Characteristics of soil organic carbon and total nitrogen under various grassland types along a transect in a mountain-basin system in Xinjiang, China Postprint

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Abstract

Soil organic carbon (SOC) and soil total nitrogen (STN) in arid regions are important components of global C and the N cycles, and their response to climate change will have important implications for both ecosystem processes and global climate feedbacks. Grassland ecosystems of Funyun County in the southern foot of the Altay Mountains are characterized by complex topography, suggesting large variability in the spatial distribution of SOC and STN. However, there has been little investigation of SOC and STN on grasslands in arid regions with a mountain-basin structure. Therefore, we investigated the characteristics of SOC and STN in different grassland types in a mountain-basin system at the southern foot of the Altai Mountains, north of the Junggar Basin in China, and explored their potential influencing factors and relationships with meteorological factors and soil properties. We found that the concentrations and storages of SOC and STN varied significantly with grassland type, and showed a decreasing trend along a decreasing elevation gradient in alpine meadow, mountain meadow, temperate typical steppe, temperate steppe desert, and temperate steppe desert. In addition, the SOC and STN concentrations decreased with depth, except in the temperate desert steppe. According to Pearson' s correlation values and redundancy analysis, the mean annual precipitation, soil moisture content and soil available N concentration were significantly positively correlated with the SOC and STN concentrations. In contrast, the mean annual temperature, pH, and soil bulk density were significantly and negatively correlated with the SOC and STN concentrations. The mean annual precipitation and mean annual temperature were the primary factors related to the SOC and STN concentrations. The distributions of the SOC and STN concentrations were highly regulated by the elevation-induced differences in meteorological factors. Mean annual precipitation and mean annual temperature together explained 97.85% and 98.38% of the overall variations in the SOC and STN concentrations, respectively, at soil depth of 0–40 cm, with precipitation making the greatest contribution. Our results provide a basis for estimating and predicting SOC and STN concentrations in grasslands in arid regions with a mountain-basin structure.

Full Text

Characteristics of Soil Organic Carbon and Total Nitrogen Under Various Grassland Types Along a Transect in a Mountain-Basin System in Xinjiang, China

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Abstract

Soil organic carbon (SOC) and soil total nitrogen (STN) in arid regions are important components of global carbon and nitrogen cycles, and their response to climate change has significant implications for both ecosystem processes and global climate feedbacks. Grassland ecosystems in Fuyun County at the southern foot of the Altai Mountains are characterized by complex topography, suggesting substantial variability in the spatial distribution of SOC and STN. However, few investigations have examined SOC and STN in grasslands of arid regions with a mountain-basin structure. Therefore, we investigated the characteristics of SOC and STN across different grassland types in a mountain-basin system at the southern foot of the Altai Mountains, north of the Junggar Basin in China, and explored their potential influencing factors and relationships with meteorological factors and soil properties.

We found that SOC and STN concentrations and storages varied significantly among grassland types, showing a decreasing trend along an elevation gradient from alpine meadow, mountain meadow, temperate typical steppe, temperate steppe desert, to temperate desert steppe. Additionally, SOC and STN concentrations decreased with depth, except in temperate desert steppe. Pearson’ s correlation analysis and redundancy analysis revealed that mean annual precipitation, soil moisture content, and soil available nitrogen concentration were significantly positively correlated with SOC and STN concentrations, while mean annual temperature, pH, and soil bulk density were significantly negatively correlated. Mean annual precipitation and mean annual temperature were the primary factors regulating SOC and STN concentrations. The distributions of SOC and STN concentrations were strongly controlled by elevation-induced differences in meteorological factors. Mean annual precipitation and mean annual temperature together explained 97.85% and 98.38% of the total variation in SOC and STN concentrations, respectively, in the 0–40 cm soil layer, with precipitation making the greatest contribution. Our results provide a basis for estimating and predicting SOC and STN concentrations in grasslands of arid regions with a mountain-basin structure.

Keywords: mountain-basin system; grassland types; soil organic carbon; soil total nitrogen; meteorological factors; soil properties

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1 Introduction

The carbon (C) and nitrogen (N) cycles of terrestrial ecosystems have received increasing worldwide attention in recent decades due to their substantial roles in global climate change and ecosystem sustainability. Soils represent the largest terrestrial C pool and contribute to nitrous oxide (N_2O) emissions. Soil nitrogen can also profoundly impact ecosystem productivity and carbon sequestration. Therefore, a better understanding of the characteristics and controlling factors of soil C and N at both regional and global scales is critical for evaluating C and N cycles and for predicting soil C and N feedbacks to global climate change.

As one of the major terrestrial ecosystems, grasslands in China cover approximately 40% of the total land surface and represent 13% of global grasslands. Grasslands are the most important terrestrial C pools in China, with 41.03 Pg C stored in soils. During the past several decades, numerous studies on soil C and N have focused on grasslands at various scales in China, including site, transect, and national scales. However, most studies have assessed C and N storage values for specific grassland types, particularly temperate grasslands and alpine grasslands. Additionally, many studies have examined soil C and N in grasslands of Inner Mongolia and the Qinghai-Tibetan Plateau. Few studies have investigated SOC and STN storage variations among different grassland types at the southern foot of the Altai Mountains due to limited soil surveys and high spatial variability of soils in this arid region.

Arid regions cover approximately 12.0% of Earth' s land area. The distribution of alternating mountains and basins is a fundamental characteristic of natural geography in Central Asian arid ecosystems. Zhang (2001) defined this landform as a mountain-basin system (MBS). Therefore, grasslands in arid regions with an MBS structure represent an important component of global C and N cycles, and their response to climate change will have important implications for both ecosystem processes and global climate feedbacks.

Fuyun County lies in the arid region of Xinjiang, China, and represents a typical MBS, consisting of a vertical mountain vegetation gradient and a concentric annular vegetation gradient in a desert basin. This region provides an ideal setting for studying soil C and N cycles across different grassland types and their feedback interactions with global climate change. Investigating SOC and STN in the grassland ecosystems of Fuyun County can improve our understanding of grassland C and N cycles and provide guidance for assessing and predicting C and N storage in grasslands of arid regions. Thus, we studied the characteristics of SOC and STN and their relationships with meteorological factors and soil properties across different grassland types in Fuyun County through field investigations and sampling.

Soil C and N are often tightly coupled and significantly impacted by many factors, including climate, elevation, vegetation, and soil properties. Climate is commonly considered the most important factor regulating SOC and STN storage because it affects the balance of C and N inputs from soil organic matter and outputs through decomposition and mineralization. Precipitation affects SOC storage by constraining plant production and decomposition, especially in arid ecosystems. Some studies have shown that higher temperatures tend to accelerate microbial decomposition of soil organic matter, thereby causing C loss. In contrast, other studies have suggested that warming can lead to a net gain in SOC by promoting biomass input into the soil that exceeds the increase in decomposition. In most cases, SOC and STN increase with decreasing temperature and increasing precipitation. SOC and STN also change along elevation gradients, as different elevations are characterized by different climatic conditions. SOC generally increases with increasing elevation. In addition to climate, soil properties such as pH, bulk density, total phosphorus, and soil moisture content are also strongly related to SOC and STN.

Based on these findings, we hypothesize that SOC and STN values vary among grassland types and decrease with decreasing elevation. Furthermore, SOC and STN concentrations are correlated with meteorological factors and soil properties. Meteorological factors are decisive in the distributions of SOC and STN, and SOC and STN values increase with decreasing temperature and increasing precipitation. Our objectives are to (1) estimate SOC and STN concentrations, storages, and distribution characteristics across different grassland types along an elevation gradient, and (2) assess the relationships between temperature, precipitation, soil properties, and SOC and STN concentrations in this arid region.

2.1 Site Description

The study area in Fuyun County (45°00 -48°03 N, 88°10 -90°31 E) is shown in Figures 1 and 2. Located in a border region in the northern part of the Xinjiang Uygur Autonomous Region of China, it extends from the southern foot of the Altai Mountains to the northern margin of the Junggar Basin. The study area covers 32,186 km^2, with elevations ranging from 317 to 3863 m. It lies in the semi-arid and arid climatic belt of the temperate zone, with a mean annual temperature of 4.60°C (2007-2016) and mean annual precipitation of 208.41 mm (2007-2016). The Irtysh River and the Ulungur River originate from the

Altai Mountains and flow through Fuyun County.

The landscape encompasses complex landforms alternating between mountains and basins. Grassland is the main ecosystem type in this area, covering 87.46% of the total area, with grazing as the primary land use. According to China' s grassland resource classification system, there are ten grassland types in Fuyun County: alpine steppe, alpine meadow, mountain meadow, temperate meadow steppe, temperate typical steppe, temperate steppe desert, temperate desert steppe, lowland meadow, temperate desert, and swamp. Nomads migrate among different grasslands at various elevations according to the seasons to utilize grasslands with different conditions.

2.2 Sampling and Measurement Methods

We investigated the grassland ecosystem in July 2016 and established a transect from north to south. Our study was conducted along this transect across five natural grassland types: alpine meadow (AM), mountain meadow (MM), temperate typical steppe (TTS), temperate steppe desert (TSD), and temperate desert steppe (TDS) (Fig. 2). The spatial distances among plots in AM, MM, TTS, TSD, and TDS were 12.47, 68.73, 39.31, and 38.61 km, respectively. The plots were distributed along an elevation gradient decreasing from 2432 to 772 m. Four sampling plots (10 m × 10 m, with intervals of 500-1000 m) were investigated in each grassland type. In each plot, three soil profiles were selected in an S-shaped pattern, and three quadrats of 1 m × 1 m were established to investigate vegetation characteristics.

We collected core samples from all depth intervals using stainless steel tubes with a volume of 100 cm^3 (5.1 cm height and 5.0 cm diameter) to quantify bulk density. Soil samples were collected at depths of 0-10, 10-20, and 20-40 cm. We recorded vegetation species and coverage, then harvested aboveground biomass in each quadrat. All aboveground parts (green parts and litter) of individual species were cut, collected, and placed in envelopes. Aboveground biomass was measured by weighing plant parts after drying at 65°C to constant weight. Plot details are shown in Table 1 .

Temperature and precipitation data were obtained from the China Meteorological Data Sharing Service System. To avoid effects of extreme values in single years and reflect long-term means, we used annual temperature and precipitation data from 2007-2016 to calculate ten-year mean annual temperature (MAT, in °C) and mean annual precipitation (MAP, in mm) for meteorological stations in the Xinjiang Uygur Autonomous Region. To improve calculation accuracy, we applied the regression tree method, incorporating latitude, longitude, and topographic elements into climate data calculations. We used longitude (Lng, in °), latitude (Lat, in °), and altitude (Alt, in m) from 54 meteorological stations (elevations ranging from 34.5 to 3504.4 m) in the Xinjiang Uygur Autonomous Region to establish regression equations for temperature and precipitation, which were then used to estimate MAT and MAP for the five plots:

$$\mathrm{MAT} = -0.039 \times \mathrm{Lng} - 1.1095 \times \mathrm{Lat} - 0.005 \times \mathrm{Alt} + 64.204 \quad (R^2 = 0.848)$$

$$\mathrm{MAP} = -6.505 \times \mathrm{Lng} + 31.527 \times \mathrm{Lat} + 0.093 \times \mathrm{Alt} - 750.872 \quad (R^2 = 0.781)$$

SOC and STN were determined using a TOC-Analyzer (Multi N/C 3100, Analytik Jena AG, Germany) and the modified Kjeldahl method (Bao, 2005), respectively. Soil available nitrogen (AN) concentration was measured via the alkali diffusion method (Bao, 2005). Soil total phosphorus (STP) was fused with sodium hydroxide, and concentration was determined via Mo-Sb colorimetry. Soil pH was measured at a soil-water ratio of 1:2.5 (w:v) with a pH meter (SG2, Mettler Toledo, Switzerland). Soil bulk density (BD) was measured with a soil core sampler (Bao, 2005). Soil moisture content (SMC) was measured via the oven method. SOC storage (t/hm^2) and STN storage (t/hm^2) were calculated as follows (Xie et al., 2007):

$$\text{SOC storage} = \sum_{i=1}^{m} \mathrm{SOC}_i \times \mathrm{B}_i \times \mathrm{D}_i \times (1 - \theta\%) \times 0.1$$

$$\text{STN storage} = \sum_{i=1}^{m} \mathrm{STN}_i \times \mathrm{B}_i \times \mathrm{D}_i \times (1 - \theta\%) \times 0.1$$

where SOC , STN , B , and D are the SOC concentration (g/kg), STN concentration (g/kg), bulk density (g/cm^3), and thickness (cm) of the ith layer, respectively; % is the percentage of rock fragments >2 mm. The total volume of rock fragments accounted for far less than 10% in all samples and had negligible effects on calculations.

2.3 Statistical Analysis

Data followed a normal distribution based on normality tests. One-way analysis of variance (ANOVA) and least significant difference (LSD) tests were used to analyze differences in soil properties among the five grassland types. Analyses were performed using SPSS version 20.0 (IBM, Chicago, IL, USA). Correlations between SOC, STN, meteorological factors, and soil properties were calculated using Pearson' s correlation, and graphs were drawn using R (version 3.2.2). Redundancy analysis (RDA) is an alternative to canonical correlation analysis that examines relationships between two sets of X and Y variables, with statistical significance tested via Monte Carlo permutation. We used RDA to investigate the proportion of variability in SOC and STN explained by environmental variables. Eigenvalues are proportional to the total variance explained by each axis, extracted from soil variables as linear combinations of environmental attributes (Lepš and Šmilauer, 1988). RDA was performed using Canoco 4.5 software. Additionally, we applied a general linear model (GLM) to assess the integrative effects of meteorological factors on SOC and STN distribution, performed in SPSS version 20.0.

3.1 Concentrations and Storages of SOC and STN in Different Grassland Types

Figure 3 [Figure 3: see original paper] shows SOC and STN concentrations in different soil layers across grassland types. SOC concentrations in each soil layer decreased from AM, MM, TTS, TSD to TDS (Fig. 3a). STN concentrations showed a similar decreasing trend, except for MM at 0–10 cm depth (Fig. 3b). Both SOC and STN concentrations decreased with depth in all grassland types except TDS (Fig. 3). In AM, MM, TTS, and TSD, SOC and STN concentrations were significantly higher at 0–10 cm than at 10–20 and 20–40 cm depths (Fig. 3). Across the entire 0–40 cm soil layer, SOC and STN concentrations decreased among the five grassland types with decreasing elevation, with SOC values of 44.77, 35.85, 8.49, 5.89, and 2.26 g/kg (Fig. 4a [Figure 4: see original paper]) and STN values of 4.40, 4.27, 0.99, 0.51, and 0.15 g/kg, respectively (Fig. 4b).

Both SOC and STN storages decreased from AM to TDS. SOC and STN storages were significantly higher in AM and MM than in TTS, TSD, and TDS across all soil layers (Table 2). In the 0–20 cm layer, SOC storages of AM, MM, TTS, TSD, and TDS accounted for 56.3%, 60.9%, 60.8%, 59.1%, and 43.2%, respectively, of total SOC storage in the entire 0–40 cm layer; STN storages accounted for 58.1%, 63.7%, 59.4%, 56.5%, and 45.9%, respectively (Table 2). Thus, SOC and STN storages were greater in the 0–20 cm layer than in the 20–40 cm layer, except in TDS.

3.2 Soil Properties of Different Grassland Types

SMC values for AM, MM, TTS, TSD, and TDS were 20.68%, 28.25%, 8.15%, 5.18%, and 2.27%, respectively. SMC values in the 0–40 cm layer decreased with decreasing elevation from AM to TSD, except in MM (Fig. 5a [Figure 5: see original paper]). BD in the 0–40 cm layer increased from AM to TDS with decreasing elevation, except in MM (Fig. 5b). BD values for AM, MM, TTS, TSD, and TDS were 1.25, 1.15, 1.37, 1.70, and 1.74 g/cm^3, respectively. pH values for AM, MM, TTS, TSD, and TDS were 4.77, 5.02, 7.94, 8.61, and 8.33, respectively (Fig. 5c). AN concentration was highest in MM (283.83 mg/kg) and decreased from AM to TTS, TSD, and TDS (Fig. 5d). STP concentrations for the five grassland types were 0.48, 0.42, 0.60, 0.53, and 0.36 g/kg, respectively (Fig. 5e).

3.3 Correlations Among Meteorological Factors, Soil Properties, and SOC and STN Concentrations

Pearson' s correlation analysis revealed close relationships among SOC and STN concentrations, meteorological factors, and soil properties (Fig. 6 [Figure 6: see original paper]). SOC and STN concentrations exhibited significant positive correlations with MAP ($r = 0.933$, $P < 0.01$; $r = 0.938$, $P < 0.01$, respectively), AN ($r = 0.905$, $P < 0.01$; $r = 0.948$, $P < 0.01$, respectively), and SMC ($r = 0.875$, $P < 0.01$; $r = 0.922$, $P < 0.01$, respectively), and negative correlations with MAT ($r = -0.928$, $P < 0.01$; $r = -0.933$, $P < 0.01$, respectively), pH ($r = -0.931$, $P < 0.01$; $r = -0.946$, $P < 0.01$, respectively), and BD ($r = -0.809$, $P < 0.01$; $r = -0.846$, $P < 0.01$, respectively). SOC concentrations were also highly correlated with STN concentrations ($r = 0.977$, $P < 0.01$) (Fig. 6).

RDA was employed to assess factors best explaining variability in SOC and STN concentrations. Seven environmental factors were selected for RDA after unified data treatment: MAP and MAT representing meteorological factors, and five soil properties (AN, STP, BD, pH, and SMC). The RDA ordination accurately reflected relationships among SOC, STN, and environmental factors, yielding canonical coefficients for the two axes (Fig. 7 [Figure 7: see original paper]; Table 3). Monte Carlo permutation tests showed that eigenvalues for the first and second axes accounted for 92.5% of variation in SOC and STN ($P < 0.01$; Table 3). Axis 1 was positively correlated with AN, SMC, and MAP and negatively correlated with pH, BD, MAT, and STP. Axis 2 was positively correlated with AN, SMC, MAP, and STP but negatively correlated with other factors (Table 3; Fig. 7). Correlations and eigenvalues from RDA indicated that MAP and MAT were the main regulators of SOC and STN variation (MAP: $r_{axis1} = 0.94$, and MAT: $r_{axis1} = -0.93$, $P = 0.002$; Table 3).

Furthermore, we applied GLM to assess integrative effects of meteorological factors on SOC and STN concentration variation and determine the proportion of variability explained by MAT and MAP separately. Results showed that MAP and MAT together explained 97.85% and 98.38% of total variation in SOC and STN concentrations, respectively, in the 0–40 cm soil layer. MAP, as the most important meteorological factor, explained 54.83% and 54.79% of variation in SOC and STN concentrations, respectively, in the 0–40 cm layer (Table 4).

4.1 SOC and STN Variations Among Grassland Types and Soil Depths

Our study investigated SOC and STN concentrations and storages across different grassland types in the MBS of Fuyun County, Xinjiang, China. Regional-scale estimates of SOC and STN storage commonly use vegetation type as a reference. Vegetation is the primary source of SOC and STN and can significantly affect SOC and STN concentrations through variations in the quantity and quality of organic matter input into soil, resulting in different SOC and STN concentration and storage values. The grasslands of AM and MM primarily consist of gramineous and leguminous species with relatively high aboveground biomass, representing high grassland productivity. In contrast, TTS grassland primarily consists of short grasses and semi-shrub species with moderate aboveground biomass, while TSD and TDS grasslands are dominated by semi-shrub species and bunchgrasses with low aboveground biomass (Table 1). Shifts in aboveground biomass and species composition from AM to TDS (i.e., from higher to lower elevation) likely caused variation in C and N inputs from plant biomass to soils. Therefore, SOC and STN concentrations and storages decreased from AM to TDS in each soil layer, except for STN concentration in the 0-10 cm layer. The higher STN concentration in the 0-10 cm layer of MM compared to AM may be due to vegetation species composition. In addition to gramineous species, MM contained leguminous species (*Trifolium incarnatum*) capable of N fixation.

SOC and STN storages for 0-40 cm decreased from AM (208.83 and 20.16 t/hm^2, respectively), MM (146.64 and 16.92 t/hm^2, respectively), TTS (43.68 and 5.17 t/hm^2, respectively), TSD (37.84 and 3.36 t/hm^2, respectively), to TDS (16.47 and 1.09 t/hm^2, respectively). This trend agrees with the overall decreasing pattern in China, where median soil C storage values in alpine meadow, alpine steppe, temperate typical steppe, temperate deserted steppe, and temperate desert are 182, 170, 123, 87, and 62 t/hm^2, respectively, at 0-100 cm depth. Yang et al. (2007) estimated SOC storage in five Chinese biomes and showed the same decreasing trend (meadow > steppe > desert). Liu et al. (2012) observed that SOC and STN storages in alpine meadow (87.0 and 8.1 t/hm^2, respectively) were higher than in desert steppe (70.9 and 9.9 t/hm^2, respectively) and desert (43.9 and 6.8 t/hm^2, respectively) in the upper 1-m soil layer on the Qinghai-Tibetan Plateau. However, due to spatial heterogeneity, SOC and STN storages in our study differed from those in other regions. Although grassland types were similar, soil types and climate conditions differed substantially, both of which play important roles in determining SOC storage distributions.

Our results showed that, except in TDS, SOC and STN concentrations decreased with depth (Fig. 3), and total SOC and STN storages in the 0-10 and 10-20 cm layers were higher than in the 20-40 cm layer (Table 2). This finding agrees with observations on the Qinghai-Tibetan Plateau and other ecosystems. Topsoil is more readily affected by litter falling on the soil surface, while C and N inputs to subsoil primarily depend on migration from topsoil. In our study area, AM and MM typically exhibited thick humus layers, considered the most important soil C sink. However, this was not observed in TDS, where the 20-40 cm layer showed higher SOC and STN concentrations and storages. Liu et al. (2012) previously observed the same trend in desert steppe of the Qinghai-Tibetan Plateau. These results may be related to scarce vegetation and low plant coverage on the surface in TDS, resulting in low C input. Additionally, SOM decomposition in topsoil is enhanced by relatively higher temperatures. Low plant coverage and high temperature also result in lower topsoil moisture. Some studies have shown that low soil moisture favors belowground biomass allocation. Another possible reason is high sediment input, where fine sand and silt deposited on the surface frequently bury humic horizons of earlier soil formation beneath fresh sediment.

4.2 SOC and STN Relationships with Meteorological Factors

SOC and STN concentrations and storages decreased with decreasing elevation throughout the entire 40 cm soil profile (Fig. 4; Table 2), similar to previous studies in other regions. Previous research showed that MAP was positively correlated with SOC and STN concentrations, while MAT was negatively correlated. Our results are consistent with global-scale studies. However, consensus is lacking at regional scales. Yang et al. (2010) found that SOC concentration increased with MAT in Tibetan grasslands, while our study showed SOC and STN concentrations decreased with MAT but were significantly positively correlated with MAP (Figs. 6 and 7). In Fuyun County, temperature and precipitation differed among elevations. Our results indicated that variations in MAP and MAT along the elevation gradient controlled SOC and STN concentrations (Fig. 7; Table 3).

Temperature and precipitation affect SOM input from vegetation litter production and output through decomposition and mineralization. At high elevations, higher precipitation increases plant biomass, resulting in greater organic matter and nitrogen input. Additionally, SOM decomposition and mineralization are inhibited in low-temperature environments, resulting in soil C and N accumulation. In contrast, in low-elevation arid areas, higher temperature reduces plant water use efficiency by increasing evapotranspiration. Water deficit induced by higher temperature and lower precipitation may restrict plant growth. Furthermore, higher decomposition and mineralization rates from higher temperatures may accelerate SOC and STN concentration decreases. This effect was significant in Fuyun County, where vegetation growth is primarily limited by natural precipitation. GLM analysis suggested that precipitation explained a higher proportion of SOC and STN distribution than temperature (Table 4). These results imply that precipitation is a limiting factor for vegetation growth and productivity in the studied arid grassland ecosystem, as small precipitation increases may significantly enhance vegetation productivity, thus contributing to SOC and STN accumulation. The results showed that climate condition differences caused by elevation differences are the most important environmental factors affecting spatial heterogeneity of SOC and STN.

To simply estimate SOC and STN concentrations in arid regions with an MBS structure, we established predictive models based on MAP (in mm) and MAT (in °C):

$$SOC = 0.904 \times MAP - 0.919 \times MAT + 0.977$$

$$STN = 0.919 \times MAP - 0.933 \times MAT + 0.948$$

The equations effectively fit relationships between meteorological factors and SOC and STN concentrations, with R^2 values of 0.904 and 0.919, respectively.

4.3 SOC and STN Relationships with Soil Properties

The C cycle is closely linked with the N cycle through production and decomposition. Our results showed that STN concentration was significantly positively correlated with SOC concentration in the 0–40 cm soil layer across grassland types (Fig. 6) because the main N sources were litter, animal residue, biological nitrogen fixation, and organic matter.

AN was positively correlated with SOC and STN in this study (Fig. 6). AN includes inorganic N derived from SOM mineralization and organic N derived from SOM decomposition. Therefore, high SOM concentration is usually associated with high SOC, STN, and AN concentrations.

Our results indicated that SMC was positively correlated with SOC and STN (Fig. 6), consistent with previous studies. Anoxic decomposition of SOM tends to be inhibited under higher SMC conditions, resulting in SOC accumulation. Moreover, SMC affects N, as higher SMC can limit soil microbial activities, creating an environment unfavorable for mineralization and decomposition of soil organic nitrogen. Therefore, high SMC can lead to high STN concentration. In our study, SMC in the 0–40 cm layer decreased from AM to TDS with decreasing elevation, except in MM (Fig. 5a). MM did not follow the general trend because it was located in a valley through which the Irtysh River flowed. The riverbed had a gentle slope, broad channel, large runoff, and low current velocity, with a high groundwater table, resulting in higher SMC in MM.

Soil pH exhibited a significant negative correlation with SOC and STN (Fig. 6), consistent with other studies. Soil pH influences SOC and STN by regulating microbial structure, function, and activities. SOM decomposition is inhibited at lower pH values and accelerated at higher pH values. SOC, STN, and pH interact through meteorological factors. Cui et al. (2005) reported that topsoil pH is closely correlated with precipitation at large spatial scales in arid areas.

Our results indicated that pH was significantly negatively correlated with MAP (Fig. 6). Hence, high precipitation increased SOC and STN (Figs. 6 and 7) and promoted root system development. Consequently, more carbonic and organic acids were produced by root exudation and soil respiration, which may be responsible for pH decrease.

BD was significantly negatively correlated with SOC and STN concentrations in the 0-40 cm soil layer (Fig. 6), a relationship recognized by other studies. SOC and STN concentrations were negatively correlated with BD, possibly because mineralization of SOC and nitrification of ammonium nitrogen were suppressed in soils with high BD values. Low BD soil can store more SOC and STN, as these can be mobilized in porous soil spaces. Furthermore, higher biomass levels can produce more soil nutrients through decomposition, and soil BD was negatively correlated with soil nutrients. Lister et al. (2004) also reported that BD can be influenced by root development and soil microbial activities and would decrease under higher nutrient levels due to creation of more and larger soil pores. Additionally, BD in the 0-40 cm layer increased from AM to TDS with decreasing elevation, except in MM (Fig. 5b). Aboveground biomass was highest in MM, and a thick humus layer existed on the surface due to abundant litter and roots, resulting in a loose, porous soil structure (and thus lower BD) in MM.

STP was not correlated with SOC and STN in our study (Fig. 6), similar to findings in other regions. P is primarily derived from rocks, and its poor mobility results in relatively high independence from other nutrients. Its spatial distribution is highly heterogeneous, and influencing factors are complex. In addition to soil parent material, climate and biota also play important roles. Although STP concentrations have been associated with SOM, STP concentrations in our study showed no significant correlation with SOC or STN concentrations.

Our results accurately reflect SOC and STN concentration and storage characteristics across different grassland types along an elevation gradient and their relationships with meteorological factors and soil properties. This study effectively complements available data on regional SOC and STN concentrations and storage estimates for grasslands in arid regions with an MBS structure.

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5 Conclusions

In Fuyun County, SOC and STN varied significantly among grassland types. Our results indicated that SOC and STN concentration and storage values in the 0-40 cm soil layer decreased across the five grassland types along a decreasing elevation gradient and also decreased with increasing soil depth, except in TDS. SOC and STN concentration and storage values of different grassland types in Fuyun County exhibited obvious vertical zonation characteristics. Pearson' s correlation and RDA analysis showed that SOC and STN concentrations in the 0-40 cm soil layer were significantly positively correlated with MAP, SMC, and AN and negatively correlated with MAT, pH, and BD. SOC and STN concentrations were significantly affected by meteorological factors. MAP and MAT together explained 97.85% and 98.38% of total variation in SOC and STN concentrations, respectively, in the 0–40 cm soil layer. Moreover, MAP explained 54.83% and 54.79% of variation in SOC and STN concentrations, respectively, at 0–40 cm depth. Our results demonstrate that precipitation and temperature are simple and effective predictors of SOC and STN concentration and storage values in grasslands of arid regions with a mountain-basin system structure.

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Note: Figure translations are in progress. See original paper for figures.