RESEARCH

Spatial variability of soil organic carbon fractions and aggregate stability along an elevation gradient in the alpine meadow grasslands of the Qilian Mountains, China

Theophilus Atio Abalori[1], Wenxia Cao[1*], Conrad Atogi-Akwoa Weobong[2], Shilin Wang[1], Dominic Kwadwo Anning[3], Faisal Eudes Sam[4], Wanting Liu[1], and Wenhu Wang[1]

[1]Grassland Ecosystem Key Laboratory of Ministry of Education, Sino-US Research Centre for Sustainable Grassland and Livestock Management, Grassland Science College of Gansu Agricultural University, Lanzhou, 730030, China.
[*]Corresponding author (caowenxia@foxmail.com).
[2]University for Development Studies, Faculty of Natural Resources and Environment, P.O. Box TL 1882, Tamale, Ghana.
[3]Gansu Agricultural University, College of Resources and Environmental Science, Lanzhou 730070, China.
[4]Gansu Agricultural University, College of Food Science and Engineering, Lanzhou 730070, China.

Received: 14 July 2021; Accepted: 25 November 2021; doi:10.4067/S0718-58392022000100052

ABSTRACT

Grasslands contain substantial amount of soil organic C (SOC) and thus have a key function in global C cycle. Thus knowledge on SOC contents and aggregate stability is vital in exploring their impact as a C storage or source under climate change simulations. The research investigated the spatial variability of SOC and its fractions and stability of aggregates and their relationships with factors like vegetation, climate and soil conditions along an elevation gradient of the alpine meadow grassland (3105-4200 m a.s.l.) The SOC concentrations had an increasing trend with elevation from 76.04 g kg^{-1} at 3105 m a.s.l. up to 110.42 g kg^{-1} at 3710 m a.s.l. and 103.87g kg^{-1} and then decreased to 71.25 g kg^{-1} at the peak of the slope at 4200 m a.s.l. The results indicated that macro- and micro-aggregate organic C, mean weight diameter, geometric weight diameter, percentage of > 0.25 mm water-stable aggregates ($W_{0.25}$), and stability of water-stable aggregates ratio increased with increasing elevation, attaining a peak at 3710 or 3925 m a.s.l. and afterwards decreased. The findings of this research show that prospective global climate warming could have a telling effect on SOC and soil aggregate stability by affecting the distribution of aboveground biomass. Due to the low structural stability of soils at the lower parts of the elevations, we proposed that these areas should be barred from continuous grazing to enhance high grassland productivity and be able to cope with prospective climate change in this area.

Key words: Aggregate organic carbon, degree of humification, humic carbon, labile organic carbon, soil structural stability.

INTRODUCTION

In the terrestrial ecosystems, soil is regarded as the biggest C pool with an estimated 2344 Gt organic C stored in its upper 3 m layers (Stockmann et al., 2013). Soil organic C (SOC) has a key function in soil fertility and ecology due to its significant impact on soil attributes such as its structure (Kong et al., 2020), water holding capacity (Zhu et al., 2018), activities of soil microbes (Zhao et al., 2017; Guan et al., 2018) and nutrient availability (Oelofse et al., 2015). Soils in mountainous terrains in temperate areas are susceptible to temperature changes. Warming may speed up the rate of decomposition of SOC in these areas and affect global climate change (Ayoubi et al., 2012; Guan et al., 2018). The SOC has a significant impact on soil structure and properties and hence affects vegetation productivity. Spatial variability of SOC is complex and is substantially affected by environmental conditions and anthropogenic factors (Qiu et al., 2015; Conforti et al., 2016), which in one way or the other determines changes in the soil C pool. Thus, the SOC spatial distribution reckons on the relative effect of various factors such as vegetation, climate, and soil and their interaction which usually yields overlapping consequences on its spatial distribution pattern (Oueslati et al., 2013). A proper understanding of the quality and chemical composition of SOC will be vital to clarify how it reacts to actual conditions and the implicit mechanisms of prospective climate change.

Soil organic matter (SOM) is a diversified mixture of organic compounds and comprises diverse fractions with differences in stability, decomposition and turnover rate (Smith et al., 2014). The various fractions of SOC present distinct effects on soil and the environment (O'Brien and Jastrow, 2013). The labile fractions of SOC, such as readily oxidizable organic C (ROC) and water-soluble organic C (WSOC) have been regarded as being more responsive indicators for land use changes as compared to SOC (Li et al., 2017). Then again, most SOC exists as recalcitrant humic substances, viz, humic acid C (HAC), fulvic acid C (FAC) and humin C (HUC), which is estimated to be made up of roughly 60%-75% of SOC (Grinhut et al., 2011). Both the labile and chemical resistant fractions are regarded as possible indicators of climate change (Cao et al., 2016; Wang et al., 2016; Hu et al., 2017; Li et al., 2017). In addition, soil aggregate organic C is usually regarded as a vital indicator in measuring SOC sequestration and stability (Kong et al., 2020). Micro-aggregate organic C is usually more stable as compared to macro-aggregate and silt + clay organic C (Yu et al., 2012; Huang et al., 2016). Because of their recalcitrant attributes, humic substances play an essential function in soil C sequestration (Li et al., 2017). Soil aggregate stability is considered a key indicator of soil physical quality (Kong et al., 2020). The establishment and stabilization of soil aggregates in most cases enhance soil C sequestration and renders protection for soil C (Cheng et al., 2015). Therefore, the study of SOC fractions is essential for proper apprehension of the turnover and stabilization techniques of SOC.

The Tibet Plateau is considered the highest and largest plateau in the world with an estimated land area of 2.5 × 106 km^2 and an average elevation of 4000 m a.s.l. (Shang et al., 2016). At the same time, literature shows that this area is susceptible to global climate changes (Zhang et al., 2014). Alpine grasslands make up approximately 50% of the whole this area (Chen et al., 2014a; Tang et al., 2015). Studies have shown that the alpine grassland soils contain a substantial quantity of organic C and hence have a key function in the C cycles. Thus, there have been numerous studies on SOC in this area in the past decades (Wang et al., 2013). On high mountain terrains, weather conditions such as climate and vegetation change markedly along an elevation gradient. Thus studies of the variations in features of SOC contents along elevation gradient in this region is vital in order to be able to scientifically evaluate their impact in C sequestration or source under climate change simulations. Notwithstanding, earlier researches mainly concentrated on the storage of SOC among diverse types of alpine grasslands on the Tibet Plateau (Cao et al., 2016; Li et al., 2017). Till present, only a few studies have been carried out to investigate the differences in SOC fractions and soil aggregates stability among the different grasslands in this area, even though such studies are vital. Furthermore, it is yet not clear how the differences in environmental conditions affect the variations in quantitative and qualitative features of SOC storage and soil structural stability at various elevations in this area. In this research along an elevation of 3105-4200 m a.s.l. across the North-eastern slope of the Qilian Mountains on the Tibet Plateau, we investigated the variations in the concentrations of SOC fractions (viz, ROC, WSOC, humic C, and aggregate organic C) in addition to the stability of soil aggregates. In addition, we examined the factors that affect SOC fractions and soil structural stability in the perspective of climate (mean annual temperature and mean annual precipitation), vegetation (aboveground biomass), and soil factors (pH, moisture content, temperature, and particle size distribution). We premised our hypothesis that SOC fractions and soil structural stability varied across elevation gradients owing to changes in conditions.

MATERIALS AND METHODS

Site description

In this study, field experiments were conducted in the alpine grasslands of the Qilian Mountains in Zhuaxixiulong Township in the Tianzhu Tibetan Autonomous County of Gansu Province of China. The area has a typical alpine climate and is usually cold and wet for most parts of the year. It also has weather conditions such as thin air with low oxygen concentrations, high solar, and high ultraviolet radiation. The area has an average annual temperature of 0.13 °C, and average annual rainfall of 414.98 mm, which usually falls from July to September. The planting season is about 120 d, ranging from May to September. The soil is a typical alpine Chernozem with bulk density of about 0.73 g cm^{-3}, organic C of about 138.45 g kg^{-1}, total N of about 4.31 g kg^{-1}, and total P of about 0.65 g kg^{-1}. Figure 1 presents a map showing the vegetation types and altitude of the study area. Typical alpine plant species include *Kobresia humilis*, *Elymus nutans*, *Koeleria pers*, *Blysmus sinocompressus*. The study was carried out across a north-eastern slope of the Qilian Mountains. The elevation ranges from 3105 to 4200 m a.s.l., with the apex at approximately 4200 m a.s.l. The elevation was covered by pasture, except the apex which had few scattered grasses with bare land. In late August 2020, six sampling sites were set up along the elevation gradient, i.e., at 3105, 3350, 3480, 3710, 3925, and 4200 m, Table 1 shows the basic characteristics of these sampling sites.

Field sampling

Five 30 × 30 m^2 plots were randomly located in the alpine grassland on a north-eastern slope, for a total of 30 sample plots. Five samples were collected using a core sampler at depth 0-20 cm. In total, 150 samples were collected at six elevations. Quadrats 1 m × 1 m were laid at approximately 5 m intervals and above ground plants were harvested, oven dried, and used for estimating aboveground biomass (AGB). Soil samples were sieved, homogenized, and air-dried, and used for analyzing soil aggregates, SOC, and other properties.

Figure 1. A map of the study area showing types of vegetation and altitude.

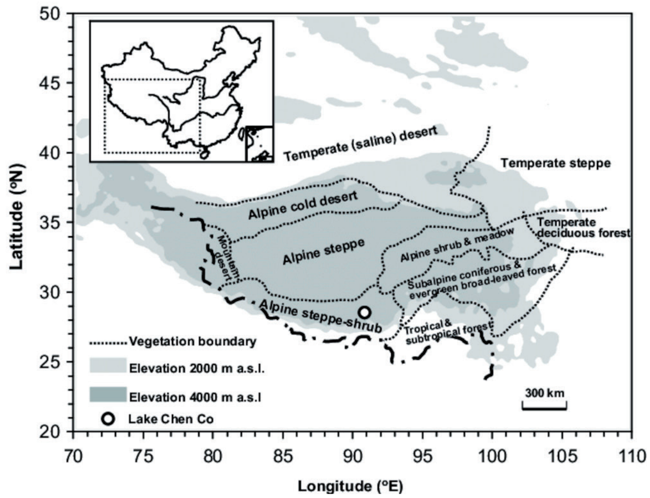


Table 1. Basic characteristics of the sampling sites across an elevation gradient.

Elevation	AGB	MC	TEMP	pH	Sand	Silt	Clay	MAT	MAP
m a.s.l.	g m^{-2}	%	°C		%	%	%	°C	mm
3105	83.97 ± 0.33e	30.28 ± 0.04f	15.43 ± 0.57a	8.02 ± 0.03a	54.30 ± 0.70e	22.40 ± 0.53c	23.30 ± 0.66a	1.58	465.8
3350	70.70 ± 0.47f	34.83 ± 0.20e	13.25 ± 0.05b	8.04 ± 0.01a	66.33 ± 0.40b	17.67 ± 0.15e	16.00 ± 0.26c	1.32	414.2
3480	167.19 ± 1.35c	37.07 ± 0.05d	12.70 ± 0.10c	7.85 ± 0.01b	56.30 ± 0.46c	23.83 ± 0.35d	19.87 ± 0.15b	0.89	453.6
3710	274.60 ± 0.90b	40.33 ± 0.07c	11.90 ± 0.20d	7.80 ± 0.02c	55.10 ± 0.70d	24.67 ± 0.32b	20.23 ± 0.91b	0.36	494.6
3925	386.83 ± 0.53a	44.08 ± 0.03b	10.57 ± 0.06e	7.75 ± 0.01d	50.10 ± 0.17f	26.60 ± 0.36a	23.30 ± 0.53a	-0.03	532.2
4200	129.11 ± 0.59d	54.39 ± 0.60a	10.07 ± 0.12f	7.67 ± 0.02e	78.83 ± 0.32a	10.73 ± 0.21f	10.43 ± 0.12d	-0.48	510.1

Mean values ± standard error. Values in the same column with different letters show significant difference according to Tukey's test ($P \leq 0.05$). AGB: Above ground biomass; MC: soil moisture content; TEMP: soil temperature; MAT: mean annual temperature; MAP: mean annual precipitation.

Soil analysis

Organic C concentrations were estimated using sulphuric acid-potassium dichromate oxidation method. For oxidizable organic C (ROC) analysis, bulk soil samples were oxidized with 333 mM $KMnO_4$ solution for 1 h, and the quantity of ROC was estimated by spectrophotometry. For water-soluble organic C (WSOC) and humic C analysis, water soluble and humic fractions were estimated by extracting soil samples with distilled water and 0.1 M NaOH + 0.1 M $Na_4P_2O_7$ solution, respectively. Humic acid (HA) was separated from fulvic acid (FA) by acidifying the alkaline supernatants to pH 1.0 and the alkaline insoluble residue was humin (HUC). The concentrations of WSOC, humic acid C (HAC) and fulvic acid C (FAC) were determined via the use of a total organic C (TOC) analyzer (Shimadzu, Kyoto, Japan), while that of HUC was estimated as the difference of the sum of WSOC, HAC, and FAC from SOC.

The conventional wet-sieving method was used to separate soil aggregate fractions (Cambardella and Elliott, 1993). Briefly, a 100 g air-dried soil sample was wet-sieved with mesh sizes of 2, 1, 0.25 and 0.053 mm to separate it into four size fractions of water-stable aggregate, i.e., macro-aggregate (> 2 mm, 1-2 mm, 0.25-1.00 mm), and micro-aggregate (0.053-0.250 mm). The sample was pre-soaked in distilled water on top of 2 mm sieve for 10 min before vertical oscillation in water for 10 min with 30 oscillations per minute and amplitude of 4 cm. Organic material floating on water after sieving was discarded because it is not considered to be soil organic matter (Han et al., 2015). Finally, each fraction was dried at 50 °C for 24 h, and weighed for calculating the proportions of each aggregate fraction in bulk soils and for further chemical analysis. Each aggregate fraction was calculated as a percentage relative to the total dry sample. The index of stability was expressed as the percentage of aggregates larger than 0.25 mm diameter following wet sieving and drying. The aggregate-size classes and the concentration of soil aggregate organic C were expressed on a sand-free basis (Chen et al., 2014b). Nonetheless, SOC concentration in the macro-aggregates at the apex of the elevation (i.e., 4200 m) was not corrected for sand because it contained very high sand quantities. The mean weight diameter (MWD), geometric mean diameter (GMD), percentage of > 0.25 mm water-stable aggregates ($W_{0.25}$), structure deterioration rate (SDR), and stability ratio of water-stable aggregate (WSAR) of water-stable aggregates were estimated according to Choudhury et al. (2014) and Liu et al. (2014).

Water-stable macro- and micro-aggregates: The macro-aggregates were determined by adding the aggregates retained over 0.25-2.0 mm sieves while the micro-aggregates referred to aggregates retained on 0.05-0.25-mm sieves.

$$\text{WSA (\%)} = [(\text{weight of soil + sand}) \times i - (\text{weight of sand}) \times i]/\text{weight of sample} \quad (1)$$

where i denotes the size of the sieve. The percentage of water-stable macro-aggregates and water-stable micro-aggregates is the summation of soil aggregate size fractions of > 0.25 mm and < 0.25 mm, respectively. These two were summed up to estimate the total water stable aggregates.

The mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates were calculated as:

$$\text{MWD (mm)} = \frac{\sum_{i=1}^{n} X_i W_i}{\sum_{i=1}^{n} W_i} \quad (2)$$

$$\text{GMD (mm)} = \text{Exp}\left[\frac{\sum_{i=1}^{n} W_i \log X_i}{\sum_{i=1}^{n} W_i}\right] \quad (3)$$

where n is the number of fractions (0.1-0.25, 0.25-0.5, 0.5-1.0, 1.0-2.0, > -2.0 mm), X_i is the mean diameter (mm) of the sieve size class (0.175, 0.375, 0.75, 1.5 and 2.0 mm) and W_i is the weight of soil (g) retained on each sieve.

Statistical analysis

We used SPSS 16.0 software for the analysis (SPSS, Chicago, Illinois, USA). One-way ANOVA with least significant difference (LSD) test was used to examine the differences between SOC contents, soil structural stability, and humic C fractions among the various elevations. We used Pearson correlation to determine the connections between SOC and its fractions and aggregate stability indices with environmental conditions, i.e., elevation, mean annual temperature (MAT), mean annual precipitation (MAP), and AGB and other soil properties, i.e., particle size distribution, moisture content (MC), temperature, and pH. The $P < 0.001$ level was considered to be significant. Principal component analysis was carried out using PAST software version 2.17c (Hammer et al., 2001).

RESULTS

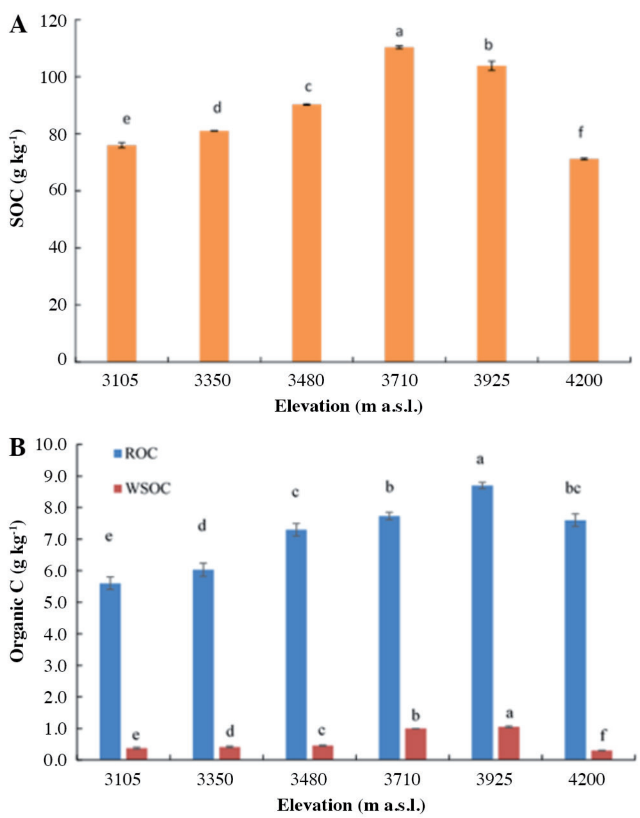
Distribution of SOC, ROC, WSOC, and humic C

The SOC concentrations had an increasing trend with elevation from 76.04 g kg^{-1} at 3105 m up to 110.42 g kg^{-1} at 3710 m and 103.87 g kg^{-1} and then decreased to 71.25 g kg^{-1} at the peak of the slope at 4200 m (Figure 2). The elevations 3710 and 3925 m recorded significantly higher amounts of SOC compared to the others. There was a significant difference in SOC quantity at the lowest elevation (3105 m) and that of the highest elevation (4200 m). The concentrations of ROC, WSOC (Figure 2), and HUC (Figure 3) in the soils followed the same trends as SOC along the elevation. Both HAC and FAC recorded their highest concentrations at 3925 m while HAC/FAC had its highest concentration at 3480 m (Figure 3). The middle portions of the elevation recorded the largest concentrations of the SOC fractions and were significantly higher compared to the foot and apex of the slope.

Soil aggregate organic C and aggregate stability

There were variations in aggregates size distributions across the elevation (Figure 4). Along the elevations, the ratio of micro-aggregates was greater than macro-aggregates and silt + clay fractions except at the 3925 m where macro-aggregates ratio was higher than micro-aggregates and silt + clay fractions. Across the elevations, the amount of micro-aggregate organic C (MicAOC) was higher compared to macro-aggregate and silt + clay organic C (Figure 4). In a similar trend to SOC, the amount of macro- and micro-aggregates and silt + clay organic C were also significantly higher at 3710 and 3925 m compared to the rest. Furthermore, the ratio of macro-aggregates organic C (MacAOC) to MicAOC was significantly higher at 3710 and 3925 m elevations and significantly lowest at 4200 m in relation to the other elevations (Figure 5). Ratio MacAOC/MicAOC along the elevation gradient equally followed the same trend as organic C and its fractions by increasing with increasing elevation and attaining a peak at 3480 and 3710 m and then decreased afterward.

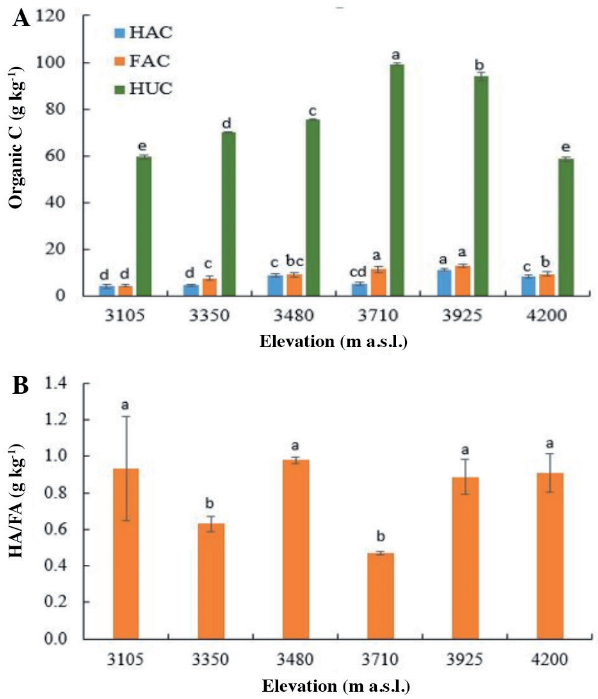
Figure 2. Concentration of soil organic C (A) and its labile fractions (B).



Bars with different letters show significance at $p < 0.001$.
SOC: Soil organic C; ROC: readily oxidizable organic C; WSOC: water-soluble organic C.

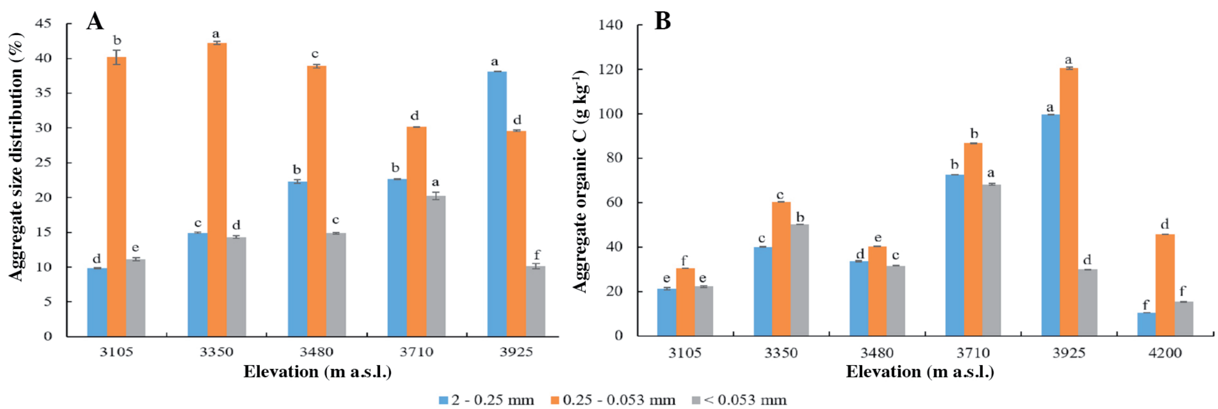
The MWD, GMD, $W_{0.25}$, and water-stable aggregates ratio (WASAR) of the soil aggregates increased with increasing elevation and got to a maximum at 3925 m and then decreased (Table 2). The 3925 m elevation recorded significantly larger values than the others. The SDR of the soils along the elevation gradient was lowest at 3925 m and highest at the peak of 4200 m.

Figure 3. Concentrations of resistant organic C fractions (A) and degree of humification (B).



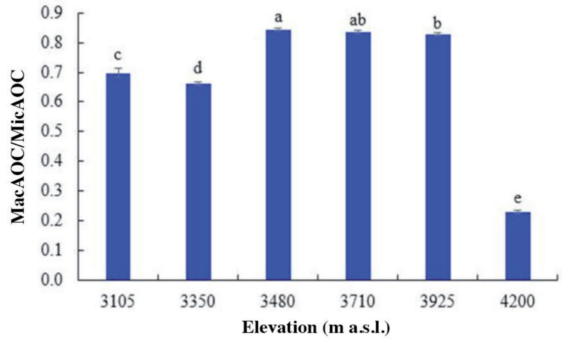
Bars with different letters show significant difference at $p < 0.001$.
HAC: Humic acid C; FAC: fulvic acid C; HUC: humin C; HA/FA: degree of humification.

Figure 4. Aggregate size distribution (A) and aggregate organic C concentrations (B).



Bars with different letters show significant difference at $p < 0.001$.

Figure 5. Ratio of soil macro-aggregate to micro-aggregate organic C (MacAOC/MicAOC).



Bars with different letters show significant difference at $p < 0.001$.

Table 2. Spatial distribution of soil aggregate stability indices along elevation gradient.

Elevation	MWD	GMD	$W_{0.25}$	SDR	WASAR
m a.s.l.	mm	mm	%	%	%
3105	0.24 ± 0.03d	0.30 ± 0.02d	2.46 ± 0.15e	83.83 ± 0.10b	5.63 ± 0.50d
3350	0.36 ± 0.03c	0.32 ± 0.02d	3.47 ± 0.02d	75.70 ± 0.15c	5.80 ± 0.20d
3480	0.43 ± 0.03b	0.38 ± 0.02c	6.28 ± 0.03c	68.83 ± 0.32d	15.73 ± 0.15c
3710	0.46 ± 0.02b	0.42 ± 0.01b	8.29 ± 0.02b	60.23 ± 1.04e	29.60 ± 0.10b
3925	0.65 ± 0.02a	0.57 ± 0.01a	24.07 ± 0.02a	52.70 ± 1.00f	48.30 ± 0.15a
4200	0.18 ± 0.02e	0.24 ± 0.01e	2.27 ± 0.15f	90.37 ± 0.15a	5.40 ± 0.30d

Mean values ± standard errors. Values with different letters show significant difference show significant difference according to Tukey's test ($P \leq 0.05$).
MWD: Mean weight diameter; GMD: geometric mean diameter; $W_{0.25}$: percentage of > 0.25 mm water-stable aggregates; SDR: structure deterioration rate; WASAR: stability ratio of water-stable aggregates.

Relation between SOC content, aggregate stability, and environmental factors

The correlations between SOC fractions, aggregate stability with environmental factors are presented in Table 3, SOC and its fractions had significantly positive correlations with AGB. However, HAC/FAC, silt + clay-associated C had negative correlations with AGB. In addition, there were positive correlations between ROC, WASAR, FAC, HAC, and $W_{0.25}$ with MAP. Nonetheless, SOC and its fractions had nonsignificant correlations with MAT, except micro-aggregates which had a positive correlation with MAT. On the whole, the aggregate stability indices had significant positive correlations with AGB except SDR, which was significantly and negatively correlated with AGB. The correlations between SOC fractions and aggregate stability indices are presented in Tables 4 and 5. There were significant positive correlations between SOC and its fractions except for HAC and HAC/FAC. In addition, there were strong positive correlations between SOC and its fraction with the aggregate stability indices. Principal component analysis (PCA) was carried out to evaluate the effects of elevation gradient on soil organic C fractions, aggregate stability, and environmental factors. Principal component 1 (PC1) explained 61.17%, principal component 2 (PC2) explained 19.91% while principal component 3 (PC3) explained 12.73% of the total variations (Figure 6). The elevations 3710 and 3925 m showed significant separations compared to the others; 3925 m elevation had the highest score, and 3710 m elevation followed. The lowest score was recorded at 4200 m elevation along PC1. However, 3480 m elevation had the highest score along PC2 and that of 3925 m recorded the highest score along PC3. Four of the elevations (3105, 3710, 3925, and 4200 m) were far from the origin, indicating that elevation strongly affects SOC fractions, aggregate stability, and environmental factors.

Table 3. Pearson correlation coefficients between soil organic C (SOC) and its fractions and aggregate stability indices with environmental factors along an elevation gradient.

	Elevation									
	3105	3350	3480	3710	3925	4200	AGB	pH	MAT	MAP
			m a.s.l.				$g\ m^{-2}$		°C	mm
SOC, $g\ kg^{-1}$	-0.399	-0.243	0.046	0.674	0.470	-0.549	**0.841**	-0.252	-0.212	0.367
HAC, $g\ kg^{-1}$	-0.510	-0.415	0.301	-0.303	0.693	0.234	0.642	-0.721	-0.682	0.628
FAC, $g\ kg^{-1}$	**-0.756**	-0.249	0.000	0.370	0.590	0.045	**0.846**	-0.706	-0.730	0.621
HUC, $g\ kg^{-1}$	-0.476	-0.171	-0.017	0.659	0.506	-0.501	**0.854**	-0.282	-0.269	0.378
HA/FA, $g\ kg^{-1}$	0.274	-0.357	0.371	-0.690	0.177	0.225	-0.107	-0.150	-0.038	0.151
MWD, mm	-0.411	-0.070	0.135	0.183	**0.768**	-0.606	**0.838**	-0.160	-0.147	0.301
GMD, mm	-0.301	-0.218	0.019	0.213	**0.838**	-0.551	**0.910**	-0.237	-0.220	0.464
$W_{0.25}$, %	-0.315	-0.256	-0.090	0.029	**0.959**	-0.326	**0.921**	-0.382	-0.398	0.617
SDR, %	0.409	0.129	-0.107	-0.403	-0.662	0.634	**-0.862**	0.171	0.148	-0.315
WASAR, %	-0.359	-0.355	-0.075	0.315	**0.840**	-0.366	**0.985**	-0.438	-0.429	0.651
ROC, $g\ kg^{-1}$	-0.659	-0.476	0.059	0.241	0.649	0.185	**0.871**	**-0.855**	**-0.838**	**0.788**
WSOC, $g\ kg^{-1}$	-0.329	-0.270	-0.212	0.584	0.663	-0.436	**0.925**	-0.334	-0.339	0.556
MacA, %	-0.376	-0.163	0.146	0.161	**0.808**	-0.576	**0.876**	-0.212	-0.189	0.378
MicA, %	0.359	0.454	0.299	-0.112	-0.138	**-0.862**	-0.276	**0.886**	**0.926**	-0.745
Silt + clay, %	-0.457	-0.033	0.040	0.751	-0.585	0.285	-0.058	-0.306	-0.293	-0.033
MacAOC, $g\ kg^{-1}$	-0.365	-0.091	-0.184	0.385	**0.777**	-0.521	**0.901**	-0.219	-0.253	0.446
MicAOC, $g\ kg^{-1}$	-0.485	-0.054	-0.342	0.328	**0.817**	-0.264	**0.898**	-0.389	-0.470	0.565
Silt+clay C, $g\ kg^{-1}$	-0.351	0.349	-0.116	0.801	-0.160	-0.523	0.220	0.221	0.182	-0.263
MacAOC/MicAOC	0.030	-0.039	0.334	0.320	0.300	-0.945	0.457	0.346	0.437	-0.142

AGB: above ground biomass; MAT: mean annual temperature; MAP: mean annual precipitation: HAC: humic acid C; FAC: fulvic acid C; HUC: humin C; HA/FA: humification degree; MWD: mean weight diameter; GMD: geometric mean diameter; $W_{0.25}$: percentage of > 0.25 mm water-stable aggregates; SDR: structure deterioration rate; WASAR: stability ratio of water stable aggregate; ROC: readily oxidizable organic C; WSOC: water-soluble organic C; MacA: Macro-aggregate; MicA: micro-aggregate; MacAOC: macro-aggregate-associated organic C; MicAOC: micro-aggregate-associated organic C; Bolded values are significant according to Tukey's test ($P \leq 0.05$).

Table 4. Pearson correlation coefficients between soil organic C (SOC) and is fractions and soil aggregate stability.

	SOC	HAC	FAC	HUC	HA/FA	MWD	GMD	$W_{0.25}$	SDR
SOC, $g\ kg^{-1}$	1	0.264	0.716	**0.992**	-0.412	**0.837**	**0.844**	0.694	**-0.943**
HAC, $g\ kg^{-1}$	0.264	1	0.680	0.290	0.480	0.507	0.529	0.683	-0.402
FAC, $g\ kg^{-1}$	0.716	0.680	1	0.767	-0.248	0.671	0.697	0.719	-0.709
HUC, $g\ kg^{-1}$	**0.992**	0.290	0.767	1	-0.446	**0.850**	**0.850**	0.719	**-0.945**
HA/FA, $g\ kg^{-1}$	-0.412	0.480	-0.248	-0.446	1	-0.141	-0.097	0.040	0.274
MWD, mm	**0.837**	0.507	0.671	**0.850**	-0.141	1	**0.965**	**0.896**	**-0.966**
GMD, mm	0.844	0.529	0.697	**0.850**	-0.097	**0.965**	1	**0.948**	**-0.953**
W0.25, %	0.694	0.683	0.719	0.719	0.040	**0.896**	**0.948**	1	**-0.838**
SDR, %	**-0.943**	-0.402	-0.709	**-0.945**	0.274	**-0.966**	**-0.953**	**-0.838**	1
WASAR, %	**0.862**	0.592	**0.796**	**0.874**	-0.126	**0.906**	**0.964**	**0.954**	**-0.917**
ROC, $g\ kg^{-1}$	0.626	**0.817**	**0.909**	0.661	0.037	0.620	0.669	0.744	-0.625
WSOC, $g\ kg^{-1}$	**0.943**	0.328	0.751	**0.954**	-0.380	**0.838**	**0.895**	**0.822**	**-0.915**
MacA, %	**0.834**	0.567	0.692	**0.840**	-0.069	**0.989**	**0.983**	**0.929**	**-0.963**
MicA, %	0.079	-0.451	-0.458	0.030	-0.062	0.213	0.113	-0.092	-0.197
Silt+clay, %	0.222	-0.258	0.250	0.232	-0.551	-0.242	-0.285	-0.403	0.058
MacAOC, $g\ kg^{-1}$	**0.892**	0.391	0.730	**0.917**	-0.316	**0.929**	**0.956**	**0.902**	**-0.952**
MicAOC, $g\ kg^{-1}$	**0.784**	0.476	**0.810**	**0.839**	-0.319	**0.837**	**0.876**	**0.897**	**-0.841**
Silt+clay C, $g\ kg^{-1}$	0.668	-0.399	0.297	0.682	**-0.805**	0.372	0.293	0.060	-0.529
MacOC/MiaOC	**0.740**	-0.008	0.198	0.686	-0.189	0.748	0.705	0.479	**-0.797**

SOC: Soil organic C; HAC: humic acid C; FAC: fulvic acid C; HUC: humin C; HA/FA: humification degree; MWD: mean weight diameter; GMD: geometric mean diameter; $W_{0.25}$: percentage of > 0.25 mm water-stable aggregates; SDR: structure deterioration rate; WASAR: stability ratio of water-stable aggregate; ROC: readily oxidizable organic C; WSOC: water-soluble organic C; MacA: macro-aggregate; MicA: micro-aggregate; MacAOC: macro-aggregate organic C; MicAOC: micro-aggregate organic C.
Bolded values are significant according to Tukey's test ($P \leq 0.05$).

Table 5. Pearson correlation coefficients between soil organic C (SOC) and is fractions and soil aggregate stability

	WASAR	ROC	WSOC	MacA	MicA	Silt+clay	MacAOC	MicAOC	Silt+clay C	MacAOC/ MicAOC
SOC, g kg^{-1}	**0.862**	0.626	**0.943**	**0.834**	0.079	0.222	**0.892**	**0.784**	0.668	0.740
HAC, g kg^{-1}	0.592	0.817	0.328	0.567	-0.451	-0.258	0.391	0.476	-0.399	-0.008
FAC, g kg^{-1}	**0.796**	**0.909**	0.751	0.692	-0.458	0.250	0.730	**0.810**	0.297	0.198
HUC, g kg^{-1}	**0.874**	0.661	**0.954**	**0.840**	0.030	0.232	**0.917**	**0.839**	0.682	0.686
HA/FA, g kg^{-1}	-0.126	0.037	-0.380	-0.069	-0.062	-0.551	-0.316	-0.319	**-0.805**	-0.189
MWD, mm	**0.906**	0.620	**0.838**	**0.989**	0.213	-0.242	**0.929**	**0.837**	0.372	0.748
GMD, mm	**0.964**	0.669	**0.895**	**0.983**	0.113	-0.285	**0.956**	**0.876**	0.293	0.705
$W_{0.25}$, %	**0.954**	0.744	**0.822**	**0.929**	-0.092	-0.403	**0.902**	**0.897**	0.060	0.479
SDR, %	**-0.917**	-0.625	**-0.915**	**-0.963**	-0.197	0.058	**-0.952**	**-0.841**	-0.529	**-0.797**
WASAR, %	1	**0.795**	**0.942**	**0.935**	-0.123	-0.156	**0.952**	**0.921**	0.266	0.563
ROC, g kg^{-1}	**0.795**	1	0.683	0.660	-0.591	0.143	0.646	0.738	0.042	0.098
WSOC, g kg^{-1}	**0.942**	0.683	1	**0.848**	-0.070	0.064	**0.959**	**0.912**	0.530	0.607
MacA, %	**0.935**	0.660	**0.848**	1	0.168	-0.277	**0.930**	**0.838**	0.299	0.735
MicA, %	-0.123	-0.591	-0.070	0.168	1	-0.346	0.060	-0.185	0.318	0.692
Silt+clay, %	-0.156	0.143	0.064	-0.277	-0.346	1	-0.127	-0.081	0.576	-0.169
MacAOC, g kg^{-1}	**0.952**	0.646	**0.959**	**0.930**	0.060	-0.127	1	**0.954**	0.478	0.650
MicAOC, g kg^{-1}	**0.921**	0.738	**0.912**	**0.838**	-0.185	-0.081	**0.954**	1	0.384	0.394
Silt+clay C, g kg^{-1}	0.266	0.042	0.530	0.299	0.318	0.576	0.478	0.384	1	0.533
MacAOC/MicAOC	0.563	0.098	0.607	0.735	0.692	-0.169	0.650	0.394	0.533	1

WASAR: Stability ratio of water-stable aggregate; ROC: readily oxidizable organic C; WSOC: water-soluble organic C; MacA: macro-aggregate; MicA: micro-aggregate; MacAOC: macro-aggregate organic C; MicAOC: micro-aggregate organic C; MacOC/MicOC; SOC: soil organic C; HAC: humic acid C; FAC: fulvic acid C; HUC: humin C; HA/FA: humification degree; MWD: mean weight diameter; GMD: geometric mean diameter; $W_{0.25}$: percentage of > 0.25 mm water-stable aggregates; SDR: structure deterioration rate.
Bolded values are significant according to Tukey's test ($P \leq 0.05$).

DISCUSSION

Variability of SOC and its fractions across the selected elevation gradient

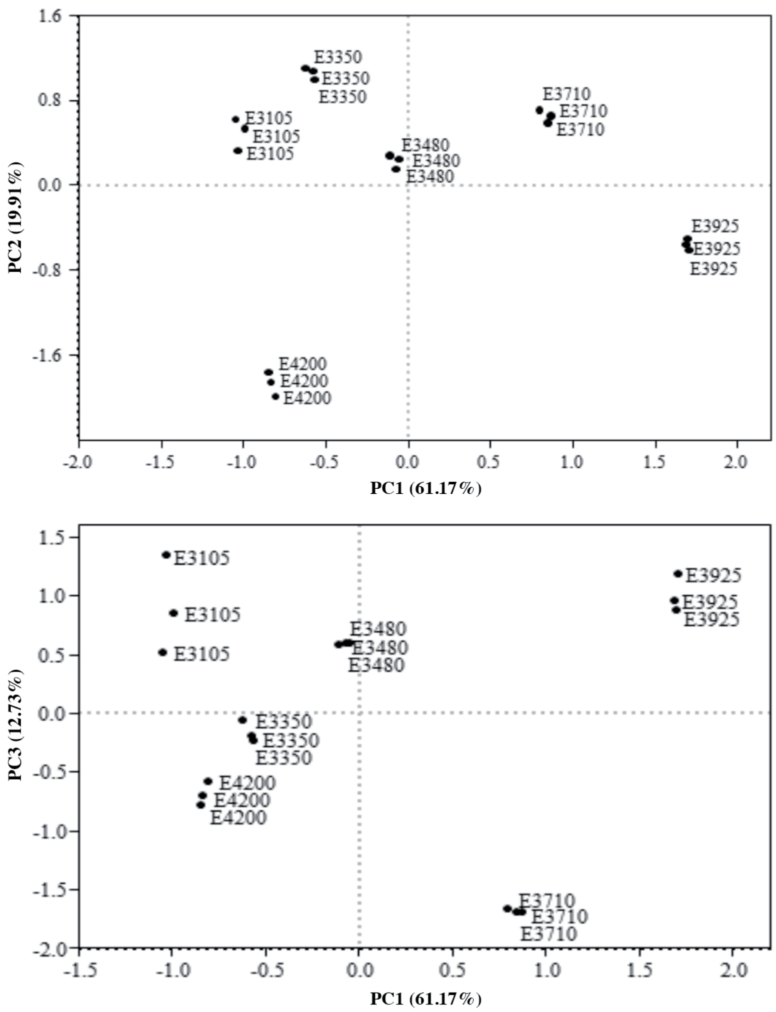
The study revealed that there was significantly larger SOC, including labile SOC fractions, recalcitrant SOC fractions, and stable aggregate-associated organic C fractions at higher elevations of 3710 and 3925 m compared to the lower and apex of the elevation (Figures 2 and 3). This is an indication that the apportioning of SOC fractions across the elevation gradient had a unimodal pattern. These results are in line with those of Yuan et al. (2014) and Li et al. (2017). For instance, Li et al. (2017) recorded significantly higher values of SOC storage in the middle of the elevation as compared to the lower and peak of the elevation. In addition, Fu et al. (2014) found that SOC and WSOC increased with increasing elevation. The ratio HAC/FAC is regarded as an indicator of the degree of humification (Putra et al., 2016). The differences in HAC/FAC ratio (Figure 3) indicated that the degree of humification is also affected by elevation gradient, with the highest value recorded at 3480 m. A large HAC/FAC shows a high degree of humification (Seran, 2011; Reddy et al., 2012). Therefore, these results indicated that the degree of humification of SOC was higher in the middle portion of the elevation gradient as compared to the lower and the top. The SOC and its fractions had a positive correlation with AGB (Table 3) indicating that vegetation productivity was a key factor affecting SOC distribution along elevation gradient. This could be attributable to the fact that SOC is formed primarily via the decomposition and turnover of vegetative residue and therefore higher plant biomass could lead to higher SOC concentrations. Hence elevations below 3710 m with low plant biomass recorded low SOC and humification values. The effect of altitude on SOC content is principally due to the combination of moisture and temperature. The temperature in the Qilian Mountains is reported to decrease at a rate of 0.58 °C/100 m with increasing altitude, and precipitation increases at a rate of 18.6 mm/100 m with increasing altitude (Wan et al., 2019). The findings showed that SOC concentration increased with increasing altitude primarily due to high precipitation and low temperature. High moisture and low temperature decrease microbial activity and hence slows decomposition and mineralization rate of SOC. Soil pH decreases with elevation, and this beyond doubt affects soil microbial activity. Soil pH is a driver of soil microbial activity (Fierer, 2017; Tripathi et al., 2018). Low pH and high moisture leads to slower microbial growth rates that limits decomposition of organic matter causing accumulation of SOC (Tripathi et al., 2018). Our results revealed that the labile, recalcitrant, and soil aggregate organic C fractions were strongly positively correlated with SOC concentration

(Tables 4 and 5). In addition, the labile, recalcitrant, and soil aggregate organic C were significantly correlated with each other, showing that they are closely interconnected.

Soil aggregate stability across the selected elevation gradient

The MWD, GMD, $W_{0.25}$, SDR, and WASAR are widely used as indicators for exploring soil aggregate stability. For an all-round exploration of soil aggregate stability, it is important to employ a combination of these indices. A bigger MWD, GMD, $W_{0.25}$, and WASAR, and a smaller SDR suggest the structural stability of the soil aggregates was higher (Choudhury et al., 2014; Liu et al., 2014; Li et al., 2017). Therefore, our results (Table 2) indicated that the structural stability of the soil aggregates was highest in the middle part of the elevation (3925 m). This could be attributable to higher SOC which is the chief binding material for the establishment and stability of soil aggregates at higher elevations (Li et al., 2017). There were also significant correlations between SOC concentrations and soil aggregate stability indices in the present study (Tables 4 and 5). Furthermore, the soil aggregate stability indices had strong positive correlations with AGB (Table 3). These results are consistent with Cao et al. (2016) and Li et al. (2017). Aside SOC, labile and recalcitrant C contents also have key roles in soil aggregate stability. Several studies revealed that the quantum of WSOC (Padbhushan et al., 2016) and humic fractions (Kong et al., 2020) in the soil had a significant positive impact on aggregate stability, this was in line with the present study (Tables 4 and 5). The AGB is regarded as a key determinant of SOC concentration and soil aggregate stability across the elevation gradient. However, the low AGB at the lower elevations might be the result of

Figure 6. Principal component analysis (PCA) of the effects of elevation (E) gradient on soil organic C fractions, aggregate stability and environmental factors.



climate warming as found by Du et al. (2012). The negative impact of warming on AGB (Fu et al., 2013) could be the reason for the low SOC and low soil structural stability at the foot of the elevations. Therefore if the tendency of global warming is to increase the Earth's temperature, then in the future those cooler regions in higher altitude will produce less biomass and thus have lower soil stability. Tables 4 and 5 clearly indicate that soil aggregate stability was closely connected with ROC, WSOC, HAC, FAC, HUC, macro- and micro-aggregate associated C in comparison with silt + clay-associated organic C, implying that both the labile and recalcitrant forms of C were major determinants of soil aggregate stability in the study. The PCA showed that elevations 3710 and 3925 m showed significant separations compared to the others and also recorded the highest scores. This implies that those sites contributed much to variations in SOC fractions and aggregate stability. This could be attributed to the high plants' biomass at those sites. In general, elevation has a strong influence on soil microclimates and hydrothermal processes by controlling the climatic conditions across the vertical gradients. In turn, these microclimate variations then result in major differences in SOC along altitude gradients (Karst and Landhäusser, 2014; Zhang et al., 2018). Also, temperature and precipitation along the elevation gradients are the major factors affecting C budget by controlling C inputs from plant biomass and decomposition (Conant et al., 2011; Guan et al., 2018) and this may further affect the stability of soil aggregates. Clay also plays a vital function in aggregate stability of SOC because soil mineral particles provide protection for organic matter. This could be the reason why aggregate stability at 4200 m elevation was the least because it contains a significant amount of sand and less clay content.

Protection mechanisms of SOC along elevation gradient

Aggregate formation has the possibility of physically protecting SOC (Li et al., 2017). In the present research, the significant MicAOC along the elevation gradient indicated that the major mechanisms of SOC protection were by micro-aggregates. Yu et al. (2012) and Huang et al. (2016) reported that micro-aggregate-associated organic C is more stable as compared to macro-aggregates-associated organic C and silt + clay fractions. The significantly lower ratio MacAOC/MicAOC recorded at 4200 m elevation as compared with the rest (Figure 4) indicates that micro-aggregate-associated organic C could be the main factor contributing to SOC preservation at the highest elevation.

CONCLUSIONS

The content of soil organic C (SOC) and its recalcitrant, labile, and soil aggregate stability increased with increasing elevation, attaining peak concentrations at 3710 or 3925 m. There were positive correlations between SOC, oxidizable organic C, water-soluble organic C, humic acid C, fulvic acid C, humin C, macro- and micro-aggregate organic C, aboveground biomass (AGB), and all the aggregate stability indices except structure deterioration rate. The positive correlations between the fractions of SOC and soil aggregate stability indices imply that both the resistant and labile forms of C were the major determinants of soil structural stability in the study. The findings of this research show that prospective global climate warming could have a telling effect on SOC and soil structural stability by affecting the distribution of AGB. Due to the low structural stability of soils at the foot of the elevations, we proposed that these areas should be barred from continuous grazing to enhance high grassland productivity and ability to cope with prospective climate change in this area.

ACKNOWLEDGEMENTS

This study was supported by the National Natural Science Foundation of China (32060269).

REFERENCES

Ayoubi, S., Karchegani, P.M., Mosaddeghi, M.R., and Honarjoo, N. 2012. Soil aggregation and organic carbon as affected by topography and land use change in western Iran. Soil and Tillage Research 121:18-26.

Cambardella, C.A., and Elliott, E.T. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Science Society of America Journal 57:1071-1076. doi:10.2136/sssaj1993.03615995005700040032x.

Cao, Z., Wang, Y., Li, J., Zhang, J., and He, N. 2016. Soil organic carbon contents, aggregate stability, and humic acid composition in different alpine grasslands in Qinghai-Tibetplateau. Journal of Mountain Science 13:2015-2027.

Chen, Y., Day, S.D., Wick, A.F., and McGuire, K.J. 2014b. Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. Science of the Total Environment 494-495:329-336. doi:10.1016/j.scitotenv.2014.06.099.

Chen, B., Zhang, X., Tao, J., Wu, J., Shi, P., and Yu, C. 2014a. The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. Agriculture and Forest Meteorology 189-190:11-18. doi:10.1016/j.agrformet.2014.01.002.

Cheng, M., Xiang, Y., Xue, Z., An, S., and Darboux, F. 2015. Soil aggregation and intra-aggregate carbon fractions in relation to vegetation succession on the Loess Plateau, China. CATENA 124:77-84. doi:10.1016/j.catena.2014.09.006.

Choudhury, S.G., Srivastava, S., Singh, R., Chaudhari, S.K., Sharma, D., Singh, S.K., et al. 2014. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. Soil and Tillage Research 136:76-83. doi:10.1016/j.still.2013.10.001.

Conant, R.T., Ryan, M.G., Gren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., et al. 2011. Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. Global Change Biology 17:3392-3404.

Conforti, M., Lucà, F., Scarciglia, F., Matteucci, G., and Buttafuoco, G. 2016. Soil carbon stock in relation to soil properties and landscape position in a forest ecosystem of southern Italy (Calabria region). CATENA 144:23-33. doi.10.1016/j.catena.2016.04.023.

Du, M., Yonemura, S., Zhang, X., He, Y., Liu, J., and Kawashima, S. 2012. Climatic warming due to overgrazing on the Tibetan Plateau-an example at Damxung in the central part of the Tibetan Plateau. Journal of Arid Land 22:119-122.

Fierer, N. 2017. Embracing the unknown: disentangling the complexities of the soil microbiome. Nature Reviews Microbiology 15:579-590.

Fu, G., Zhang, X., Yu, C., Shi, P., Zhou, Y., Li, Y., et al. 2014. Response of soil respiration to grazing in an alpine meadow at three elevations in Tibet. Science World Journal 2014:1-9.

Fu, G., Zhang, X., Zhang, Y., Shi, P., Li, Y., Zhou, Y., et al. 2013. Experimental warming does not enhance gross primary production and above-ground biomass in the alpine meadow of Tibet. Journal of Applied Remote Sensing 7:6451-6465.

Grinhut, T., Hertkorn, N., Schmitt-Kopplin, P., Hadar, Y., and Chen, Y. 2011. Mechanisms of humic acids degradation by white rot fungi explored using 1H NMR spectroscopy and FTICR mass spectrometry. Environmental Science and Technology 45:2748-2754. doi:10.1021/es1036139.

Guan, S., An, N., Zong, N., He, Y., Shi, P., Zhang, J., et al. 2018. Climate warming impacts on soil organic carbon fractions and aggregate stability in a Tibetan alpine meadow. Soil Biology and Biochemistry 116:224-236.

Hammer, O., Harper, D.A.T., and Ryan, P.D. 2001. PAST: Paleontological Statistics software package for education and data analysis. Paleontologia Electronics 4(1):4.

Han, C.L, Sun, Z.X, Shao, S, Wang, Q.B, Libohova, Z, and Owens, P.R. 2021. Changes of soil organic carbon after wildfire in a boreal forest, Northeast China. Agronomy 11(10):1925. doi.10.3390/agronomy11101925.

Hu, Y., Wang, Z., Wang, Q., Wang, S., Zhang, Z., Zhang, Z., et al. 2017. Climate change affects soil labile organic carbon fractions in a Tibetan alpine meadow. Journal of Soil Sediments 17:326-339.

Huang, X., Jiang, H., Li, Y., Ma, Y., Tang, H., Ran, W., et al. 2016. The role of poorly crystalline iron oxides in the stability of soil aggregate-associated organic carbon in a rice-wheat cropping system. Geoderma 279:1-10.

Karst, J., and Landhäusser, S.M. 2014. Low soil temperatures increase carbon reserves in *Picea mariana* and *Pinus contorta*. Annals of Forest Science 71:371-380.

Kong, J., He, Z., Chen, L., Yang, R., Du, J., Lin, P., et al. 2020. Elevational gradients and distributions of aggregate associa ted organic carbon and nitrogen and stability in alpine forest ecosystems. Soil Science Society of America Journal 1971-1982. https://doi.org/10.1002/saj2.20121.

Li, C., Cao, Z., Chang, J., Zhang, Y., Zhu, G., Zong, N., et al. 2017. Elevational gradient affect functional fractions of soil organic carbon and aggregates stability in a Tibetan alpine meadow. CATENA 156:139-148. doi.10.1016/j.catena.2017.04.007.

Liu, M., Chang, Q., Qi, Y., Liu, J., and Chen, T. 2014. Aggregation and soil organic carbon fractions under different land uses on the table land of the Loess Plateau of China. CATENA 115:19-28. doi:10.1016/j.catena.2013.11.002.

O'Brien, S.L., and Jastrow, J.D. 2013. Physical and chemical protection in hierarchical soil aggregates regulates soil carbon and nitrogen recovery in restored perennial grasslands. Soil Biology and Biochemistry 61:1-13.

Oelofse, M., Markussen, B., Knudsen, L., Schelde, K., Olesen, J.E., Jensen, L.S., et al. 2015. Do soil organic carbon levels affect potential yields and nitrogen use efficiency? An analysis of winter wheat and spring barley field trials. European Journal of Agronomy 66:62-73. doi:10.1016/j.eja.2015.02.009.

Oueslati, I., Allamano, P., Bonifacio, E., and Claps, P. 2013. Vegetation and topographic control on spatial variability of soil organic carbon. Pedosphere 23(1):48-58. doi.10.1016/S1002 0160 (12)60079-4.

Padbhushan, R., Rakshit, R., Das, A., and Sharma, R.P. 2016. Effects of various organic amendments on organic carbon pools and water-stable aggregates under a scented rice-potato-onion cropping system. Paddy and Water Environment 14:481-489. doi:10.1007/s10333-015-0517-8.

Putra, M.J.N.F.I.A., Soemarno, N., and Suntra, R. 2016. Humification degree and its relationship with some soil physical characteristics on robusta coffee (*Coffea canephora*) plantation. Journal of Degraded and Mining Lands Management 3(4):649-658. doi:10.15243/jdmlm.2016.034.649.

Qiu, L., Wei, X., Gao, J., and Zhang, X. 2015. Dynamics of soil aggregate-associated organic carbon along an afforestation chronosequence. Plant and Soil 391:237-251.

Reddy, S., Nagaraja, M.S., Raj, T.S.P., Dumgond, P., and Vignesh, N.S. 2012. Soil humic and fulvic acid fraction land use under different systems. The Madras Agricultural Journal 99 (7-9):507-510.

Seran, D. 2011. Humifikasi pada tanah di beberapa tipe tegakan hutan Papua Barat dengan pendekatan spektrofotometrik. Jurnal Penelitian Hutan dan Konservasi Alam 8(1):87-94.

Shang, W., Wu, X., Zhao, L., Yue, G., Zhao, Y., Qiao, Y., et al. 2016. Seasonal variations in labile soil organic matter fractions in permafrost soils with different vegetation types in the central Qinghai-Tibet Plateau. CATENA 137:670-678.

Smith, A.P., Marín-Spiotta, E., de Graaff, M.A., and Balser, T.C. 2014. Microbial community structure varies across soil organic matter aggregate pools during tropical land cover change. Soil Biology and Biochemistry 77:292-303.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., et al. 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems and Environment 164:80-99.

Tang, L., Dong, S., Liu, S., Wang, X., Li, Y., Su, X., et al. 2015. The relationship between soil physical properties and alpine plant diversity on Qinghai Tibet Plateau. Eurasian Journal of Soil Science 4:88-93. doi:10.18393/ejss.31228.

Tripathi, B.M., Stegen, J.C., Kim, M., Dong, K., Adams, J.M., and Lee, Y.K. et al. 2018. Soil pH mediates the balance between stochastic and deterministic assembly of bacteria. ISME Journal 12:1072-1083. doi.10.1038/s41396-018-0082-4.

Wan, Q., Zhu, G., Guo, H., Zhang, Y., Pan, H., Yong, L., et al. 2019. Influence of vegetation coverage and climate environment on soil organic carbon in the Qilian Mountains. Scientific Reports 9:17623. doi.10.1038/s41598-019-53837-4.

Wang, S., Fan, J., Song, M., Yu, G., Zhou, L., Liu, J., et al. 2013. Patterns of SOC and soil ^{13}C and their relations to climatic factors and soil characteristics on the Qinghai-Tibetan Plateau. Plant and Soil 363:243-255. doi:10.1007/s11104-012-1304-6.

Wang, Z., Hartemink, A.E., Zhang, Y., Zhang, H., and Ding, M. 2016. Major elements in soils along a 2.8-km altitudinal gradient on the Tibetan Plateau, China. Pedosphere 26:895-903.

Yu, H., Ding, W., Luo, J., Geng, R., Ghani, A., and Cai, Z. 2012. Effects of long-term compost and fertilizer application on stability of aggregate-associated organic carbon in an intensively cultivated sandy loam soil. Biology and Fertility of Soils 48:325-336.

Yuan, Y., Si, G., Wang, J., Luo, T., and Zhang, G. 2014. Bacterial community in alpine grasslands along an altitudinal gradient on the Tibetan Plateau. FEMS Microbiology Ecology 87:121-132.

Zhang, Q., Shao, M.A., Jia, X., and Zhang, C. 2018. Understory vegetation and drought effects on soil aggregate stability and aggregate-associated carbon on the Loess Plateau in China. Soil Science Society of America Journal 82:106-114.

Zhang, W., Wu, X., Liu, G., Dong, Z., Zhang, G., Chen, T., et al. 2014. Tag-encoded pyrosequencing analysis of bacterial diversity within different alpine grassland ecosystems of the Qinghai-Tibet Plateau, China. Environmental Earth Sciences 72:779-786. doi:10.1007/s12665-013-3001-z.

Zhao, H., Sun, J., Xu, X., and Qin, X. 2017. Stoichiometry of soil microbial biomass carbon and microbial biomass nitrogen in China's temperate and Alpine Grasslands. European Journal of Soil Biology 83:1-8. doi:10.1016/j.ejsobi.2017.09.007.

Zhu, G., Lei, D., and Shangguan, Z. 2018. Effects of soil aggregate stability on soil N following land use changes under erodible environment. Agriculture, Ecosystems and Environment 262:18-28.