence of silt and clay as soil binders ultimately led to the transformation of aggregates >2 mm into aggregates <2 mm [25]. The results of the RDA showed that BD and soil nutrients were the main influencing factors of the composition and stability of aggregates (Figure 7, Table 1). It was concluded that grazing mainly affected the composition and stability of aggregates of MM and TS by reducing the nutrient input of plants to soil, and it affected TSD by increasing the soil bulk density. Further, the deterioration of soil quality also exacerbates the degradation of plants, forming a vicious circle [38]. Ultimately, overgrazing leads to the degradation of grassland ecosystems, especially in vulnerable arid regions [4,39,40].

Our study found significant differences in the compositions of soil aggregates with different particle sizes and soil stability among the grassland types. The proportion of aggregates >2 mm and the MWD value in MM, with the highest precipitation, were significantly higher than those of the other two grassland types (Figure 3). Previous studies have shown that, at the soil layer of 0–20 cm, the MWD values of meadow steppe were significantly greater than those of typical and desert steppes, which indicated that high precipitation was conducive to the formation and stability of aggregates [20]. In this study, the soil of MM, with high precipitation, was wetter compared with TS and TSD, causing rich species diversity, high vegetation coverage, and a developing root system, which was more conducive to the accumulation of binding agents of soil aggregates and resulted in good soil stability [20]. Meanwhile, the high mean annual temperatures of TS and TSD led to high evaporation, which was not conducive to the maintenance of soil moisture and plant growth and resulted in low values in aggregate stability [19,20]. Despite the varying climatic conditions of the three grasslands, they were all situated in an arid region, resulting in similar soil mechanical compositions. Hence, the differences observed in grassland soil aggregates of this region cannot be attributed to variations in soil mechanical composition.

In addition, from the aggregate compositions among the three grassland types, we found that different grassland types displayed different response intensities to grazing. The response of the proportion of aggregates >2 mm to grazing in TSD was the strongest, followed by MM, which indicated that the soil structure of TSD was the most fragile. Similar to a previous analysis, the low vegetation coverage and root biomass in TSD resulted in weak support from plants, leading to a greater impact of livestock trampling on soil bulk density. In MM, where vegetation conditions were the best but grazing pressure was the greatest, livestock severely damaged both the vegetation and soil quality [5]. In general, the results from our study showed that both grazing and climatic condition affected the compositions of aggregates with different particle sizes and the stability of soil aggregates, determining the soil structure and quality of the different types of grassland.

4.2. Effects of Grazing and Grassland Type on Soil Aggregation Nutrients

Soil aggregates physically protect the nutrients, and any factor that causes change in the composition and stability of aggregates directly leads to nutrient change in them [5,25,41]. In our study, grazing had the greatest impact on the nutrient concentration of aggregates >2 mm (Figures 4 and 5b). We found that the nutrient concentration in aggregates >2 mm was higher than that of other particle size aggregates (especially in MM), and the results of the RDA also showed a stronger correlation between soil nutrient concentration and the proportion of aggregates >2 mm (Figure 7). This indicated that a large proportion of nutrients were stored in aggregates >2 mm. However, grazing significantly decreased that part of the nutrients, especially SOC, which exhibited noticeable responses to grazing in all sizes of aggregates (Table S3). In general, aggregates of different particle sizes play different performances in maintaining soil nutrient availability. Macroaggregates (>0.25 mm) contain more labile nutrients than microaggregates, and those nutrients are more likely to be lost when disturbed (Table S3) [41]. Zhang et al. and Han et al. had similar findings [4,42]. This is because (1) the grazing of plants by livestock decreases the amount of SOC that is input into the soil from the aboveground parts of plants, resulting in a loss of SOC [5]. (2) Moreover, the exposed area of soil increases after vegetation is gnawed, which leads to enhanced soil erosion and results in decreases in silt and clay contents. These are not conducive to the accumulation of SOC [43]. (3) Macroaggregates can provide physical protection for SOC, preventing it from being decomposed by microorganisms. However, soil becomes compacted due to severe overloading and continuous trampling of livestock, causing a change in soil aggregates from >2 mm to <2 mm. As a result, SOC loses the physical protection provided by aggregates [5,44]. Furthermore, several studies have demonstrated that the change in soil nutrients caused by variations in the quantity and quality of litter considerably affects SOC dynamics [45,46]. In our study, SOC was significantly positively correlated with TP and TN contents (Figure 6). When TN decreases, more C is lost through respiration. The reduction in P may affect the symbiotic nitrogen fixation and change the soil N:P ratio [47,48]. This indicates that the loss of other nutrients due to grazing had an important role in driving the change in SOC storage. However, SOCD showed a different response to grazing, with a minor effect on MM, decreasing SOC density in TS, and increasing in TSD (Figure 5a). This was because, although grazing significantly reduced the SOC concentration of MM, it increased the soil bulk density to a certain extent, finally resulting in a minor change in the SOCD of MM. Conversely, in TDS, a significant increase in soil bulk density led to a significant increase in SOCD under grazing. However, the increase in SOCD of TSD due to the increase in soil bulk density could not indicate the improvement of soil quality; on the contrary, it further proved the damage to the soil structure caused by repeated trampling.

Vegetation differences among grassland types determine the local litter mass addition, microbial activities, and nutrient cycles in soil, which strongly affects the soil structure and properties, resulting in more obvious spatial heterogeneity [49]. This study found that, regardless of grazing or not, nutrient concentrations in soil aggregates in MM were notably higher than those of the other two grassland types, which may relate to the vegetation, soil type, and climatic conditions (including air temperature and precipitation, Table 1). The mean annual precipitation showed a trend of MM >TS > TSD, while the mean annual temperature showed an opposite trend. MM typically experienced higher levels of precipitation and lower temperatures compared to the other areas. The presence of abundant vegetation coverage in these meadows helps to reduce water evaporation, while the well-developed root systems of plants provide physical support to the soil. These factors contribute to the formation and stability of soil aggregates, as well as the preservation of nutrients. However, macroaggregates can hold more nutrients, but these parts are particularly vulnerable to environmental change due to their strong activity and become easier to decompose [41]. Due to the significant shortage of grass in the spring/autumn pastures of TS and the winter pastures of TSD, MM experiences immense grazing pressure. As a result, the nutrient content of MM aggregates exhibited a pronounced response to grazing. At the same time, changes in soil TN and TP also affect the accumulation of SOC [50]. Our results indicated that both grazing and grassland type had significant effects on nutrients in aggregates, with the interaction primarily observed in aggregates >2 mm (Figure 4, Table S3). This result is similar to previous studies [51], further illustrating the instability of nutrients in large aggregates to environmental disturbance. From the nutrient changes in aggregates among the three grassland types, we found that different grassland types displayed differential response intensities to grazing, with stronger responses in aggregates of MM. Influenced by the type of grassland itself, MM soils contain a larger proportion of large particulate matter, which is highly reactive, so grazing damages these parts more severely. Therefore, continuous grazing pressure caused an obvious decrease in the proportion of macroaggregates and the concentrations of various nutrients in MM [4]. Where other grassland types were concerned, aggregate-associated nutrients of TS and TSD did not exhibit as conspicuous of responses as MM due to grazing. This may be because the nutrient concentrations in TS and TSD were lower, and there was no room for reduction, even faced with interference [19].

5. Conclusions

In this study, we evaluated the composition, stability, and nutrient distribution of soil aggregates at the 0–10 cm soil layer under grazing and within fenced plots among three grassland types in northern Xinjiang. The results indicated that grazing increased the content of sand and decreased the contents of silt and clay compared to fenced plots. The proportion of aggregates >2 mm and the MWD of MM with high precipitation were the highest. Grazing decreased the proportions of aggregates >2 mm (on average 51.7%) and aggregate stability (on average 25.1%) in the three grassland types, with reductions in MM and TS mainly due to the reduction in binding agents of soil aggregates and that in TSD due to the increase in soil bulk density. The aggregate-associated nutrients of MM were significantly higher than those of TS and TSD. A large proportion of nutrients was stored in aggregates >2 mm, which had the strongest responses to grazing disturbance. The SOC concentrations of aggregates of MM and TS were significantly reduced by grazing, but the SOCD of TSD was significantly increased because the soil bulk density was significantly increased by grazing. Collectively, this study provides detailed insights into the composition, stability, and nutrient distribution of soil aggregate changes in different grassland types under grazing.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12081575/s1. Table S1: Two-way ANOVA of the impact of grassland type and grazing on grassland soil physical and chemical properties.; Table S2: Two-way ANOVA of the impact of grassland type and grazing on grassland soil aggregates and stability; Table S3: Two-way ANOVA of the impact of grassland type and grazing on nutrients in different particle size aggregates; Table S4: Two-way ANOVA of the impact of grassland type and grazing on soil organic carbon density.

Author Contributions: L.F. and Y.L. (Yuanye Liang) contributed equally to this work. L.F. analyzed the data and drafted the manuscript. Y.L. (Yuanye Liang) performed the experiments and analyzed the data. X.M., X.L. and G.W. performed parts of the experiments. Y.L. (Yaoming Li) and J.M. conceived the study. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Regional Collaborative Innovation Project of Xinjiang Uygur Autonomous Region (2020E01015), the Third Xinjiang Scientific Expedition Program (2021xjkk0603), the "West Light" Talent Program of the Chinese Academy of Sciences (2019–XBQNXZ–B–005), and the National Natural Science Foundation of China (42077327).

Data Availability Statement: The original contributions presented in the study are included in the article material, and further inquiries can be directed to the corresponding author.

Acknowledgments: We thank the Altay Forest and Grassland Bureau for providing us with a research platform where we could conduct this study. We also thank all the staff working at the three national fenced grassland-monitoring field stations for their significant and effective assistance.

Conflicts of Interest: The authors declare no conflict of interest.

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