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Research article

Environmental and management controls of soil carbon storage in grasslands of southwestern China

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A R T I C L E I N F O

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Topographical variation

A B S T R A C T

In order to predict the effects of climate change on the global carbon cycle, it is crucial to understand the environmental factors that affect soil carbon storage in grasslands. In the present study, we attempted to explain the relationships between the distribution of soil carbon storage with climate, soil types, soil properties and topographical factors across different types of grasslands with different grazing regimes. We measured soil organic carbon in 92 locations at different soil depth increments, from 0 to 100 cm in southwestern China. Among soil types, brown earth soils (Luvisols) had the highest carbon storage with $19.5 \pm 2.5\,kg\,m^{-2}$, while chernozem soils had the lowest with $6.8 \pm 1.2\,kg\,m^{-2}$. Mean annual temperature and precipitation, exerted a significant, but, contrasting effects on soil carbon storage. Soil carbon storage increased as mean annual temperature decreased and as mean annual precipitation increased. Across different grassland types, the mean carbon storage for the top 100 cm varied from $7.6 \pm 1.3\,kg\,m^{-2}$ for temperate desert to $17.3 \pm 2.9\,kg\,m^{-2}$ for alpine meadow. Grazing/cutting regimes significantly affected soil carbon storage with lowest value ($7.9 \pm 1.5\,kg\,m^{-2}$) recorded for cutting grass, while seasonal ($11.4 \pm 1.3\,kg\,m^{-2}$) and year-long ($12.2 \pm 1.9\,kg\,m^{-2}$) grazing increased carbon storage. The highest carbon storage was found in the completely ungrazed areas ($16.7 \pm 2.9\,kg\,m^{-2}$). Climatic factors, along with soil types and topographical factors, controlled soil carbon density along a soil depth in grasslands. Environmental factors alone explained about 60% of the total variation in soil carbon storage. The actual depth-wise distribution of soil carbon contents was significantly influenced by the grazing intensity and topographical factors. Overall, policy-makers should focus on reducing the grazing intensity and land conversion for the sustainable management of grasslands and C sequestration.

1. Introduction

Grasslands cover ~30–40% of the earth's land surface and with 20% of the global soil carbon pool, play an important role in the terrestrial C cycle (Jobbágy and Jackson, 2000; Schipper et al., 2007). In addition, they contain more soil C per unit area than the global average and often store carbon to a great depth (Jobbágy and Jackson, 2000). The soil organic carbon density (SOCD) is mass of C per unit area (Dorji et al., 2014). Additionally, quite small changes in these stores brought about by management methods (Bellamy et al., 2005; Davidson and Janssens, 2006) and shifts in temperature and precipitation (Allison and Treseder, 2008) can potentially alter the soil SOCD and the concentration of

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atmospheric CO_2. Recent studies showed that large areas of grassland in recent decades have experienced soil carbon loss due to anthropogenic activities such as cropland conversion and intensive grazing. Moreover, the present quantitative and mechanistic understanding of environmental and topographical controls on SOCD in the grassland ecosystems of China is still elusive. Most of the existing recent studies are focused on the chronological changes in SOCD along decades, which are based on data from the second national soil survey of China many years ago (1979–1986) and pay little attention to the grazing effect (Wang et al., 2003; Yu et al., 2005, 2009; Xie et al., 2007; Yang et al., 2007). Further, the C storage estimation remain controversial, such as SOCD decreased (Xie et al., 2007), increased (Piao et al., 2009) and no significant change (Fang et al., 2010; Yang et al., 2010). Therefore, it is important to update the estimates of carbon storage at regional, national, and global scales to help in predicting the future response of carbon storage under climate change and management scenarios.

The spatial and depth-wise distribution pattern of soil organic carbon (SOC) storage is significantly influenced by environmental factors such as mean annual temperature and precipitation (Li et al., 2010; Hobley et al., 2015; Ma et al., 2016) and topography (Du et al., 2014; Ma et al., 2016). Furthermore, soil temperature and rainfall are the major factors that are believed to regulate terrestrial C storage (Barron-Gafford et al., 2014). Wang et al. (2005) showed that the SOC storage decreases with increasing mean annual temperature (MAT) and increases with increasing mean annual precipitation (MAP) in forest and steppe ecosystems in China. However, Percival et al. (2000) found that SOC in New Zealand grasslands was only weakly correlated with temperature and precipitation across all soils and within each depth (along 1 m) of soil. These contrasting relationships among climatic factors and spatial and depth-wise distribution of SOC storage at global and regional levels make it difficult to accurately predict changes in SOC density under various climate change scenarios.

Several previous studies (Schindlbacher et al., 2010; Mishra and Riley, 2012; Duan et al., 2014) indicated that high-altitude regions tend to store large amounts of SOC owing to the decreased decomposition rates under very low-temperature condition. In addition, Lee et al. (2016) showed that SOC density increased across a latitudinal transect in East-Central Asia, particularly in northern latitudes. Besides, anthropogenic activities including the conversion of grasslands into cropland, grazing and regimes of cutting (after cutting, grasses were dried and stored for winter fodder) have significant impacts on grassland soil carbon density due to the change in C input through litter biomass and C fixation *via* photosynthetic activities (Liu et al., 2012).

Grasslands are one of the dominant landscapes in the People's Republic of China. Studies by Chen and Wang (2000) and Sun (2000) showed that grasslands accounted for 40% of the total land surface in China (4 million km^{-2}) and contribute 9–16% of total carbon (vegetation and soil) in the world's grasslands (Ni, 2002). Piao et al. (2009) reported that 28–35% of soil organic carbon (SOC) is stored in the southwest region of China. Yunnan province, situated in the southwest region, has diverse topographical features, including abundant natural grasslands that range from the southwestern tropical grasslands to the northwestern alpine grasslands. Grassland ecosystems in Yunnan province play a vital role in the regional carbon cycle (Zhang et al., 2017). In addition, Yunnan province is strongly affected by the East Asian monsoon, Indian monsoon, and cold air from the Qinghai-Tibet Plateau. For these reasons, mean annual precipitation and temperature vary greatly, making Yunnan province highly vulnerable to climate change (Xu et al., 2015). For similar reasons, Yunnan is an excellent locality for establishing relationships between ecological processes and climatic variables.

Assessing the storage and distribution of SOC in grassland soils is necessary to assess the future response of C sinks and C sequestration to global climate change. Our major objectives were: 1) to quantify SOC content and storage along a temperature and precipitation gradient across different grassland types and 2) to explain the variation and controlling factors such as soil type, topography, and grazing regimes on SOC density in the grasslands of Yunnan province. We hypothesize that topography and grassland types would be the most important factors affecting the SOC density in grassland ecosystems.

2. Materials and methods

2.1. Study site description

Yunnan province, located in southwestern China, has a total area of 3,94,000 km^2 and lies between 21°9′–29°15′N and 97°30′–106°E. The terrain declines steeply from the northwest to the southeast, and elevations vary from 500 to 6000 m (Fig. 1). The Yunnan Plateau unit is characterized by a relatively level ground surface with dispersed valleys, lakes, and basins. Generally, average temperatures in January (winter) range from 8 to 17 °C, and in July (summer) range from 21 to 27 °C. Mean annual rainfall varies from 600 to 2300 mm, with over half of the rain occurring between June and August.

Grasslands were classified mainly based on the vegetation and climatic condition (Ma et al., 2016). In order to explain the variations in SOCD in different types of grasslands, we grouped the soil data into five types: alpine meadows (AM), tropical shrub tussocks (TST), temperate deserts (TD), temperate meadow–steppes (TMS), and warm temperate shrub tussocks (WST). Dominant plant species occurring in different types of grasslands are listed in Table S1. Additionally, for the purpose of evaluating the spatial and depth-wise differences in SOC along topographical gradients, the data were grouped into different slope, altitudinal, latitudinal, and longitudinal gradients. The soil types were classified on the basis of the genetic soil classification system of China (GSCC) (CRGCST, 2001; Shi et al., 2006a & 2006b) as well as the WRB (World Reference Base for soil resources, IUSS Working Group WRB, 2006) system. To understand the variations in SOC storage in grasslands with different grazing intensity, we grouped the soil data into four types of disturbance regimes: cutting grass (CG), grazing prohibition (GP), seasonal grazing (SG) and yearlong grazing (YG). 'Grazing' here refers to domestic livestock only. The animals concerned are yak, cow, sheep, and goats. We also observed few horses grazing on sampling areas in grasslands of Shangri-La. Grazing types and intensities are based on interview with land-users/local residents, counting number of animals and amount of animal excreta (data not included). In yearlong grazing sites, the grazing is at a level of approximately 15–50 animals per hectare in nearby plots. According to the farmers and local residents, plots were not fertilized. The seasonality of grazing intensity varies from spring and autumn seasonal grazing to year-round. In other cases, grass is cut by the farmers and stored for use in winter. The grasslands were further grouped by different ranges of MAT (5–10 °C, 10–15 °C, 15–20 °C, and 20–25 °C) and MAP (0–500 mm, 500–1000 mm, 1000–1500 mm, 1500–2000 mm, and 2000–2500 mm) to explain the influence of MAT and MAP on SOC storage.

2.2. Soil sampling and analyses

Soil cores were collected from 92 sampling sites, each composed of larger than 7 ha of grassland, widely distributed in Yunnan province (Fig. 1). At each site, we selected a 100×100 m plot and five 1.0 m $\times$ 1.0 m subplots set equidistant along the diagonal line (Fig. S1). From each subplot, three soil pits were dug randomly to collect samples for physico-chemical analyses. From each soil pit, soil samples from 0 to 5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, 50–70 cm, and 70–100 cm were collected using a soil corer 5 cm in diameter. From each pit, 3 replicates of samples for each soil depth were collected and composited together to get one composite sample per depth. In total, there were 105 (5 sub-plots $\times$ 3 soil pit $\times$ 7 soil depth) soil samples from each site. In addition, intact soil cores of each depth also collected for bulk density determination and pH (soil: water = 1:5). In the laboratory, soil samples were air-dried and passed through a 2 mm sieve to remove

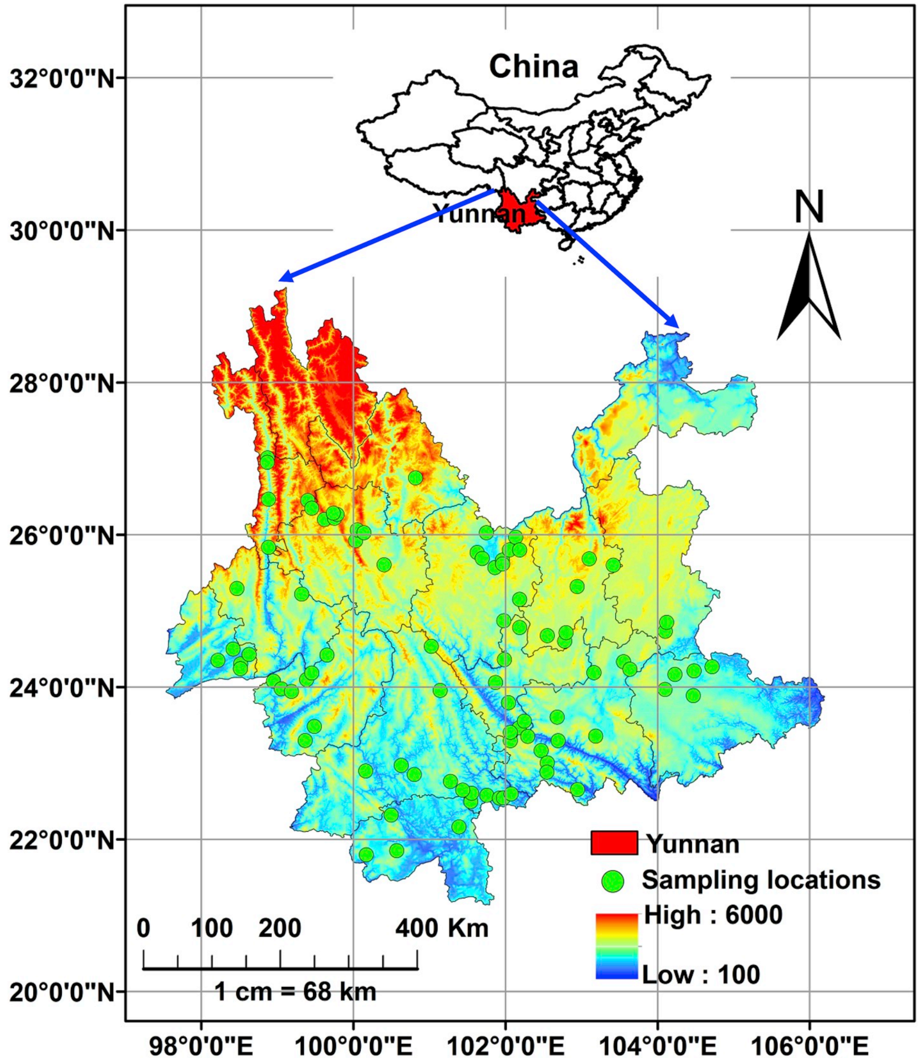

Fig. 1. Study site and soil sampling locations in Yunnan Province, Southwest China.

adhering coarse living roots, soil fauna, and stones. The stones remaining on the 2-mm sieve were manually separated and weighed. The mass-based >2 mm content was converted to a volumetric equivalent (Cools and De Vos, 2010). Subsequently, they were ground with a mill and passed through a 0.149 mm mesh sieve before chemical analyses. The carbon and nitrogen content was determined with a Vario EL III element analyzer (Elementar, Germany). Despite one of the important C pools, carbonates have the longest turnover time (Monger and Gallegos, 2000). Inorganic forms of carbon are mainly controlled by precipitation, soil acidity, and soil leaching potential (Lal, 2008; Yang et al., 2012). In the present sampling sites, the soil receives high rainfall (>900 mm) and thereby, soluble carbonates could be removed continuously by leaching. In addition, high soil acidity could prevent the accumulation of inorganic forms of carbon (Eswaran et al., 2000; Mi et al., 2008). Even though some carbonates may re-precipitate following leaching, its contribution to net C sequestration potential is insignificant (Lal, 2008; Monger and Gallegos, 2000). Hence, we focused mainly on SOC storage in grasslands.

2.3. Soil carbon density calculation and statistical analysis

SOC density was calculated for an individual soil profile with i interval depth layers as

$$SOCD = ST_i{*}SBD_i{*}SOC_i{*}[1-(F_i/100)]{*}0.01 \tag{1}$$

where $SOCD$ is SOC density (kg m^{-2}), ST_i is the soil thickness (cm) of interval depth i (0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, 50–70 cm, and 70–100 cm), SBD_i is the soil bulk density (g cm^{-3}) of interval depth i, SOC_i is the SOC (g C kg^{-1}) at interval depth i, F_i is the percentage of the volume fraction > 2 mm (gravel fragments) in interval depth i, and and 0.01 is unit conversion factor.

The data were subjected to homogeneity of variance and normality test at the 5% level before statistical analyses. The mean values were calculated for each group of grassland types, grazing regimes, soil types, climate variables (MAT and MAP), and topographical variables (altitude, slope position, and slope inclination) for each soil depth. Further, an analysis of variance (ANOVA) and multiple comparisons was performed to evaluate whether mean SOC storage significantly (at $p = 0.05$) influenced by different grassland types, grazing regimes, soil types, climate and topographical variables, and their interaction with soil depth. Further, multiple comparisons were used to determine Fisher's least significant difference (LSD). In order to find the best fit model that explains relationship between SOCD and the environmental variables (altitude, MAT, MAP, and pH), we applied different models such as linear, logarithmic, polynomial, power and exponential using the STATISTICA 8.0 and the best fit models were selected on the basis of higher significant coefficient of determination (R^2). Correlations coefficient amongst different climate variables (MAT and MAP) and topographical variables (altitude, slope position, and slope inclination) for each soil depths were calculated using Pearson's correlation coefficient (r). All the figure makings and data analysis were done with appropriate statistical methods using STATISTICA 8.0, R (R Development Core Team, 2012), and Microsoft Excel 2010.

3. Results

3.1. Influence of soil types on soil carbon storage

An overview of mean SOC contents and SOCD across different soil types along different soil depth increments in the top 1 m of soil depth is presented in Fig. S2 and Table 1. Among soil types, brown earth soil and meadow soil had the higher mean SOC contents (17.3 ± 1.9 and 15.6 ± 1.5 g kg^{-1}) and SOCD (19.5 ± 2.5 and 17.8 ± 2.1 kg m^{-2}), while sierozem and chernozem had the lowest carbon contents (0.9 ± 0.1 and 1.5 ± 0.4 g kg^{-1}) and SOCD (7.2 ± 1.4 and 6.8 ± 1.3 kg m^{-2}) values, respectively (Fig. S2 and Table 1). The significant interaction effect of soil types and soil depths on SOC contents ($F = 98.1$) and SOCD ($F = 20.1$) reveals that soil types can potentially influence the SOC storage in deeper soil layers (Fig. S2 and Table 1).

3.2. Relationship between topography, climate, and soil carbon storage

SOC contents ($F = 98.1$) and SOC density ($F = 36.0$) in all soil depths significantly ($p < 0.05$) increased with altitude (Fig. S3 and Fig. 2). Further, the SOC contents ($F = 20.6$) and SOCD ($F = 7.0$) under different altitudinal ranges were significantly ($p < 0.05$) influenced by soil depth (Fig. S3 and Fig. 2). The interaction between altitude and soil depth on SOC contents ($F = 98.1$) and SOCD ($F = 20.1$) was also significant ($p < 0.05$) (Fig. S3 and Fig. 2).

The SOC contents ($F = 180.6$, $p < 0.05$) and SOCD ($F = 30.7$, $p < 0.05$) at different soil depths were significantly decreased by MAT (Fig. S4a and Fig. S5). Besides, within different MAT gradients, SOC contents ($F = 53.5$, $p < 0.05$) and SOCD ($F = 61.2$, $p < 0.05$) significantly differed with soil depth intervals. The interaction of MAT with soil depth also had a significant effect on SOC contents ($F = 21.1$, $p < 0.05$) and SOCD ($F = 9.5$, $p < 0.05$) (Fig. S4a and Fig. S5). In contrast to MAT, SOC contents ($F = 147.3$, $p < 0.05$) and SOCD ($F = 52.1$, $p < 0.05$) were significantly increased with increasing MAP (Fig. S4b and Fig. S5). SOC contents were significantly greater ($F = 69.0$, $p < 0.05$) in the surface soil layer (0–30 cm) and decreased with soil depth (Fig. S4b). SOCD significantly ($F = 17.8$, $p < 0.05$) increased with soil depth in all MAP ranges (Fig. S5). In addition, SOC contents ($F = 103.7$) and SOCD ($F = 17.8$) were significantly ($p < 0.05$) affected by the interaction between MAP and soil depth intervals (Fig. 3 and Fig. S5).

Table S2 shows that slope inclination (SOC, $F = 59.2$; SOCD, $F = 10.0$) and slope position (SOC, $F = 33.9$; SOCD, $F = 15.6$) have significantly ($p < 0.05$) affected soil carbon content and storage. Further, soil carbon content and storage were significantly ($p < 0.05$) varied with soil depths (slope inclination: SOC, $F = 70.2$; SOCD, $F = 5.6$; and, slope position: SOC, $F = 18.1$; SOCD, $F = 6.9$) and its interaction with slope inclination (SOC, $F = 19.1$; SOCD, $F = 46.2$) and position (SOC, $F = 24.0$; SOCD, $F = 31.2$) (Table S2). Carbon storage was higher at lower slopes compared with middle and upper slopes. Similarly, when compared along slope inclination gradients, carbon storage was lower in 41–70° and higher in 0–20° slope (Table S2). The slope position exhibited a significant ($p < 0.001$) negative correlation with SOC and SOCD in the top 50 cm soil depth (Table S2).

The correlation between SOC contents, SOCD, and environmental factors are shown in Fig. 3a–d and Table S3. Soil pH had significant ($p < 0.001$) negative relationship with SOC contents and SOCD (Fig. 3d), while total nitrogen showed significant ($p < 0.001$) positive correlations across soil depths (Table S3). Remarkably, we found that the correlation coefficients of SOC contents and SOCD with topographical and environmental factors decreased with soil depth, where higher correlations coefficients confined only to top 0–30 cm soil depth (Table S3). Polynomial models are one of the most common models used in many previous studies SOCD modeling and they are highly useful in determining which factors drive SOC storage in range of soil types and its direction of response. In the present study, the polynomial model was found to have better fit in describing the relationships between SOCD and environmental variables compared to other models (Fig. 3a–d and Table 2). The polynomial model revealed that MAT, MAP elevation and soil properties pH) together explained about 62% of the variation in SOCD (Table 2).

3.3. Effects of grassland type and grazing regimes on SOCD

SOC contents were significantly varied with grassland types ($F = 77.6$; $p < 0.05$) and soil depth ($F = 12.1$; $p < 0.05$) (Table 3). Generally, for 1 m soil depth, soil carbon density is increased in grassland types in the following order: alpine meadow (17.3 ± 2.9 kg m^{-2}), temperate meadow steppe (14.7 ± 1.2 kg m^{-2}), tropical shrub tussock (11.1 ± 1.5 kg m^{-2}), warm temperate shrub tussock (9.6 ± 0.9 kg m^{-2}) and temperate desert (7.7 ± 0.9 kg m^{-2}), and significantly varied amongst different grassland types ($F = 190.2$; $p < 0.05$) and soil depth intervals ($F = 69.7$; $p < 0.05$) (Table 3). In addition, there was a significant ($p < 0.05$) interaction between grassland types and soil depths on SOC ($F = 49.3$) and SOCD ($F = 15.9$) (Table 3). Across of grassland types, the top 20 cm layer store about 60%, and the top 0–50 cm layer significantly ($F = 8.1$; $p < 0.05$) contributed almost 80% of the total carbon and the contribution was not significant ($F = 0.9$; $p > 0.05$) between different grassland types (Fig. S6). Our results further showed that the sub-soil layer (70–100 cm) also stored 5–10% of total soil carbon, particularly in high-altitude grasslands (Fig. S3).

Table 1
SOC storage in different soils types in grasslands of Yunnan province, SW China.

GSCC soil great group	WRB reference soil group	Soil depth/SOCD (kg m^{-2})						
		0–5 cm	5–10 cm	10–20 cm	20–30 cm	30–50 cm	50–70 cm	70–100 cm
Dark brown soil (*n=15*)	Cambisols	1.69 ± 0.04^c	0.88 ± 0.02^d	0.35 ± 0.01^e	0.28 ± 0.01^e	2.87 ± 0.15^a	2.40 ± 0.12^b	2.88 ± 0.08^a
Brown earth soil (*n=17*)	Luvisols	1.50 ± 0.07^e	1.02 ± 0.03^f	2.56 ± 0.12^d	2.42 ± 0.11^d	3.41 ± 0.23^c	3.93 ± 0.18^b	4.70 ± 0.20^a
Chernozem (*n=6*)	Chernozems	0.14 ± 0.02^d	0.21 ± 0.01^d	0.28 ± 0.01^d	0.23 ± 0.01^d	1.64 ± 0.05^b	1.37 ± 0.01^c	2.96 ± 0.11^a
Chestnut soil (*n=5*)	Kastanozems	1.04 ± 0.04^e	0.87 ± 0.03^f	2.16 ± 0.10^c	1.77 ± 0.08^d	2.72 ± 0.12^b	2.53 ± 0.09^b	3.36 ± 0.17^a
Aeolian sandy soil (*n=5*)	Arenosols	1.47 ± 0.05^a	0.97 ± 0.02^b	1.50 ± 0.09^a	1.43 ± 0.05^a	1.28 ± 0.07^a	0.62 ± 0.02^b	0.82 ± 0.02^b
Brown calcic soil (*n=10*)	Cambisols	1.19 ± 0.06^d	1.27 ± 0.05^d	1.90 ± 0.07^c	1.81 ± 0.08^c	2.02 ± 0.11^b	2.16 ± 0.10^b	2.58 ± 0.13^a
Grey calcic soil (*n=4*)	Cambisols	0.92 ± 0.01^d	0.61 ± 0.01^e	1.12 ± 0.09^c	0.96 ± 0.02^d	1.90 ± 0.07^a	1.61 ± 0.06^b	2.01 ± 0.06^a
Meadow soil (*n=21*)	Cambisols	2.38 ± 0.14^c	1.79 ± 0.09^e	2.08 ± 0.15^d	2.01 ± 0.13^d	2.60 ± 0.13^b	2.72 ± 0.15^b	4.17 ± 0.24^a
Sierozem (*n=4*)	Cambisols	0.11 ± 0.01^e	0.08 ± 0.00^e	0.91 ± 0.01^c	0.80 ± 0.02^c	1.67 ± 0.07^b	0.50 ± 0.01^d	3.12 ± 0.17^a
Volcanic ash soil (*n=5*)	Andosols	1.23 ± 0.06^e	1.51 ± 0.06^d	2.63 ± 0.12^a	1.94 ± 0.15^c	2.10 ± 0.09^b	1.89 ± 0.07^c	2.01 ± 0.09^b
		Soil type (ST)		**Soil depth (SD)**		**ST*SD**		
F values at $p < 0.05$		95.87		14.08		31.20		

Values are mean ± standard error; **GSCC** – Genetic Soil Classification of China; **WRB** – World Reference Base for soil resources.
Different lower-case letters indicate significant differences at $p < 0.05$.

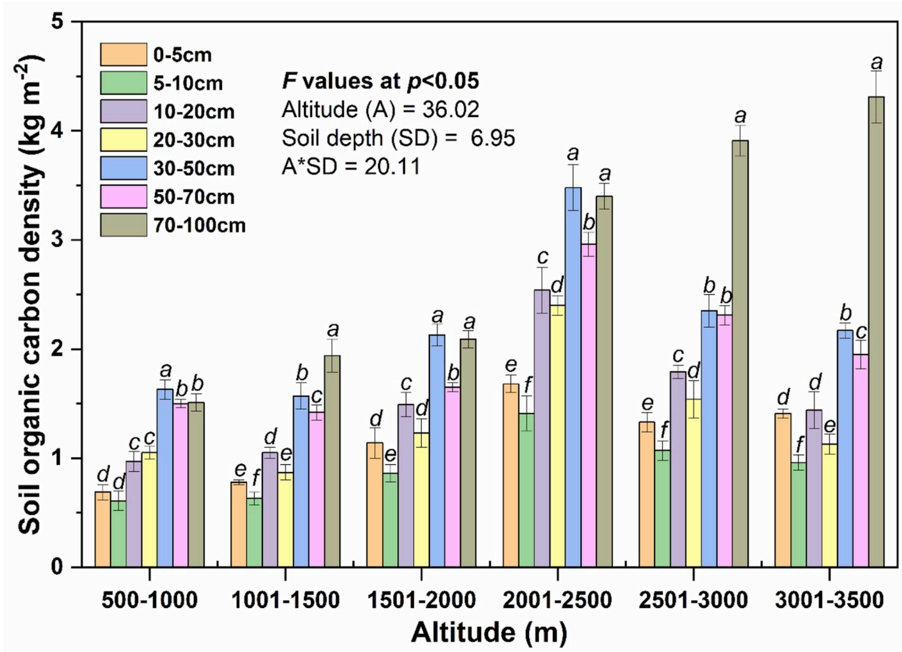

Fig. 2. Soil organic carbon density (kg m^{-2}) along altitudinal gradients in different soil depth increments in Yunnan province, SW China. Different lower-case letter indicates that values are significant at p = 0.05.

The results showed that carbon storage was significantly ($p < 0.05$) affected by different grazing regimes (Table 3). The soil carbon contents and SOCD followed the order of GP > YG > SG > CG (Table 3). SOCD under grazing prohibited grasslands (16.7 ± 2.9 kg m^{-2}) in the top 1 m of soil was significantly ($F = 20.5$, $p < 0.05$) higher than the other grazing regimes. Additionally, the interaction of grazing regimens with soil depth significantly ($F = 107.1$, $p < 0.05$) affected the distribution of SOCD along soil depth intervals (Table 3). Grasslands with cutting regimes had the lowest C storage with the values of 7.9 ± 1.5 kg m^{-2}. Interestingly, grasslands under year-long grazing had a higher SOCD (12.2 ± 1.8 kg m^{-2}) than seasonally grazed grasslands (11.4 ± 0.6 kg m^{-2}) for the top 1 m of soil.

4. Discussion

4.1. Influence of soil types

Soil types may potentially affect soil carbon storage (Zinn et al., 2005; Mayes et al., 2014). However, soil types are not the only single factor that directly controls the SOC storage, but along with the other factors such as climatic and topographical settings, soil type can influence the C storage capacity of soil (He and Zhang, 2005; Wiesmeier et al., 2015). The underlying mechanisms of variations in soil carbon contents and storage in each soil types could be due to land-use, vegetation types and different processes involved in soil organic matter stabilization, rather than the direct effect of soil types (Liu et al., 2007; Li et al., 2012). The factor soil parent material can also strongly influence SOC storage by affecting soil mineralogy and fertility which in turn determine the soil type (Hobley et al., 2015; Wiesmeier et al., 2015). Apparently, Zinn et al. (2005) for Brazilian Cerrado soils reported that soil carbon storage largely depends on the soil type as soil organic matter turnover process differs among soil types which results in variations SOC content. Consistently, the higher SOC contents and SOCD in brown earth soils (Luvisols) and meadow soil (Cambisols) in our study could be associated with topographical situation of these soils with grass species diversity and functional composition, and moderate precipitation (Hobley et al., 2015; Johnson et al., 2015; Wiesmeier et al., 2015). Moreover, soil type had a strong influence on both surface and sub-surface soil SOCD and that could be associated with variations in drainage and organic matter stabilization process in different soil types (Jobbágy and Jackson, 2000; Johnson et al., 2015). The significant interaction effect between soil types and soil depth on SOC contents and SOCD suggests that they can potentially influence SOC density in the deeper soil layers (Hobley and Wilson, 2016). Evidently, several previous studies revealed the effect of soil type on SOC storage along soil depths (Hobley et al., 2015; Hobley and Wilson, 2016). Increasing SOCD along soil depths could be attributed to differences in soil thickness (increment) sampled and bulk density. Overall, the variations in SOC contents and SOCD amongst different soil types in the present study could be mainly attributed to the combined influences of land-use (grassland types and grazing regimes), climate (MAT and MAP) and topography (altitude, slope).

4.2. Influence of soil properties, topography, and climate

Soil pH was negatively associated with soil carbon contents and storage across different soil types. At low pH soil, microbial activities inhibited and thereby increasing soil carbon accumulation (Chen et al., 2018). Previously, Chen et al. (2018) and Funakawa et al. (2014) showed significant relationship between soil carbon contents soil pH.

High-altitude grasslands stored more carbon when the temperature ranged from 5 to 10 °C. The lower temperature in high-altitude grasslands leads to a slower decomposition rate and thus soil carbon accumulation (Davidson and Janssens, 2006). Temperature and precipitation are principal factors affecting soil carbon density (Jobbágy and Jackson, 2000; Mao et al., 2015). Strong negative relationships were observed between SOCD and MAT at all soil depths, which could be probably due to counterbalance between inputs and outputs of soil organic matter. Duan et al. (2014) also stipulated that soil carbon densities were highest when the annual temperatures ranged from 0 to 2 °C. MAT in alpine and temperate grasslands ranged between 0–5 °C and 5–10 °C and had higher carbon storage. Yang et al. (2007) also reported a negative relationship between MAT and soil carbon storage.

In contrast with MAT, MAP showed a strong positive correlation with soil carbon density. Meersmans et al. (2011) found a similar increase in carbon in Belgian grasslands, under very wet climate conditions with

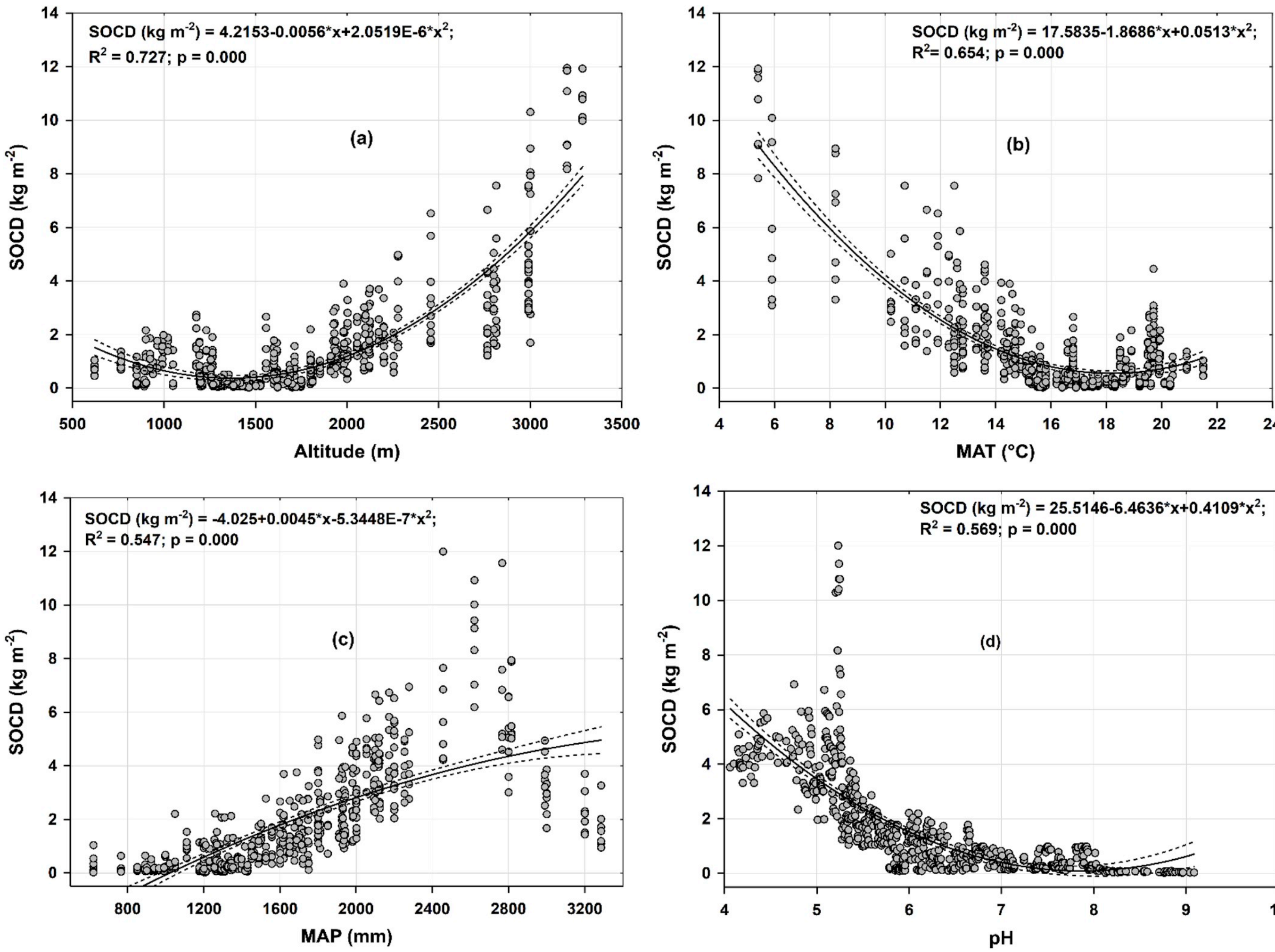

Fig. 3. Relationships between SOC density (SOCD) in top 1 m soil depth and altitude (**a**), mean annual temperature (**b**), mean annual precipitation (**c**) and soil pH (**d**) in grasslands of Yunnan province, SW China.

Table 2
R^2 of different regression models for SOCD.

Parameters	Linear	Exponential	Logarithmic	Power	Polynomial
Altitude	0.509**	0.383*	0.365*	0.282*	0.727***
MAT	0.453**	0.276*	0.556**	0.298*	0.654***
MAP	0.491**	0.406*	0.512**	0.427*	0.547**
BD	0.573**	0.612***	0.596**	0.579**	0.638***
pH	0.470**	0.526**	0.509**	0.541**	0.569**
C:N	0.532**	0.518**	0.472**	0.498**	0.551**

MAT, mean annual temperature; **MAP**, mean annual precipitation; **C:N**, carbon to nitrogen ratio; Relationship is significant at $***p < 0.001$; $**p < 0.01$; $*p < 0.05$.

precipitation between 900 and 1100 mm. Correspondingly, our results and findings of Jobbágy and Jackson (2000) revealed that soil C storage increases with increasing precipitation. This could be due to faster growth and activity of soil microorganisms and grass biomass production under moderate precipitation, which leads to a higher decomposition rate (high litter turnover) and thus an accumulation of carbon through offset between litter input and decomposition (Zhou et al., 2009). The underlying mechanism behind this phenomenon could be that under moderate rainfall conditions soils were anaerobic and poorly drained, which in turn enhances the accumulation and transportation of SOC across deeper soil layers (Schuur et al., 2001). In addition, C inputs in the form of grass biomass significantly increase with precipitation. Similarly, lowest SOC density registered with precipitation regimes of 0–500 and 500–1000 mm could be attributed to decreased plant C input, mainly due to lower net primary production. Interestingly, we found that carbon density decreased when MAP ranged between 2000 and 2500 mm. This could be related to increased carbon leaching (in the form of dissolved organic carbon) and microbial decomposition under extreme precipitation (Li et al., 2013). Moreover, extreme precipitation potentially increases soil respiration and leaching, resulting in rapid loss of C and thus less SOC preservation (Liu et al., 2018). Decreasing soil carbon under higher precipitation regime also reported in several other studies (Meier and Leuschner, 2010; Liu et al., 2012).

Topography in Yunnan province varied along latitude (21°N–27°N) and longitude (98°E−105°E) gradients. Despite the close relationship between carbon storage and altitudinal gradients, the SOCD had an inconsistent distribution pattern along different latitudinal and longitudinal gradients. This may be due to the variations in SOC storage in response to local land-use management, vegetation, soil type, and the prevailing climate. Wang et al. (2001) reported an increasing pattern of soil carbon with a decrease of latitude in western China. Later, Wang et al. (2005) reported that soil carbon storage increased with increasing longitude along the Northeast China transect. In spite of the lack of correlation among latitude, longitude and carbon density, distribution of soil carbon was strongly associated with altitude and slope features. Soil carbon density was greater in high-altitude northern regions of Yunnan and low in the tropical southern plateau regions.

Although temperature and rainfall decrease with increasing

Table 3
SOC and SOCD under different grassland types and grazing regimes in Yunnan province, SW China.

Environmental factors	Soil depth/SOCD (kg m^{-2})						
	0–5 cm	5–10 cm	10–20 cm	20–30 cm	30–50 cm	50–70 cm	70–100 cm
Grassland types							
SOC (g kg^{-1})							
Alpine meadows *(n=4)*	24.30 ± 4.37^{a}	18.71 ± 3.83^{b}	16.31 ± 1.50^{c}	12.45 ± 2.45^{d}	12.33 ± 3.68^{d}	11.54 ± 1.63^{e}	10.76 ± 1.12^{f}
Temperate deserts *(n=3)*	9.65 ± 1.05^{a}	7.52 ± 0.33^{b}	6.14 ± 1.67^{c}	4.25 ± 0.56^{d}	2.51 ± 0.83^{e}	2.70 ± 0.45^{e}	2.04 ± 0.45^{f}
Temperate meadow–steppes *(n=27)*	18.27 ± 2.91^{a}	16.57 ± 1.76^{b}	15.41 ± 4.52^{c}	12.44 ± 3.73^{d}	9.87 ± 2.02^{e}	7.48 ± 1.46^{f}	6.65 ± 1.78^{g}
Tropical shrub-tussocks *(n=46)*	15.63 ± 3.57^{a}	11.45 ± 1.27^{b}	9.95 ± 1.09^{c}	6.89 ± 1.80^{d}	6.06 ± 1.17^{e}	5.66 ± 1.60^{f}	4.81 ± 1.44^{g}
Warm temperate shrub-tussocks *(n=12)*	9.68 ± 1.54^{a}	8.16 ± 2.87^{b}	6.41 ± 0.55^{c}	4.66 ± 0.45^{d}	4.02 ± 1.25^{e}	2.99 ± 0.79^{f}	2.55 ± 0.98^{g}
SOC (g kg^{-1})	***Grassland types (T)***		***Soil depth (SD)***		***T*SD***		
F values at $p < 0.05$	77.54		12.05		49.26		
SOCD (kg m^{-2})							
Alpine meadows *(n=4)*	1.86 ± 0.08^{f}	1.04 ± 0.11^{e}	2.06 ± 0.16^{d}	2.07 ± 0.12^{d}	3.48 ± 0.28^{b}	2.94 ± 0.13^{c}	3.88 ± 0.25^{a}
Temperate deserts *(n=3)*	0.67 ± 0.06^{d}	1.39 ± 0.18^{b}	1.24 ± 0.09^{b}	0.88 ± 0.18^{c}	0.97 ± 0.07^{c}	1.50 ± 0.15^{a}	0.91 ± 0.08^{c}
Temperate meadow–steppes *(n=27)*	1.29 ± 0.09^{e}	0.95 ± 0.12^{f}	1.95 ± 0.13^{d}	1.90 ± 0.18^{d}	2.79 ± 0.20^{b}	2.26 ± 0.11^{c}	3.57 ± 0.25^{a}
Tropical shrub-tussocks *(n=46)*	1.00 ± 0.05^{e}	0.61 ± 0.09^{f}	1.38 ± 0.15^{d}	1.07 ± 0.14^{e}	2.12 ± 0.19^{b}	1.81 ± 0.16^{c}	3.16 ± 0.28^{a}
Warm temperate shrub-tussocks *(n=12)*	1.04 ± 0.05^{d}	0.63 ± 0.04^{f}	1.13 ± 0.08^{d}	0.91 ± 0.05^{e}	1.74 ± 0.16^{b}	1.36 ± 0.15^{c}	2.77 ± 0.24^{a}
SOCD (kg m^{-2})	***Grassland types (T)***		***Soil depth (SD)***		***T*SD***		
F values at $p < 0.05$	190.20		69.73		15.90		
Grazing intensity							
SOC (g kg^{-1})							
Grass cutting *(n=12)*	9.41 ± 1.82^{a}	6.54 ± 1.86^{b}	4.99 ± 1.32^{c}	3.88 ± 1.18^{d}	3.10 ± 1.01^{e}	2.55 ± 0.74^{f}	2.51 ± 0.80^{f}
Grazing prohibited *(n=3)*	24.05 ± 4.43^{a}	20.32 ± 4.13^{b}	17.10 ± 3.50^{c}	12.01 ± 3.01^{d}	11.28 ± 2.75^{e}	11.17 ± 2.16^{e}	10.62 ± 1.51^{f}
Seasonal grazing *(n=30)*	12.08 ± 2.25^{a}	7.98 ± 1.44^{b}	5.74 ± 1.95^{c}	3.90 ± 0.22^{d}	3.65 ± 1.44^{e}	2.79 ± 0.45^{f}	2.74 ± 0.78^{f}
Year-long grazing *(n=47)*	16.29 ± 1.62^{a}	14.09 ± 3.10^{b}	12.45 ± 1.09^{c}	11.78 ± 2.02^{d}	9.92 ± 1.69^{e}	7.28 ± 1.48^{f}	5.38 ± 0.92^{g}
SOCD (kg m^{-2})	***Grazing intensity (I)***		***Soil depth (SD)***		***I*SD***		
F values at $p < 0.05$	93.07		105.49		31.85		
SOCD (kg m^{-2})							
Grass cutting *(n=12)*	0.62 ± 0.03^{e}	0.42 ± 0.03^{f}	1.27 ± 0.10^{c}	1.04 ± 0.08^{d}	1.65 ± 0.13^{b}	0.94 ± 0.06^{d}	2.04 ± 0.16^{a}
Grazing prohibited *(n=3)*	1.71 ± 0.19^{d}	1.48 ± 0.09^{e}	1.77 ± 0.18^{d}	1.69 ± 0.10^{d}	3.34 ± 0.11^{b}	2.78 ± 0.13^{c}	3.90 ± 0.21^{a}
Seasonal grazing *(n=30)*	0.95 ± 0.07^{e}	0.63 ± 0.09^{f}	1.82 ± 0.15^{c}	1.45 ± 0.07^{d}	2.07 ± 0.14^{b}	1.79 ± 0.15^{c}	2.66 ± 0.20^{a}
Year-long grazing *(n=47)*	1.41 ± 0.05^{d}	1.15 ± 0.13^{e}	1.34 ± 0.12^{d}	1.29 ± 0.05^{d}	1.81 ± 0.09^{c}	2.37 ± 0.18^{b}	2.83 ± 0.19^{a}
SOCD (kg m^{-2})	***Grazing intensity (I)***		***Soil depth (SD)***		***I*SD***		
F values at $p < 0.05$	20.51		71.16		107.12		

Values are mean ± standard error. Different lower-case letters indicate significant differences at $p < 0.05$.

altitudes, grassland growth, and productivity are not affected (Li and Walker, 1986; Duan et al., 2014). Hence, biomass and C input from litter countermand the environmental factors to increase C storage in high-altitude grasslands (Duan et al., 2014). Further, quantity and quality of plant litters and the rate of decomposition control the carbon storage along altitudinal gradients (Trumbore, 2000). Altitude influences temperature, precipitation and vegetation, and thereby affecting the soil physic-chemical properties that control the soil carbon storage. In general, the pattern of C density is consistent with the climatic-zone gradients corresponding to different grassland types. Many previous studies also reported a significant correlation between soil carbon storage and altitudinal gradients (Tashi et al., 2016; Tsui et al., 2013). Overall, grassland C storage is controlled by factors such as prevailing climate, topography and monsoonal influence apart from the altitudinal, latitudinal and longitudinal gradients.

The slope can affect the soil carbon storage and distribution pattern by controlling the movement of soil water and organic matter across soil layers and slope directions (Dorji et al., 2014; Hao et al., 2002). Our results revealed significant variations in soil carbon storage along slope position and inclination (°). Higher carbon storage at lower slopes (ranging from 1.3 ± 0.1 to 3.9 ± 0.2 kg m^{-2}) compared with middle (0.9 ± 0.05 to 3.1 ± 0.1 kg m^{-2}) and upper slopes (0.6 ± 0.02 to 1.7 ± 0.2 kg m^{-2}) could be attributed to soil erosion, quality and quantity of litter additions, nutrient retention capacity and different grazing related/land management practices. Similarly, slope inclination significantly affected the depth-wise distribution of carbon content and density; carbon storage values were the lowest (0.6 ± 0.03 to 2.4 ± 0.23 kg m^{-2}) for the 41–70° slope. Previously, Gessler et al. (2000) and Li et al. (2012) reported significant relationship between slope and soil carbon storage in coastal plains and grasslands of USA and China respectively. The slope position exhibited a significant negative correlation with soil C density in the top layer of soil compared with the sub-soil layers. Overall, our results concurred with the findings of Nahidan et al. (2015) and Hao et al. (2002) for rangeland and croplands, respectively.

4.3. Effects of grassland type and grazing regimes

Grassland type is a major factor that influences the spatial distribution pattern of SOC contents and SOCD. In our study, SOCD followed the trend of AM > TMS > TST > WST > TD. McSherry and Ritchie (2013) reported that grassland types, grazing regimes, and sampling depth explained 85% of the large variation in soil organic carbon in tropical grasslands. In fact, different grassland types are mainly the result of different climatic conditions, so the underlying cause for the differences in soil carbon storage could be climate along with species community composition (Delgado-Baquerizo et al., 2018). Earlier estimates of carbon densities in China have shown a wide range of values. For example, Xie et al. (2007) and Ni (2002) estimated high values of C storage in the top 1 m of soil of 15.1 kg m^{-2} and 13.2 kg m^{-2} respectively, compared with low values of C storage ranging from 8.5 kg m^{-2} to 10.0 kg m^{-2} reported by Yang et al. (2010) for the same soil depth. In the present study, the estimated mean carbon density for the top 1 m of soil is 12.1 ± 2.57 kg m^{-2}. This is much lower than the mean carbon storage in the Sanjiang Plain (21.2 kg m^{-2}, Mao et al., 2015), in Qinghai (25.9 kg m^{-2}, Liu et al., 2017) and in Yunnan province (18.4 kg m^{-2}, Duan et al., 2014); higher than the mean carbon storage (7.8 kg m^{-2}) of China as a whole (Yang et al., 2007); and comparable with the global mean carbon storage (10.8 kg m^{-2}, Post et al., 1982; 14.3 kg m^{-2}, Whittaker, 1975) (Table S4). These values could be mainly due to the extremely low temperature in northern China and in the Tibetan-Qinghai plateau compared with south-western China. However, Wu et al. (2003) estimated a mean soil carbon storage of 9.47 kg m^{-2} for alpine meadow, which is much lower than our estimate of 15.6 ± 2.98 kg m^{-2}. This discrepancy could be due to the difference in the estimation method, as Wu et al. (2003) used the second national soil survey, whereas our estimate is based on our field inventory. We observed that almost 80% of soil carbon was stored in high-altitude grasslands. Similarly, Fang et al. (2010) revealed that soil carbon storage in alpine grasslands of China constitutes about 55.6% of the total organic carbon stocks in the grasslands of China. The large variations among the previously reported SOCD estimates for China's grasslands could be due to the use of different data sources, numbers of samples, and methodologies.

Falahatkar et al. (2014) explained that grazing intensity can drastically affect the net primary production and reduce plant biomass inputs to the soil, thereby decreasing soil carbon contents and storage in Iranian grasslands. Correspondingly, the lowest SOC storage was in cutting grass (CG) regimen in our study could be a function of the complete removal of cut grasses from the system, a disruption of the soil C cycle because plant residues are the primary source of SOM (Reeder et al., 2004; Poeplau et al., 2016). Leifeld and Fuhrer (2009) and Chen et al. (2015), who noted that continuous moderate grazing resulted in the greatest accumulation of soil carbon through root biomass. Thus, a large amount of C is lost in the form of fresh aboveground biomass, although the below-ground root biomass makes a modest C contribution. In general, carbon input through fine root biomass and greater root turnover rate is higher than that in the above-ground (Derner et al., 2006; Kätterer et al., 2011; Poeplau et al., 2016). The absence of grazers (herbivores such as cattle and sheep) during the growing season could help in accumulation of SOC by increasing the net primary production and grass biomass input. According to Li et al. (2013) and Wu et al. (2014), SOCD has increased substantially when grazers were excluded. In contrary, Derner et al. (2006) and Reeder et al. (2004) reported that the grazed site had 12–24% higher soil C storage compared to the ungrazed grasslands. These findings are in accord with our observation of higher SOCD under both seasonal and year-long grazing regimens.

5. Conclusions

Environmental factors such as climate, topography and soil properties contributed about 62% of the total variation in carbon storage. In contrast to our initial hypothesis, the variations in SOCD were more highly influenced by climate and soil properties rather than the topography and grassland types. Slope attributes also significantly influenced soil carbon storage in grasslands with higher SOCD at lower slope position and 0–20° inclination. The effects of soil, climate, and topography on SOC contents and SOCD were reduced with increasing soil depths. Soil carbon storage varied among grassland types and soil types, and significantly influenced by their interaction with soil depths. Brown earth soil (Luvisols) types had stored higher SOC compared to other soil types. Among the different grassland types, SOCD was significantly higher in alpine meadow (AM) and temperate meadow-steppe (TMS). In the present study, grazing intensity had a strong effect on soil carbon storage with grass cutting regime dramatically reduced the soil carbon storage compared to grazing exclusion, seasonal and year-long grazing. Hence, effective grassland management policy is required for sustainable utilization and thereby, contributing to increased carbon sequestration. In this context, present estimates of soil carbon storage will significantly improve our understanding of carbon stock status and C sequestration potential of grassland ecosystems *per se*.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary data

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