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Relationship between Soil Organic Carbon Stocks and Clay Content under Different Climatic Conditions in Central China

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Abstract: Understanding the association between soil organic carbon (SOC) and texture under different climatic conditions is important for assessing the effects of future climate changes on SOC stocks. In this study, we conducted a climatic gradient experiment covering three climate types (humid, sub-humid, and semi-arid) with a steep rainfall ranging from 345 to 910 mm, and specifically determined SOC dynamics, clay content, and vegetation and soil characteristics. The results showed that, from semi-arid to humid regions, SOC stocks, SOC, and clay content increased synchronously and were closely related in layers of depths of both 0–10 and 10–20 cm. In contrast, under similar climatic conditions, SOC dynamics were mainly affected by vegetation and soil characteristics, especially total nitrogen and total phosphorus dynamics, but not the soil clay content. Therefore, these results suggest that the relationship between SOC stocks and clay content depended on scale sizes. Specifically, on a larger scale with different climatic gradients, the climate may partly determine the changes in SOC and clay dynamics, whereas, at a smaller scale where climate type does not vary considerably, the changes in SOC stocks and clay content may be related to vegetation diversity and soil nutrient dynamics. These results may contribute to future model development and the projection of changes in soil carbon storage.

Keywords: climatic conditions; rainfall gradient; clay content; soil organic C; soil moisture

1. Introduction

Soil organic carbon (SOC) is the largest constituent of the Earth's terrestrial carbon pool [1], and slight C losses from the soil may lead to considerable changes in atmospheric CO₂ concentration [2], which would affect the magnitude of future climate change [3]. Numerous studies [4–6] have reported SOC dynamics, particularly in the efforts to physically protect organic C. For example, Jagadamma and Lal [7] concluded that the clay fraction in the soil accumulated more SOC than other fractions from several long-term agricultural management practice studies. Based on data from several short-term litter decomposition studies, Giardina [8] reported a decline in SOC decomposition rates with increasing clay content. However, few studies have assessed the scaling properties of the relationships between SOC stocks and clay content under different climate types, which is indispensable for accurate future predictions of changes in terrestrial C sources and sinks.

In response to diverse rainfall regimes, the interactions between SOC stocks and clay content may have different responses and outcomes [9]. For example, the accumulations of SOC in heavy rainfall

areas were shown to have been largely regulated by clay minerals [10], whereas some studies showed that SOC was weakly related to clay particles in semi-arid sandy regions, e.g., [11,12]. Goebel [13] partly attributed this effect to soil water repellency, which may aggravate runoff flow and erosion [14] and ultimately result in the loss of soil organic matter (SOM) [15]. In addition, according to the theory of SOC saturation [16,17], sandy soils have a limited capacity to stabilize organic compounds on mineral surfaces compared with clay, which affects the capacity, magnitude, and rate of SOC storage [18]. Thus, this leads to the hypothesis that the relationship between the SOC dynamics and clay content may differ with climatic types.

Generally, SOC dynamics also vary because of different vegetation types locally [4,11,19]. Hence, the link between SOC stocks and clay content still remains controversial. Previous studies on various land-use practices have emphasized that the SOC levels rise linearly with increasing clay content [20,21]. However, Ren [22] and Martens [23] et al. observed little or no differences in clay content on a local scale. Gonsalves [5] demonstrated that other factors not related to soil texture could influence SOC dynamics on a small scale. Indeed, soil nutrients, moisture, and plant feedbacks may also contribute to the effects of vegetation dynamics on the C-cycle [24]. In addition, Angers and Caron [25] showed that soil structure (e.g., clay content) might also be modified by vegetation characteristics through a range of mechanisms. Therefore, the effects of different biotic and abiotic factors on SOC dynamics [10] and clay grains [26,27] could vary substantially. Under such situations, the responses of clay particles or SOC may differ with the research scale. Therefore, these profound differences present a hindrance to our understanding of soil C cycling under future climate scenarios and, therefore, research studies on the link between SOC stocks and clay content are urgently needed.

To elucidate SOC dynamics and their association with the clay content, a climatic gradient experiment covering three climate types (humid, sub-humid, and semi-arid) with rainfall ranging from 345 to 910 mm was designed. We compared the responses of SOC and clay to changes in vegetation and soil properties. We hypothesized that (1) SOC stocks showed a close relationship with clay content on a regional scale with different climatic gradients; and (2) the relationship was driven by the wide gradients of soil moisture; however; (3) on the local scale, SOC dynamics may be mainly affected by soil nutrients, while the clay content was modified by vegetation characteristics. Based on this hypothesis, the present study aimed to: (1) examine the roles that scale properties play in the relationship between SOC stocks and clay content; and (2) dissect the driving variables of SOC dynamics and clay content, and their relationships on both regional and local scales.

2. Materials and Methods

2.1. Study Areas and Experimental Design

The study was carried out at six experimental sites (QL, FX, YC, AS, MZ, and YL) (Figure 1) in July 2016 along a precipitation gradient ranging from 345 to 910 mm (Figure 2) in central China (33°59'58" N 37°24'45" N, 107°41'30" E 110°17'59" E). Details of these sites are presented in Table 1. Of the areas in which the study was conducted, native vegetation was only present in QL and YL, while that in FX, YC, AS, and MZ, located in the Loess Plateau area, has changed greatly over the historical period—it remained natural (dominated by grassland and broadleaved forest) before A.D. 670, with a forest coverage of 53% [28]. Thereafter, the vegetation of the Loess Plateau started to deteriorate slowly. The rapid increase in human population and the demand for cultivated land during the period 1368–1912 had considerable adverse effects on the vegetation in this region, with forest coverage reducing to 4% [29]. It continued to deteriorate considerably until the 1950s owing to the influence of destructive factors such as famine, war, and so on. Vegetation rehabilitation began in this region in the 1970s, particularly the implementation of the 'Grain for Green (GGP) Project' by the Chinese government in 1999 [22]. As this is a key region for water and soil conservation, vegetation coverage in the Loess Plateau has improved considerably. The native vegetation in this area has essentially disappeared owing to human disturbance, and the existing vegetation is mainly composed

of secondary vegetation originating via human planting and closed fencing [30]. For these reasons, representative vegetation with large planting areas in this region was chosen for the present study; the specific vegetation types of each region are shown in Table 2. All the research plots selected in FX, YC, AS, and MZ were surrounded by fences from 1999 to 2002 to isolate them from disturbance and destruction by human and animals, and for the natural restoration of vegetation to carry out the long-term spot experiment. Because of the consequent greater vegetation cover and reduced anthropogenic disturbance, water and soil erosion essentially did not occur in all sampling locations, and the clay and nutrient loss caused by soil erosion was avoided; this decreased the redistribution of soil indexes and, therefore, ensured the accuracy of the experimental results.

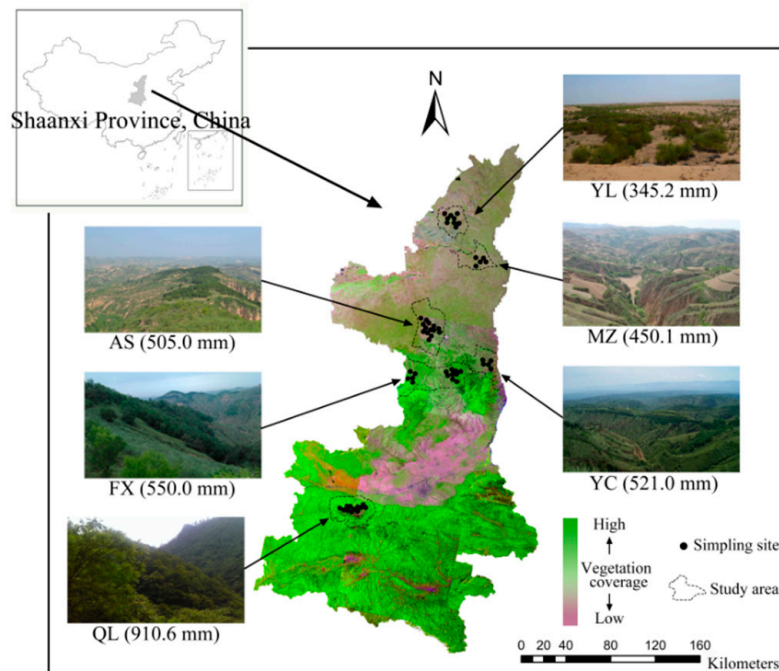


Figure 1. Variability of vegetation coverage in the study area, and location and general view of the experimental field sites.

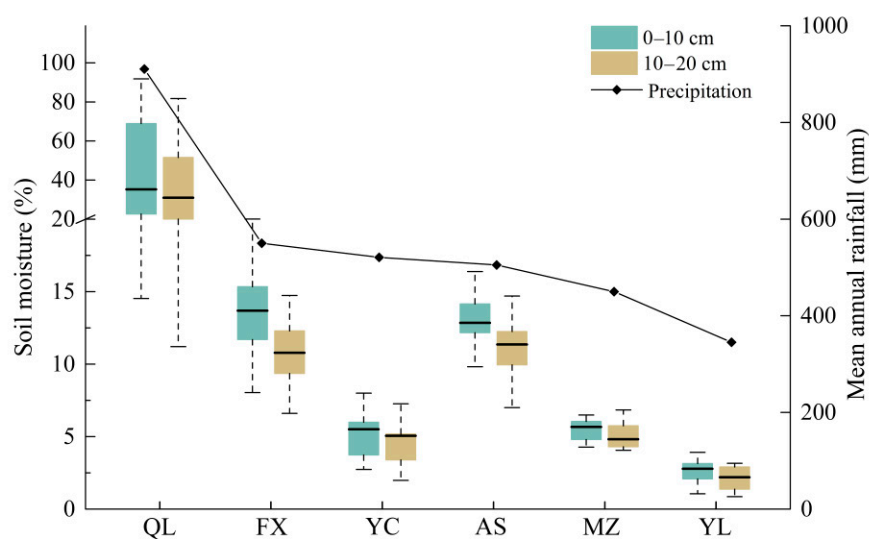


Figure 2. Mean annual rainfall and soil moisture content at different sites along the climatic gradient.

Table 1. General information of the sampling sites in our study.

	Geographical Coordinates	Altitude (m)	Slope Gradient (°)	T (°C)	PH	SBD (g/cm ³)		Soil Type ^a
						0–10 cm	10–20 cm	
QL	33°59'58"~34°05'48" N; 107°41'30"~107°48'36" E	2355	25–45	11.4	5.98 ± 0.03 d	1.05 ± 0.00 e	1.09 ± 0.00 f	Orthic Acrisols
FX	35°59'39"~36°08'42" N; 108°41'13"~109°40'45" E	1227	5–43	8.1	8.01 ± 0.08 c	1.15 ± 0.00 d	1.17 ± 0.00 e	Chromic Cambisols
YC	36°04'48"~36°09'52" N; 110°17'59"~110°18'33" E	875	0–12	10	8.25 ± 0.02 b	1.17 ± 0.01 c	1.21 ± 0.01 c	Chromic Cambisols
AS	36°43'45"~36°54'36" N; 109°15'16"~109°21'06" E	1237	12–45	8.8	8.38 ± 0.02 ab	1.15 ± 0.00 d	1.19 ± 0.00 d	Chromic Cambisols
MZ	37°45'37"~37°51'47" N; 110°10'48"~110°15'43" E	1071	18–30	8.5	8.51 ± 0.05 a	1.21 ± 0.00 b	1.24 ± 0.01 b	Calcic Cambisols
YL	37°24'45"~38°28'33" N; 109°35'42"~109°49'22" E	1151	5–35	10.7	8.39 ± 0.04 ab	1.38 ± 0.00 a	1.43 ± 0.00 a	Calcic Cambisols

Abbreviations: QL, Qinling; FX, Fuxian; YC, Yichuan; AS, Ansai; MZ, Mizhi; YL, Yulin; T, mean annual temperature; SBD, soil bulk density, and the same below. Values are means ± standard error. Different letters within a variable indicate significant differences ($p < 0.05$). “a”, the soil types were classified by FAO [31].

Table 2. Detailed vegetation characteristics of each research site.

Site	Climatic Conditions	Major Vegetation Types	TCD (%)	SCD (%)	GC (%)	Vegetation Community
QL	humid	native forest	87.31 ± 3.03 a	25.77 ± 5.03 b	27.31 ± 8.50 c	Trees: <i>Quercus liaotungensis</i> Koidz; <i>Quercus aliena</i> var. <i>acutiserrata</i> ; <i>Larix chinensis</i> Beissn; <i>Abies fargesii</i> Franch.
FX	sub-humid	secondary forest	73.16 ± 2.63 b	21.68 ± 3.40 bc	39.21 ± 5.02 bc	Trees: <i>Betula platyphylla</i> Suk; <i>Populus davidiana</i> Dode; <i>Pinus tabulaeformis</i> Carr; <i>Platycladus orientalis</i> (L.) Franco; <i>Quercus liaotungensis</i> Koidz. Shurbs: <i>Rhamnus utilis</i> Decne; <i>Acer ginnala</i> Maxim; <i>Celtis bungeana</i> Bl.
YC	sub-humid	artificial vegetation	60.00 ± 7.42 b	5.20 ± 0.80 c	48.00 ± 7.58 abc	Trees: <i>Armeniaca sibirica</i> (L.) Lam; <i>Pinus tabulaeformis</i> Carr; <i>Robinia pseudoacacia</i> Linn; <i>Platycladus orientalis</i> (L.) Franco.
AS	semi-arid	artificial vegetation	56.88 ± 4.62 b	43.75 ± 8.26 a	65.06 ± 3.72 a	Trees: <i>Robinia pseudoacacia</i> Linn. Shurbs: <i>Caragana korshinskii</i> Kom. Grass: <i>Artemisia vestita</i> Wall; <i>Astragalus melilotoides</i> Pall; <i>Carex hirta</i> Linn; <i>Stipa grandis</i> P. Smirn.
MZ	semi-arid	artificial vegetation	61.00 ± 9.11 b	11.12 ± 2.27 bc	63.00 ± 8.89 a	Trees: <i>Populus simonii</i> Carr; <i>Pinus tabulaeformis</i> Carr; <i>Armeniaca sibirica</i> (L.) Lam; <i>Platycladus orientalis</i> (L.) Franco; <i>Robinia pseudoacacia</i> Linn.
YL	semi-arid	desert scrub	3.89 ± 0.83 c	16.67 ± 5.21 bc	61.11 ± 5.32 ab	Trees: <i>Salix matsudana</i> Koidz; <i>Salix cheilophila</i> Schneid. Shurb: <i>Hedysarum scoparium</i> Fisch; <i>Artemisia ordosica</i> Krasch. Grass: <i>Artemisia desertorum</i> Spreng; <i>Amorpha fruticosa</i> Linn.

TCD, Tree crown density; SCD, Shrub crown density; GC, Grass coverage. Values are means ± standard error. Different letters within a variable indicate significant differences ($p < 0.05$).

The research sites were selected to represent three climatic regions and encompass a broad array of ecosystem characteristics. The reduction in rainfall levels along the climatic gradient caused vegetation changes ranging from a humid (QL) native forest to sub-humid (FX) secondary forest, sub-humid (YC), and semi-arid (AS and MZ) artificial vegetation. The region at the driest end of the gradient (YL) was dominated by desert scrub. A total of 59 research plots was eventually established. On each plot at each site, three subplots (25 m × 25 m) were randomly set up as true replicates, and the distance between them exceeded the spatial dependence (<13.5 m) of most soil indexes [32]. In addition, five 1 × 1 m² quadrats were randomly selected in each subplot to investigate the herbaceous plant, tree seedling, shrub, and vine characteristics under the canopies [33]. All plants were identified to species by name, and the number of individuals, mean height, and mean coverage were recorded for each plant quadrat [34].

2.2. Soil Sampling

Five random points spaced >3 m apart were selected in each subplot for soil sampling. Bulk soil samples were collected at depths of 0–10 and 10–20 cm from each subplot using a soil auger (5 cm inner diameter) after cutting the aboveground herbaceous layer and removing the litter. The samples from the five points of the same layer were homogeneously mixed into one sample for each subplot. Thus, there were 354 samples in total (59 plots × 3 subplots × 2 soil layers). The soil samples were divided into two subsamples, and one was immediately transported to the laboratory for the soil water content (SWC) analysis [22]. The other sample was air-dried and sieved using 2 mm (for soil particle-size distribution [PSD] estimation) and 0.25 mm (for soil physicochemical properties analysis) screens prior to laboratory analysis [20].

2.3. Soil Analysis

Soil organic carbon (SOC) content was determined using the Walkley-Black oil bath-K₂Cr₂O₇ titration method [35]. The concentration of soil total nitrogen (TN) was measured using the Kjeldahl method [36], and total phosphorus (TP) content was determined by the molybdenum blue colorimetric method using an Auto Discrete Analyzer (Clever Chem 200) [37]. The stocks of SOC, TN, and TP (kg/m²) at depths of 0–10 and 10–20 cm were calculated as follows:

$$S_i = \frac{C_i \times D_i \times SBD_i}{100} \quad (1)$$

where S_i (kg/m²) represents the stocks of SOC, TN, and TP in the soil layer i ; C_i (g/kg) is the content of SOC, TN, and TP of the i th soil layers; D_i (cm) is the thickness of the i th soil layers; and SBD_i (g/cm³) is the soil bulk density of the i th soil layers.

Soil particle size distribution (PSD) was described in terms of the percentages of clay (<2 μm), silt (50~2 μm) and sand (2000~50 μm), measured using a laser diffraction technique via a Malvern MS 2000 (Malvern Instruments, Malvern, England). The specific measurements of soil PSD were performed as described by Jin [19]. Soil pH was determined using the potentiometric method in a 1:2.5 air-dried soil-water (w/w) suspension and measured using a pH meter equipped with a glass electrode [38]. Soil water content (SWC) was assessed gravimetrically by oven drying to constant mass at 105 °C and values were then expressed as a percentage of soil water to dry soil weight. Soil bulk density (SBD) was sampled by the cutting ring (100 cm³ volume) method and oven-dried at 105 °C until reaching constant weight, calculated as the ratio of weight of undisturbed cores to the container volume.

2.4. Vegetation Diversity

The Shannon-Wiener diversity index (H), Gleason richness index (E), Pielou's evenness index (J), and Simpson's diversity (D) index of plant species diversity were calculated using the following formulas [33,39]:

$$H = - \sum P_i \ln P_i \quad (2)$$

$$E = (S - 1) / \ln N \quad (3)$$

$$J = H / \ln S \quad (4)$$

$$D = 1 - \sum P_i^2 \quad (5)$$

where S , N , and P_i are, respectively, the total number of species i , the total number of individuals, and the proportional density of i (the number of individuals of species i divided by the total number of individuals of all species) in each $1 \text{ m} \times 1 \text{ m}$ plant quadrat.

2.5. Data Analysis

A repeated-measures analysis of variance (ANOVA) and least significant difference (LSD) test were used to determine the statistically significant differences in the soil properties and vegetation characteristics (species diversity indexes) among the six research sites. Statistical significance was accepted at $p < 0.05$ using Duncan's test. Pearson's correlation and redundancy analysis (RDA) was used to analyze the correlations between soil chemical properties, soil PSD, and vegetation characteristics at both the regional and the local scale. Statistical analyses were performed using the statistical package for the social sciences (SPSS) version 19.0 for Windows (SPSS Inc, Chicago, IL, USA). The analysis of correlation and RDA were conducted using the R software package v.3.2.3. Figures were constructed using Origin 8.0. Each variable was replicated three times, and the results are reported as the mean \pm standard error.

3. Results

3.1. Changes in Soil Properties

Climatic gradients had considerable but different effects on soil clay, silt, and sand particle content (Table 3). The soil clay, silt, and sand content ranged from 4.9% to 30.4%, 4.9% to 60.8%, and 90.4% to 8.8%, respectively, at the 0–10 cm depth, whereas the corresponding ranges at a depth of 10–20 cm were 9.5% to 30.4%, 12.1% to 56.8%, and 78.4% to 12.8%, respectively, with increasing rainfall. Furthermore, there were no significant differences ($p > 0.05$) between values at the two sampling depths. In general, the mean clay content decreased by 84.1% and 92.1% for the 0–10 and 10–20 cm soil depths, respectively, with decreasing rainfall. In addition, the average soil bulk density (Table 1) was ranked in the following decreasing order: YL (1.38 g/cm³) > MZ (1.21 g/cm³) > YC (1.17 g/cm³) > AS (1.16 g/cm³) > FX (1.15 g/cm³) > QL (1.05 g/cm³) at the 0–10 cm depth; and YL (1.43 g/cm³) > MZ (1.24 g/cm³) > YC (1.21 g/cm³) > AS (1.19 g/cm³) > FX (1.17 g/cm³) > QL (1.09 g/cm³) at the 10–20 cm depth. Finally, the SWC increased significantly with increasing precipitation, ranging from 2.54% to 47.91% and 2.08% to 38.64% at the two soil depths at the driest (YL) and wettest (QL) ends of the gradient, respectively.

Table 3. Volume contents of sand, silt, and clay of PSD at different sampling sites in our study.

Site	Clay (<2 μm)	Silt (50~2 μm)	Sand (2000~50 μm)
0–10 cm			
QL	30.4 \pm 0.71 a	60.8 \pm 0.57 a	8.8 \pm 0.90 e
FX	23.9 \pm 0.32 b	62.3 \pm 0.34 a	13.9 \pm 0.34 c
YC	23.4 \pm 0.63 b	55.9 \pm 1.22 b	20.7 \pm 1.76 d
AS	18.1 \pm 0.29 c	45.3 \pm 0.63 c	36.5 \pm 0.62 b
MZ	18.1 \pm 0.65 c	47.1 \pm 1.59 c	34.8 \pm 2.10 b
YL	4.9 \pm 0.37 d	4.8 \pm 1.15 d	90.4 \pm 1.49 a
10–20 cm			
QL	30.4 \pm 0.95 a	56.8 \pm 0.62 a	12.8 \pm 1.24 d
FX	24.3 \pm 0.20 b	55.5 \pm 0.65 ab	20.3 \pm 0.72 c
YC	24.0 \pm 0.12 b	54.2 \pm 0.74 b	21.8 \pm 0.78 c
AS	18.5 \pm 0.150 c	49.3 \pm 0.57 c	32.2 \pm 0.59 b

Table 3. Cont.

Site	Clay (<2 μm)	Silt (50~2 μm)	Sand (2000~50 μm)
MZ	18.4 \pm 0.18 c	48.2 \pm 2.08 c	33.5 \pm 2.13 b
YL	9.5 \pm 0.44 d	12.1 \pm 0.21 d	78.4 \pm 0.36 a

PSD, Soil particle size distribution. Different letters within a variable indicate significant differences ($p < 0.05$).

With regard to soil chemistry properties (Table 1), the soil pH varied from 8.01 to 8.51 at almost all sites except for QL (5.98) and slightly increased ($p > 0.05$) with decreasing precipitation. The SOC, TN, and TP concentrations (Figure S1) and stocks (Figure 3) increased dramatically at the 0–10 cm depth with increasing rainfall and showed a similar trend to that of the variations in clay content (Figure S2). In addition, the stocks of SOC, TN, and TP tended to decrease with soil depth at all sites and showed no obvious variation trends at the 10–20 cm layer.

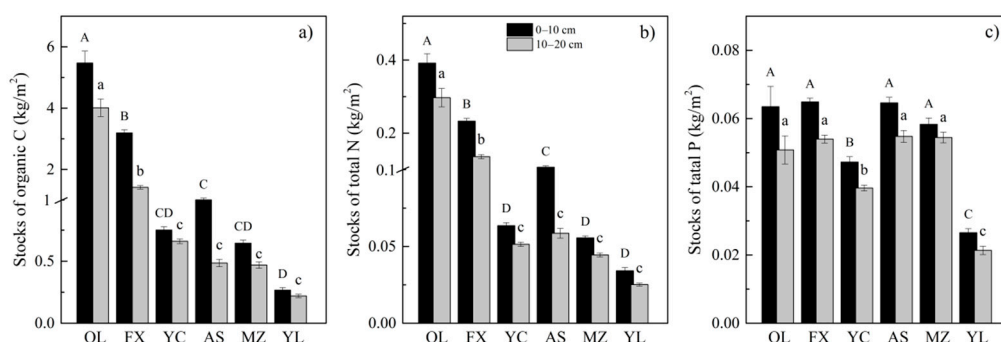


Figure 3. Variations of the stocks of soil organic carbon (a), total nitrogen (b), and phosphorus (c) at different sites along the rainfall gradient. Values are means \pm standard error. Different uppercase letters and lowercase letters indicate significant differences ($p < 0.05$) at 0–10 and 10–20 cm, respectively; this is the same below.

3.2. Changes in Vegetation Diversity along the Rainfall Gradient

According to the results of the plant species diversity analyses under different climatic conditions (Figure 4), the Shannon-Wiener's diversity index, Simpson's diversity, and Gleason richness index differed significantly along the rainfall gradient ($p < 0.05$). In addition, the Shannon-Wiener's diversity and Gleason richness indexes tended to show a unimodal change with increasing rainfall and exhibited the highest values at the AS site (3.52 and 3.48, respectively). However, Pielou's evenness index showed no obvious difference along the rainfall gradient, with the following trend: MZ (1.18) \approx YC (1.18) > YL (1.17) > AS (1.13) > QL (1.07) > FX (0.96).

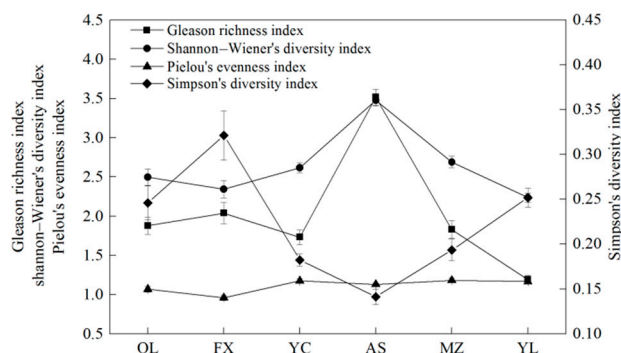


Figure 4. Variations of vegetation characteristics at different sites along the climatic gradient.

3.3. Relationship between Vegetation Characteristics, Soil PSD, and Soil Chemical Properties

Pearson's coefficient (Table 4) revealed a significant correlation ($p < 0.05$) between soil nutrients and PSD at the regional but not the local scale. Changes in SOC stock were most closely related to the clay content ($p < 0.05$). In addition, the first two axes of the RDA analysis (Figure 5) explained 78.98% of the total variance for all study sites along the climatic gradients with 345 to 910 mm and showed that the SOC stock and clay content were related to the precipitation. Furthermore, the vegetation characteristics, except for Pielou's evenness index, had no obvious effect on the soil PSD and SOC stock. The results of the RDA analysis of individual sites showed the diverse effects of soil and vegetation characteristics on SOC stock and clay content. At all sites, clay content was positively correlated with vegetation diversity (Simpson diversity index and Shannon-Wiener diversity index), but negatively correlated with the evenness (YC, AS, MZ, and YL sites) and richness (FX) of the plant community. Furthermore, Figure 6 shows that TN and TP stocks were positively correlated with SOC stocks at the QL, FX, YC, and YL sites, while SOC stocks were positively correlated with TN at the AS and MZ sites. In summary, vegetation characteristics affected soil clay content at different levels, and SOC stocks were mainly related to TN and TP stocks at the local scale.

Table 4. Correlation analysis of soil particles and soil nutrients at different sampling sites.

Study sites	PSD	Stock of Soil Nutrients			Content of Soil Nutrients		
		SOC	TN	TP	SOC	TN	TP
All sites	Clay	0.649 **	0.655 **	0.397 **	0.648 **	0.658 **	0.467 **
	Silt	0.500 **	0.507 **	0.552 **	0.491 **	0.501 **	0.589 **
	Sand	−0.565 **	−0.572 **	−0.523 **	−0.559 **	−0.569 **	−0.572 **
QL	Clay	−0.051	0.024	−0.084	−0.042	0.031	−0.073
	Silt	0.154	0.135	0.069	0.175	0.155	0.090
	Sand	−0.058	−0.100	0.019	−0.076	−0.117	−0.002
FX	Clay	−0.027	−0.034	0.073	−0.017	−0.023	0.085
	Silt	0.589 **	0.570 **	0.558 **	0.586 **	0.572 **	0.575 **
	Sand	−0.569 **	−0.549 **	−0.575 **	−0.570 **	−0.555 **	−0.596 **
YC	Clay	0.235	−0.036	−0.296	0.226	−0.025	−0.271
	Silt	0.379 *	0.344	−0.131	0.410 *	0.361	−0.064
	Sand	−0.366 *	−0.248	0.199	−0.386 *	−0.264	0.140
AS	Clay	−0.023	0.012	0.068	−0.025	0.008	0.056
	Silt	−0.132	−0.161	0.184	−0.146	−0.179	0.137
	Sand	0.137	0.155	−0.205	0.152	0.173	−0.154
MZ	Clay	0.022	−0.240	−0.159	0.029	−0.215	−0.142
	Silt	−0.157	−0.218	−0.313	−0.144	−0.193	−0.287
	Sand	0.137	0.243	0.318	0.125	0.218	0.294
YL	Clay	−0.024	−0.191	−0.099	−0.061	−0.229	−0.147
	Silt	0.161	−0.009	0.013	0.132	−0.047	−0.031
	Sand	−0.101	0.079	0.029	−0.067	0.120	0.077

“*” and “**” indicate a significant correlation at the 0.05 level and 0.01 level, respectively. All sites means correlation analysis at a regional scale. SOC, Soil organic carbon; TN, Total nitrogen; TP, Total phosphorus.

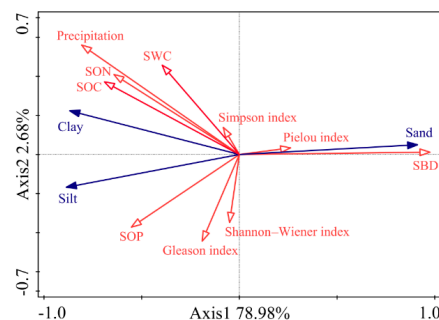


Figure 5. Ordination plots of the results from the redundancy analysis (RDA) to identify the correlations among the PSD (blue arrows), vegetation characteristics, and soil properties (red arrows) on a regional scale. SOC, stock of soil organic carbon; SON, stock of total nitrogen; SOD, stock of total phosphorus.

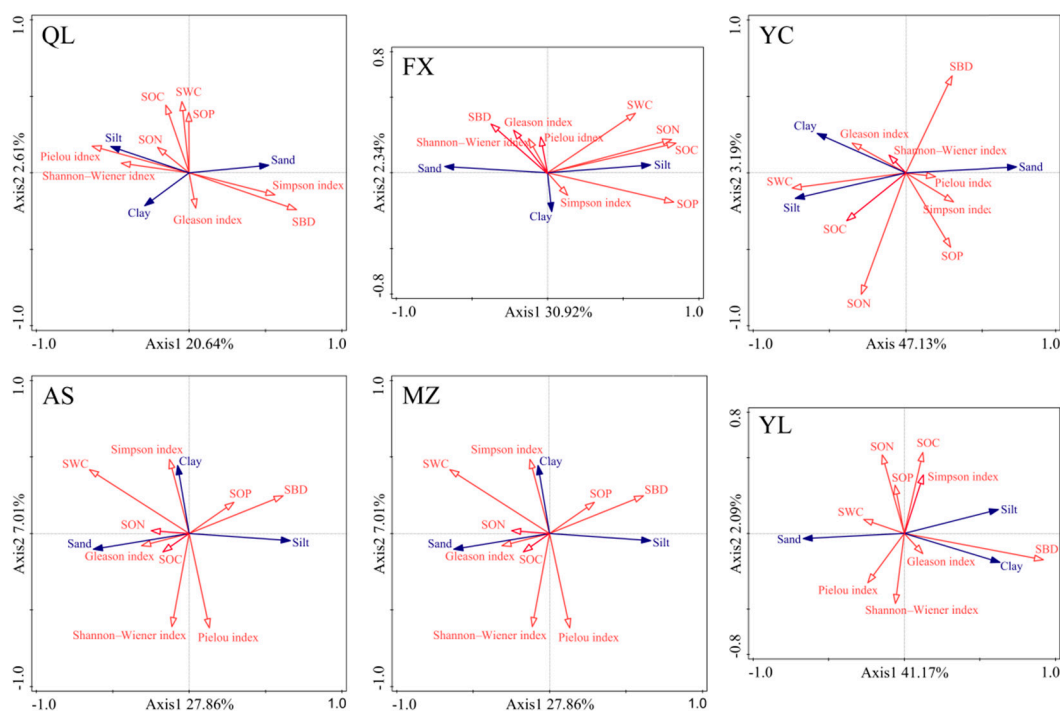


Figure 6. Ordination plots of the results from the redundancy analysis (RDA) to identify the correlations among the PSD (blue arrows), plant characteristics, and soil properties (red arrows) on a local scale. SOC, stock of soil organic carbon; SON, stock of total nitrogen; SOP, stock of total phosphorus.

4. Discussion

4.1. Relationship between Clay and SOC Depended on Precipitation in Different Climate Types

The terrestrial ecosystem SOC pool and soil physical quality are mainly controlled by climatic conditions across different biogeographical zones [26,40]. In this study, we confirmed that the SOC stocks and clay content increased with higher precipitation levels (Figure 2, Figure 3 and Figure S3 and Table 3). This observation suggests that shifts in climatic conditions may regulate the relationship between SOC stocks and clay content (Figure 5). The effect of rainfall and temperature may underlie this phenomenon, as higher rainfall and temperature favor the mineralization of soil minerals and lead to the production of more clay particles in soil [41,42]. Meanwhile, higher rainfall supplies more water to the soil and promotes the development of net primary productivity (NPP) [40,43]; the higher NPP can import carbon (C) into the soil subsystem in the form of litter and root exudates [44,45]. Moreover, a high clay content may also lead to more organic C molecules being adsorbed by clay surfaces owing to the larger surface area and the presence of polyvalent cations forming organo-mineral complexes to control the protection of SOC from microbial and enzymatic decay, in turn increasing SOC storage [7,46–48]. The present study thus demonstrated that SOC stocks increase with the increase of clay content caused by climate change on a large scale.

However, several studies, such as those by Gonsalves [5], Gruba [4], and Jobbagy and Jackson [40], have indicated that SOC stocks at a location are controlled by the combined effect of various environmental factors including climate, vegetation, parent material, soil texture, land use, etc. The three climate regions we studied underwent loess deposition during the Quaternary climatic oscillation, and loess deposition and soil formation therefore took place simultaneously [28]. However, various clay contents occurred during the soil development as a result of different climatic conditions. For example, the humid-warm vapor movement north from the south is blocked by the Qinling Mountains, and climate becomes gradually drier from QL to YL. At the QL site, eluviation could be facilitated by the hygrothermal climate, resulting in a lower content of CaCO_3 , the migration of Fe and Mn, and obvious clayization [49]. However, the decreased moisture influenced the degree of

soil development in the Loess Plateau region (sites FX, YC, AS, and MZ) and reduced clay content. Indeed, mineral composition analysis by Zheng [50] from 34 loess-paleosol samples in the Loess Plateau revealed similar mineral components in soils from FX to MZ. In addition, only 0.59% of smectite was found by Niu [42] in YL, indicating that the formation and transformation of clay minerals is closely related to climate conditions (Table S1). These results support the viewpoint that the difference in SOC pools at different regions is partly caused by the difference in clay mineral composition [41]. Furthermore, the clay content and storage of SOC may also be affected by historic land-use changes in different study areas [15,23]. For example, compared with the luxuriant vegetation and abundant litter inputs owing to the limited anthropogenic disturbances at QL, the sites in the Loess Plateau (FX, YC, AS, and MZ) suffered from serious wind erosion and soil erosion owing to historical anthropogenic activity, and these considerably contributed to the loss of SOC and fine particles [45,51]. Hence, our analysis highlights the fact that the relationship between clay content and SOC storage can be explained by the combined effects of rainfall, temperature, clay mineral composition, and land use under such climate change. These results will facilitate the future assessment of SOC stocks against the background of global climate change.

4.2. Relationship between Clay and SOC Depended on Vegetation and Soil Properties in Same Climate Type

Despite the significant correlation of clay with soil chemical characteristics reported on the local scale, e.g., [20,21], the relationship among these factors was significantly weaker in our study (Table 4 and Figure S4). Clay content was significantly increased owing to the comprehensive influence of climate, parent material, and soil formation factors on the regional scale, which is beneficial to the protection of SOM from decomposition by adsorption and aggregation, slowing turnover and effectively increasing SOC [19,26,41]. Moreover, increasing clay content also increases the water holding capacity; clay content thus interacts with climate to control the accumulation of SOC. The effects of clay, via water availability, may play an important role by influencing plant productivity and thence inputs to SOC [52]. This could underlie the significant correlation found between SOC stock and clay content at a large scale. However, the similar clay content has little effect on the accumulation of SOC under similar climatic conditions at a smaller scale with similar climate conditions (Figure 6). These trends may be explained in terms of the vegetation diversity, litter input, and root exudates under similar climate conditions (Figures 4 and 5). A previous study [26] has illustrated that vegetation characteristics might be a local modifier of clay content change. Higher plant diversity might be expected to lead to higher root trait diversity [22] and thence to the mechanical breakdown of clod because of the expansion of roots with a varying diameter [53], length, and tortuosity [27]. Furthermore, the canopy and residue cover increase caused by complex plant features decreases the rainwash of finer soil components and ultimately increases clay content [54]. Thus, our results highlighted the significant effect of vegetation characteristics in modifying clay content under similar climatic conditions (Figure 5).

Furthermore, several studies have demonstrated that the change in soil nutrients, caused by variations in the quantity and quality of litter, considerably affects SOC dynamics [11,55]. In our study, SOC was related to TP and TN stocks (Figure 6), indicating the significant role of nutrients in driving the change in SOC stocks at a local scale [56,57]. Other studies have reported that P limitation may constrain C accumulation, where the association between phosphorus and iron or aluminum sesquioxides reduces P availability for microbial growth [56,58,59]. Insufficient P might affect symbiotic nitrogen fixation, ultimately changing the N:P ratio of the soil [22,60]. A threshold value widely used in different ecosystems suggests that low leaf N:P ratios (<14) reflect N limitation, while high N:P ratios (>16) likely reflect P limitation [61,62]. Based on this, different levels of N limitation likely existed in our study area (Table S2). In general, soil N levels play a pivotal role in shaping the structure of the microbial community, which is a component of SOM decomposition [10]. Models [63] and empirical [64] studies have highlighted the fact that C tends to be allocated to microbial growth rather than lost via respiration and extracellular enzymes as TN is increased, leading to decreased respiration and an increased accumulation of organic C [57]. Although the microbial biomass C and metabolic

quotient were not evaluated in the present analyses, pioneer studies [51,65,66] at similar sites suggest that changes might occur in microbial allocation to growth versus respiration. This interpretation was partially supported by our study, in that a higher TN stock combined with a higher SOC stock (Figure 3). Therefore, the substantial synergistic effect of N and P might affect microbial characteristics and alter the decomposition process of SOM, ultimately affecting SOC dynamics.

5. Conclusions

Our study showed that SOC stock and clay percentage decreased linearly from humid climatic conditions to the semi-arid sites, suggesting that these changes were partly controlled by rainfall regimes at a regional scale. However, at the local scale, TN and TP were identified to be the key driving factors for SOC dynamics, whereas vegetation characteristics may be a local modifier of clay content under similar climatic conditions. Therefore, the correlation between SOC stock and clay content may be scale- and climate-dependent, and we speculated that the large moisture difference played an essential role in driving the significant positive relationship between SOC and clay in our research area. Further research aimed at simulating SOC dynamics under scenarios of future projected changes in the global climate may need to consider scaling effects and clay content.

Supplementary Materials: The following are available online at <http://www.mdpi.com/1999-4907/9/10/0/s1>, Figure S1: Variations of soil organic carbon, total nitrogen and phosphorus at different sites along the rainfall gradient. Values are means \pm standard error. Different uppercase letters and lowercase letters indicate significant differences ($p < 0.05$) at 0–10 and 10–20 cm, respectively, Figure S2: Variation range of SOC and clay content both at regional (All sites) and local scale (QL; FX; YC; AS; MZ and YL), Figure S3: Linear regression analysis between clay content and soil organic carbon stock on regional scale, Figure S4: Linear regression analysis between clay content and soil organic carbon stock on local scale, Table S1: The clay mineral composition of soil in different study areas, Table S2: Leaf N, P content and N:P of each research site.

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