Geoderma 352 (2019) 116–125

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Factor contribution to soil organic and inorganic carbon accumulation in the Loess Plateau: Structural equation modeling

Wei Zhao[a,b,*], Rui Zhang[b], Hua Cao[c], Wenfeng Tan[b,c,**]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences and the Ministry of Water Resources, Yangling, Shaanxi Province 712100, PR China
[c] College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, PR China

ARTICLE INFO

Handling Editor: David Laird

Keywords:
Soil organic carbon
Soil inorganic carbon
Carbon sequestration
Controlling factor
Relative contribution
Path analysis

ABSTRACT

The effects of climate, soil characteristics and management on soil carbon accumulation have been extensively investigated. However, the relative importance of these factors remains unclear, especially in arid and semiarid regions. Here we evaluated the contribution of the environmental variables (geographical location, climate, soil type, and land use type) to soil organic and inorganic carbon accumulation in the 0–100 cm soil layers across the Loess Plateau in China. A structural equation modeling (SEM) was used to distinguish direct from indirect effects of factors on soil carbon accumulation based on covariance structures. The results showed that environmental temperature and moisture were the primary controls of soil organic carbon density (SOCD) variation. The total effects (the sum of direct and indirect effect) of soil type and land use on SOCD were less than half of those of environmental temperature and moisture. In addition, the direct and negative effect of environmental temperature on SOCD increased, and the direct and positive effect of environmental moisture on SOCD decreased with soil depth. For the soil inorganic carbon densities in the 0–100 cm soil layers, soil organic carbon (SOC) content acted as the most important factor controlling the variations in soil inorganic carbon density (SICD). Environmental temperature and moisture mainly affected indirectly SICD by mediating through its impacts on soil type, SOC content, or soil pH. Less than 40% of variation in soil carbon accumulation for 0–100 cm soil depth is explained in the model. The unexplained variance highlights the need for the data on soil physicochemical properties, quality of organic carbon inputs, and soil microorganisms.

1. Introduction

Anthropogenic CO_2 emissions into the atmosphere represent the largest human contribution to climate change in the past 100 years (Canadell et al., 2007). Terrestrial carbon sequestration is considered as a promising alternative for mitigating the buildup of atmospheric CO_2 (Lai, 2004; Scholes and Noble, 2001). Soil is the largest carbon pool in terrestrial ecosystems, storing approximately 1550 Pg (1 Pg = 1015 g) of soil organic carbon (SOC) and 950 Pg of soil inorganic carbon (SIC) (Batjes, 1996); these values are more than three times the size of the atmospheric carbon pool and four times the size of the biotic carbon pool (Lai, 2004). Previous studies have shown that the carbon sequestration potential of global soils is 0.4–1.2 Pg C yr^{-1}, or 5–15% of the global fossil fuel emissions (Lai, 2004). As a key component of the global carbon cycle, a small change in the soil carbon pool may result in large changes in greenhouse gas fluxes between the soil and the atmosphere. The role of soils in the global carbon cycle remains uncertain, as the mechanisms controlling soil carbon storage are still poorly understood.

The effects of climate, soil characteristics and management on soil carbon accumulation have been extensively investigated (Alidoust et al., 2018; Hu et al., 2018; Lewis et al., 2019). Climate variables, such as precipitation and temperature, can affect the distribution and growth of vegetation, which have dominant control over the spatial distribution of SOC and SIC (Davidson and Janssens, 2006; Jia et al., 2017; Kirschbaum et al., 2008). High soil moisture and leaching intensity enhance soil weathering and development (Dixon et al., 2016), which may lead to the loss of aggregate cements, such as calcium carbonates. Land-use management practices, such as land-use change (Qiu et al., 2012) and afforestation (Berthrong et al., 2012), may have considerable

* Correspondence to: W. Zhao, State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China.
** Correspondence to: W. Tan, College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, PR China.
E-mail addresses: aoei@nwafu.edu.cn (W. Zhao), tanwf@mail.hzau.edu.cn (W. Tan).

https://doi.org/10.1016/j.geoderma.2019.06.005
Received 1 March 2019; Received in revised form 31 May 2019; Accepted 3 June 2019
0016-7061/

impacts on soil carbon stocks. Different land-use management practices can result in differences in vegetation productivity (Wu et al., 2017) and soil physicochemical properties (Wang et al., 2016), which are closely related to changes in soil carbon stocks. Furthermore, the dissolution and leaching of SIC in the soil profile are also affected by soil water content and fine root biomass (Chang et al., 2012). However, the relative importance of the influencing factors on soil carbon accumulation in soil layers remains unclear, especially in arid and semiarid regions, such as the Loess Plateau in China.

The Loess Plateau of China is a unique geographical unit characterized by extensive loess distribution, serious soil erosion, low vegetation coverage, and high soil carbonate content (Jin et al., 2014). It is well established that soil carbon varies across gradients of mean annual temperature and precipitation across the Loess Plateau (Liu et al., 2011; Mi et al., 2008). However, questions about whether this variation reflects a 'direct' effect of climate on the kinetics of soil carbon accumulation or an 'indirect' effect of climate via soil development, vegetation and about which effect is relatively large, direct or indirect, cannot be answered clearly. A structural equation model (SEM) is well suited for assessing the relationships among networks of variables, where variables can act as both predictor and response variables simultaneously. A SEM enables the integration of such unobserved variables (called latent or construct variables) as theoretical variables reflected by several directly observed variables (called manifest variables or indicators) (Grace et al., 2010). The model assumes causal relationships between latent variables and permits the decomposition of the correlations among the variables into direct and indirect effects in a model where the regressions of the relationships between the variables can be simultaneously evaluated (Prober and Wiehl, 2012). Therefore, the direct and indirect effects of combinations of factors on soil carbon storage can be calculated, including the significant regression weights from plausible interaction pathways.

In this study, we analyzed the relationships among the affecting factors, including geographical location, climate, soil type, land use, and soil organic and inorganic carbon accumulation in the different soil layers across the Loess Plateau in China. Soil carbon accumulation and influencing factors were hypothesized to be related by a set of causal pathways based on theory and relationships indicated in the scientific literature, and an a priori multivariate hypothesis was tested by SEM. The objectives were to (1) assess the direct and indirect effects of controlling factors on soil carbon accumulation and (2) to reveal the relative contribution of major controls to soil carbon accumulation across the Loess Plateau in China. The causal understanding of the direct and indirect effects of the controlling factors will enable us to make better quantitative predictions of future soil carbon sequestration.

2. Materials and methods

2.1. Study area and data sources

The Chinese Loess Plateau (CLP) is located in the upper and middle reaches of the Yellow River (Fig. 1) (Shi and Shao, 2000) and covers an area of 620,000 km^2, with an elevation range of 200–3000 m. The region is dominated by a temperate arid and semi-arid continental monsoon climate. The mean annual precipitation ranges from 150 mm in the northwest to 800 mm in the southeast, 55%–78% of which falls from June to September. The mean annual temperature is 3.6 °C in the northwest and increases to 14.3 °C in the southeast (He et al., 2003).

The parent material for the soils is yellow loess or wind deposited material that results in widespread soils with clay loam texture. There is a trend for sandier soils in the northwest and more clayey soils in the southeast. Silt-loam soils cover about 90% in the Loess Plateau. The silt content ranges from 60% to 75% for most soils (Huang et al., 2010). From the southeast to northwest, the soil types abide by the following sequence: Luvisols, Anthrosols→Chernozems, Regosols, Calcisols→Kastanozems→Calcisols→Gypisols→Arenosols (IUSS Working Group WRB, 2014); the associated vegetation zones are: forest→forest-steppe→typical-steppe→desert-steppe zones→steppe-desert zones.

The soil data employed in this study were based on the Second National Soil Survey in China including the Soil Species of China (National Soil Survey Office, 1995b; National Soil Survey Office, 1995a; National Soil Survey Office, 1998) and the provincial soil survey (He Nan Soil Survey Office, 2004; Inner Mongolia Autonomous Region's Soil Survey Office, 1994; Liu and Zhang, 1992; Qinghai Agricultural Resources and Regional Planning Office, 1995). From the Second National Soil Survey, 374 soil profiles (see Fig. 1 for the locations) were used. The information we used on each soil profile contained taxonomic classification, geographical location, altitude, depth of different soil horizons, vegetation, meteorological index, $CaCO_3$ content, organic matter content, gravel content (particle diameter larger than 2 mm) and bulk density.

2.2. Calculation of the soil organic and inorganic carbon densities

Soil profiles were divided pedogenetically into major horizons, designated by A, B, C, and D to a depth of 100 cm or to the underlying consolidated bedrock (Li and Zhao, 2001). In this study, data from China's Second National Soil Survey were converted from pedogenetical horizons to different depth increments (0–20 cm, 20–50 cm, and 50–100 cm). The calculation method of weighted SOC and SIC contents after conversion has been previously reported by Li and Zhao (2001). For example, for 0–20 cm SOC content calculation, in the survey, soil profiles were divided pedogenetically into horizon A, B, C, D…, so horizon A was not necessarily at a depth of 20 cm. To estimate SOC content of the upper 20 cm soil, the depth of the A horizon was used as the criterion to assign characteristics. When A > 20 cm, a layer of 20 cm was assumed with its other characteristics assigned directly from A. In case of A < 20 cm, a compensatory layer B_x from B was taken with other properties of B being used. Thus, the SOC content in 0–20 cm soil depth was derived by calculating a weighted average in SOC contents in the A and B_x horizons within 0–20 cm soil depth.

The soil organic carbon density ($SOCD_i$), inorganic carbon density ($SICD_i$), and pH_i of a soil layer i (i = 1, 2, and 3 for 0–20 cm, 20–50 cm, and 50–100 cm, respectively) were calculated according to the methods by Liu et al. (2011) and Tan et al. (2014), respectively. The $SOCD_i$ ($kg\,m^{-2}$) and $SICD_i$ ($kg\,m^{-2}$) of soil layer i are directly related to the soil properties according to Eqs. (1) and (2), respectively:

$$SOCD_i = 0.58 \times OM_i \times T_i \times B_i \times (1 - F_i)/10 \quad (1)$$

$$SICD_i = 0.12 \times CC_i \times T_i \times B_i \times (1 - F_i)/10 \quad (2)$$

where 0.58 is the Bemmelen index that converts organic matter concentration (OM_i) to organic carbon content and 0.12 is the conversion factor that converts calcium carbonate concentration (CC_i) to inorganic carbon content. T_i, B_i, and F_i are the thickness (cm), average soil bulk density ($g\,cm^{-3}$), and volumetric proportion of the fraction (> 2 mm) in soil layer i, respectively. B_i was obtained with the functional relationship (B = −0.107 Ln(SOC) + 1.369) between the SOC and soil bulk density found by Tan et al. (2014). The SI units that are used are indicated above.

2.3. Statistical analysis

We used the current understanding of factors influencing SOCD and SICD to identify the following independent environmental variables: elevation (EL), longitude (LO), latitude (LA), mean annual temperature (MAT), mean annual precipitation (MAP), land use type (LT), soil type zone (SZ; Integrated Survey Team of Chinese Academy of Sciences on the Loess Plateau, 1991), and soil pH. For SOCD/SICD and the continuous environmental factors, the mean, maximum and minimum, standard deviation (S.D.), and coefficient of variation (CV) were calculated. The skewness, kurtosis, and the Kolmogorov–Smirnov (K–S)

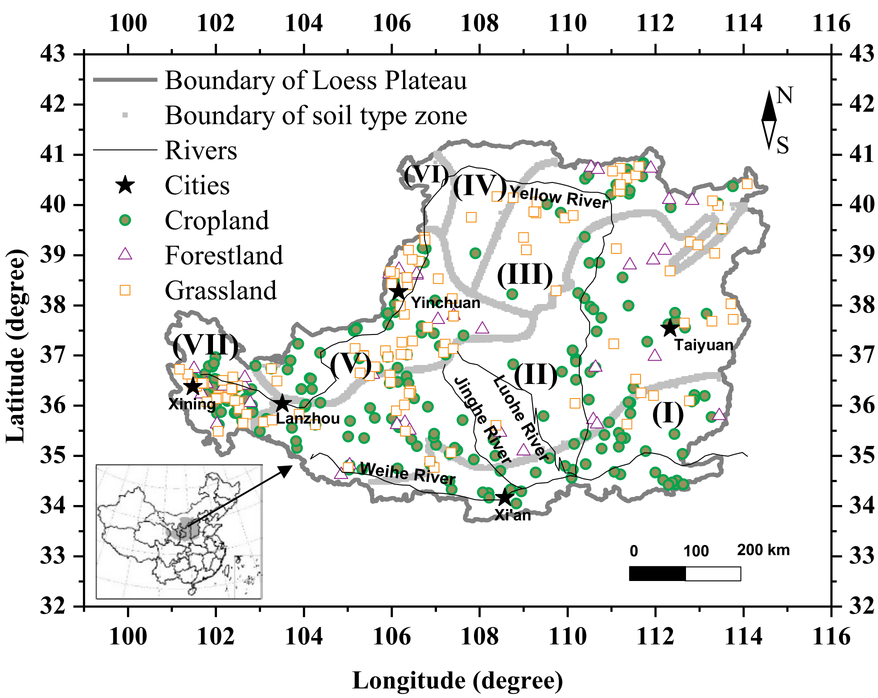

Fig. 1. Location of the Loess Plateau in China and the sampling point distribution map. (I)-(VII), Soil type zones: (I), He soil, Danzong soil zone; (II), Heilu soil, Huangmian soil zone; (III), Ligai soil, Fengsha soil zone; (IV), Zonggai soil zone; (V), Huigai soil, Fengsha soil zone; (VI), Huimo soil zone; (VII), Gan-qing plateau soil zone.

Table 1
Description of the major classes used as variables and the corresponding numeric code.

Numeric code	Land use	Soil type zones
1	Cropland	He soil, Danzong soil zone
2	Forestland	Heilu soil, Huangmian soil zone
3	Grassland	Ligai soil, Fengsha soil zone
4		Zonggai soil zone
5		Huigai soil, Fengsha soil zone
6		Huimo soil zone
7		Gan-qing plateau soil zone

test value were used to determine whether the data were normally distributed. Correlation analysis was performed using a nonparametric procedure (Spearman rank correlation coefficient; Sachs, 1992) because the data did not always show a normal distribution. Spearman correlation coefficients were used to determine the strength of possible relationships between SOCD/SICD and environmental variables. This procedure was checked by a two-sided test for significance. For the two categorical variables, i.e., land use type and soil type zone, they within a given category were denoted by a numeric code. Land use type was divided into three level based on the reported SOC accumulation under the three land use (Li et al., 2005; Wei et al., 2012), and thus, it was represented by three numerically coded variables: 1 = cropland, 2 = forestland, and 3 = grassland. And soil type zone was divided into seven level based on the literature (Integrated Survey Team of Chinese Academy of Sciences on the Loess Plateau, 1991). The coded numeric values for the two categorical variables are shown in Table 1.

To reduce the number of variables and to ensure that the subsequent analyses were not affected by the problem of multi-collinearity, factor analysis (FA) was conducted using the principal component method with varimax rotation to identify latent factors. A basic assumption of FA is that some latent variables exist in the set of measurable variables; accordingly, we used FA to extract common factors from a large number of observed variables by assuming these common factors had caused the observed variables to covary. An advantage of FA over other classification techniques, such as clustering, is that FA can recognize properties of correlations, identify inter-related variables, and reduce the number of variables in subsequent analyses. In the present study, the number of factors to extract was fixed to seven based on the seven latent variables related to soil carbon, i.e., SOC accumulation in the 0–100 cm soil layer, SIC accumulation in the 0–100 cm soil layer, environmental temperature (ENT), environmental moisture (ENM), soil type (ST), soil acidity (SAC), and land use (LU). A factor loading of ≥ 0.60 was used as a selection criterion to interpret the role that each variable (measurable variables) played in the definition of each factor (latent variables), considering the sample size of the database (N = 374) at a significance level of 5%. The factor loadings are the correlation of each variable with the factor; therefore, they indicate the degree of correspondence between the variable and the factor (Hair and Anderson, 2010). FA was performed using the SPSS 20.0 software package (GENE Inst. Inc.).

After FA, structural equation model was used to identify the structural relationships between the identified factors, using a maximum likelihood parameter estimation method. Structural equation model (SEM) represents a set of integrated multivariate techniques, including measurement theory, FA, regression, path analysis and simultaneous equation modeling, which are used to describe multiple relationships among a number of latent variables. One advantage of SEM is that one latent variable can be a dependent variable in one set of relationships, and at the same time, it can be an independent variable in another set of relationships. As our hypothetical model involves such multiple-path linkages, SEM was considered an appropriate tool for this analysis.

We started with a hypothetical model that contained all plausible interaction paths between the environmental temperature, environmental moisture, soil type, soil acidity, land use, soil organic carbon, and soil inorganic carbon (Fig. S1 in Supporting Information) based on current knowledge and results of previous studies, and it was further refined based on SEM techniques. The SEM in this study was conducted using the software package AMOS 20.0 (IBM; SPSS Inc., Chicago, IL, USA). Because some of the introduced variables were not normally distributed, the probability that a path coefficient differed from zero was tested using bootstrapping. Bootstrapping is preferred to the classical maximum-likelihood estimation in these cases because probability assessments are not based on the assumption that the data conform to a specific theoretical distribution. Bootstrapped data were randomly sampled, with replacement, to derive estimates of standard errors

Table 2
Summary statistics for soil organic carbon density (SOCD), inorganic carbon density (SICD), and environmental variables across the entire Loess Plateau region[a].

Variable	n	Min.	Max.	Mean	S.D.	CV (%)	Skewness	Kurtosis	K-S *p*
$SOCD_1$	374	0.36	22.90	2.64	2.99	113.3	4.02	19.24	0.00
$SOCD_2$	374	0	27.00	2.97	3.35	113.0	3.99	19.95	0.00
$SOCD_3$	374	0	37.16	3.49	4.02	114.9	4.20	24.58	0.00
$SICD_1$	374	0	24.07	3.29	2.16	65.7	2.71	22.92	0.00
$SICD_2$	374	0	37.93	5.31	3.22	60.6	2.82	27.47	0.00
$SICD_3$	374	0	63.21	9.14	5.61	61.5	2.75	23.71	0.00
LA	374	34.05	40.84	36.95	1.71	4.6	0.70	−0.39	0.00
LO	374	101.36	114.09	107.16	3.64	3.4	0.06	−1.24	0.00
EL	374	150.00	3860.00	1532.85	707.28	46.1	0.375	−0.23	0.00
MAT	374	−1.40	14.80	7.57	2.86	37.8	0.20	0.24	0.00
MAP	374	176.00	745.40	425.18	126.75	29.8	0.21	−0.65	0.00
pH_1	374	6.32	9.80	8.26	0.40	4.89	−1.18	4.82	0.00
pH_2	374	6.40	9.60	8.29	0.39	4.65	−1.21	5.15	0.00
pH_3	374	6.30	9.60	8.31	0.39	4.71	−1.14	5.37	0.00

[a] n, number of samples; Min., minimum value; Max., maximum value, S.D., standard deviation; CV, coefficient of variation; K–S *p*, Kolmogorov-Smirnov test for normality. LA (°), latitude; LO (°), longitude; EL (m), elevation; MAT (°C), mean annual temperature; MAP (mm), mean annual precipitation. $SOCD_1$, $SOCD_2$, and $SOCD_3$ refers to SOCD ($kg\,m^{-2}$) calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively. $SICD_1$, $SICD_2$, and $SICD_3$ refers to SICD ($kg\,m^{-2}$) calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively. pH_1, pH_2, and pH_3 refers to the average pH calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively.

associated with the distribution of the sample data. Following these data manipulations, direct and indirect effects of environmental variables on SOC and SIC were determined. The criteria for evaluation of structural equation model fit, such as the maximum likelihood χ^2 values, the goodness-of-fit index (GFI) and the root mean square error of approximation (RMSEA), were adopted (Grace, 2006). RMSEA values < 0.10 suggest an accepted model fit and the lower RMSEA value indicates the better fit, and in the GFI, the cut-off criterion ≥0.90 is indicative of a good fit (Hooper et al., 2008). The 95% confidence intervals were used to decide whether the estimated parameters differed from zero. If the confidence interval did not include zero, the estimated parameters could be seen as significant under conventional null hypothesis testing.

3. Results

3.1. Statistics for SOCD, SICD, and environmental variables

Table 2 shows that the mean SIC densities were much higher than the mean SOC densities in the 0–100 cm soil depth, especially in the 20–100 cm soil depth, indicating that the inorganic carbon pool is an important part of the soil carbon pool in arid and semiarid areas. The mean SOCD was 2.64 $kg\,m^{-2}$ for $SOCD_1$, 2.97 $kg\,m^{-2}$ for $SOCD_2$, and 3.49 $kg\,m^{-2}$ for $SOCD_3$, and the mean value of SICD was 3.29 $kg\,m^{-2}$ for $SICD_1$, 5.31 $kg\,m^{-2}$ for $SICD_2$, and 9.14 $kg\,m^{-2}$ for $SICD_3$. The mean value of pH was 8.26 for pH_1, 8.29 for pH_2, and 8.31 for pH_3. In addition, the mean value of environmental variables was 36.95° for latitude, 107.16° for longitude, 1532.85 m for elevation, 7.57 °C for mean annual temperature, and 425.18 mm for mean annual precipitation. The high CV and S.D. values indicated a strong spatial heterogeneity in SOCD and SICD across the study region (Table 2). The skewness, kurtosis and significance level of Kolmogorov-Smirnov test indicated that the raw data of both SOCD and SICD were far from the criteria for normal distributions.

3.2. Relationships between SOCD, SICD, and environmental variables

Table 3 shows the interrelationships of the SOCD and SICD in the different soil depths, as determined by simple correlations. Close correlations were observed among the soil carbon densities. There were significant positive correlations among the SOC densities in the different soil layers. Also, significant positive correlations were found between SICD in the upper layers and lower layers of soils. In addition, negative correlations occurred between the SOC and the SIC densities in the different soil layers, especially for those in the 0–50 cm soil layers ($P < 0.05$).

Table 3
Shearman correlation coefficients for the carbon densities in different soil layers[a].

	$SOCD_1$	$SOCD_2$	$SOCD_3$	$SICD_1$	$SICD_2$	$SICD_3$
$SOCD_1$	1.00	0.82**	0.63**	−0.11*	−0.17**	−0.09†
$SOCD_2$		1.00	0.80**	−0.11*	−0.17**	−0.07†
$SOCD_3$			1.00	−0.14**	−0.22**	−0.10†
$SICD_1$				1.00	0.62**	0.51**
$SICD_2$					1.00	0.79**
$SICD_3$						1.00

[a] $SOCD_1$, $SOCD_2$, and $SOCD_3$ refers to SOCD calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively. $SICD_1$, $SICD_2$, and $SICD_3$ refers to SICD calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively.
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
† No significant.

For the environmental variables, as shown in Table 4, the observed correlations among all variables were significant ($P < 0.05$) except for the relationships of land-use type with longitude and pH_i (i = 2 and 3), of latitude with elevation, of pH_i (i = 1, 2, and 3) with longitude and elevation, and of MAT with pH_1.

The interactions between the soil carbon densities and the environmental factors were also evaluated with correlation analysis (Table 5). Spearman correlation analysis showed that the environmental variables were significantly correlated with the soil carbon densities. The soil type zone had a significant effect on the soil carbon densities, and the soil types in the northwest favored the accumulation of soil carbon more than those in the southeast. Land use type had a significant impact on the SOCD in deep soil layers, and cropland benefitted SOC accumulation in deep soil layers more than that in forestland and grassland. Negative correlations were found between longitude and soil carbon densities ($P < 0.01$), and positive correlations were found between elevation and soil carbon densities ($P < 0.01$). MAT and latitude had significant negative effects on SOC densities ($P < 0.01$), but only SICD in the surface soil layers was significantly and negatively affected by latitude. In addition, MAP was positively correlated with SOC densities ($P < 0.01$) and negatively related to SIC densities ($P < 0.01$). However, soil pH was positively related to SIC densities ($P < 0.01$) and negatively correlated with SOC densities ($P < 0.01$).

Table 4
Shearman correlation coefficients for the environmental variables [a].

	SZ	LT	LA	LO	EL	MAT	MAP	pH_1	pH_2	pH_3
SZ	1.00	0.17**	0.34**	−0.71**	0.65**	−0.53**	−0.61**	0.26**	0.27**	0.26**
LT		1.00	0.27**	−0.02†	0.19**	−0.20**	−0.21**	0.11*	0.08†	0.10†
LA			1.00	0.25**	−0.05†	−0.33**	−0.56**	0.34**	0.31**	0.26**
LO				1.00	−0.80**	0.43**	0.30**	−0.03†	−0.05†	−0.10†
EL					1.00	−0.70**	−0.20**	−0.02†	−0.01†	0.04†
MAT						1.00	0.21**	−0.08†	−0.13*	−0.13*
MAP							1.00	−0.44**	−0.41**	−0.38**
pH_1								1.00	0.84**	0.70**
pH_2									1.00	0.85**
pH_3										1.00

[a] SZ, soil type zone; LT, land use type; LA, latitude; LO, longitude; EL, elevation; MAT, mean annual temperature; MAP, mean annual precipitation; pH_1, pH_2, and pH_3 refers to the average pH calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively.
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
† No significant.

3.3. Factor analysis to latent variable extraction

FA was performed to identify latent factors using the principal component method with varimax rotation on the sixteen variables, including the fourteen continuous variables and the two ordered categorical variables. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (MSA) was 0.73, which was well above a recommended cut-off threshold of 0.5. Bartlett's test of sphericity was 0.00 for the factor analysis. These results about MSA and Bartlett's test suggest that there are compact correlations and that FA should yield distinct and reliable factors (Field, 2009).

The seven extracted latent variables and the component matrix post varimax rotation are listed in Table 6. Based on the component matrix, seven latent variables were identified and corresponded to the seven factors. Factor 1 captured SOC accumulation including $SOCD_1$, $SOCD_2$, and $SOCD_3$. Factor 2 captured SIC accumulation including $SICD_1$, $SICD_2$, and $SICD_3$. Factor 3 represented the environmental temperature (ENT) indicated by mean annual temperature. Factor 4 captured the environmental moisture (ENM) indicated by mean annual precipitation. Factor 5 represented the soil type (ST) including soil type zone (SZ) and longitude. Factor 6 represented the soil acidity (SAC) indicated by soil pH. Factor 7 captured land use (LU) indicated by land use type (LT). Here, the latitude variable was not included in FA because the inclusion of the latitude variable led to no separation of factors ENT and ST (Table S1 in Supporting Information). The Cronbach's alpha coefficients are shown at the bottom of Table 6 and were used to evaluate the construct validity. Most alpha coefficients were above 0.7, a threshold recommended by Nunnally and Bernstein (1994), suggesting that our categorization was relatively robust.

Table 6
Factor analysis of the observed variables[a].

Variables	Factor[b]						
	1	2	3	4	5	6	7
	SOC	SIC	ENT	ENM	ST	SAC	LU
$SOCD_1$	0.89						
$SOCD_2$	0.91						
$SOCD_3$	0.88						
$SICD_1$		0.79					
$SICD_2$		0.91					
$SICD_3$		0.90					
MAT			0.87				
MAP				0.79			
Soil type zone					−0.87		
Longitude					0.92		
pH_1						0.88	
pH_2						0.95	
pH_3						0.91	
Land use type							0.97
Alpha coefficients	0.924	0.795	–	–	0.795 [c]	–	–

[a]Only absolute values ≥ 0.60 of factor loadings are given. SOC, soil organic carbon accumulation; SIC, soil inorganic carbon accumulation; ENT, environmental temperature; ENM, environmental moisture; ST, soil type; SAC, soil acidity; LU, land use. MAT, mean annual temperature; MAP, mean annual precipitation. The Cronbach's alpha coefficients evaluates the construct validity; [b]Elevation variable was excluded in Factor 3 for its poor consistence with other two variables (soil type zone and longitude); [c]the value was obtained after transforming positive longitude values to negative values by dividing −1.

Table 5
Spearman correlation coefficients between soil carbon density and related factors in the Loess Plateau region[a].

	SZ	LT	LA	LO	EL	MAT	MAP	pH_1	pH_2	pH_3
$SOCD_1$	0.12*	0.03†	−0.32**	−0.32**	0.44**	−0.26**	0.29**	−0.34**	−0.27**	−0.25**
$SOCD_2$	0.10†	−0.05†	−0.28**	−0.30**	0.40**	−0.26**	0.27**	−0.34**	−0.29**	−0.25**
$SOCD_3$	0.02†	−0.15**	−0.31**	−0.23**	0.33**	−0.20**	0.32**	−0.24**	−0.21**	−0.21**
$SICD_1$	0.18**	−0.01†	−0.11*	−0.26**	0.10†	−0.00†	−0.14**	0.25**	0.25**	0.25**
$SICD_2$	0.30**	0.02†	0.03†	−0.32**	0.18**	−0.06†	−0.37**	0.32**	0.32**	0.32**
$SICD_3$	0.18**	0.001†	−0.05†	−0.29**	0.17**	−0.05†	−0.27**	0.25**	0.24**	0.29**

[a] $SOCD_1$, $SOCD_2$, and $SOCD_3$ refers to SOCD calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively. $SICD_1$, $SICD_2$, and $SICD_3$ refers to SICD calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively. SZ, soil type zone; LT, land use type; LA, latitude; LO, longitude; EL, elevation; MAT, mean annual temperature; MAP, mean annual precipitation; pH_1, pH_2, and pH_3 refers to the average pH calculated for 0–20 cm, 20–50 cm, 50–100 cm soil layers, respectively.
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
† No significant.

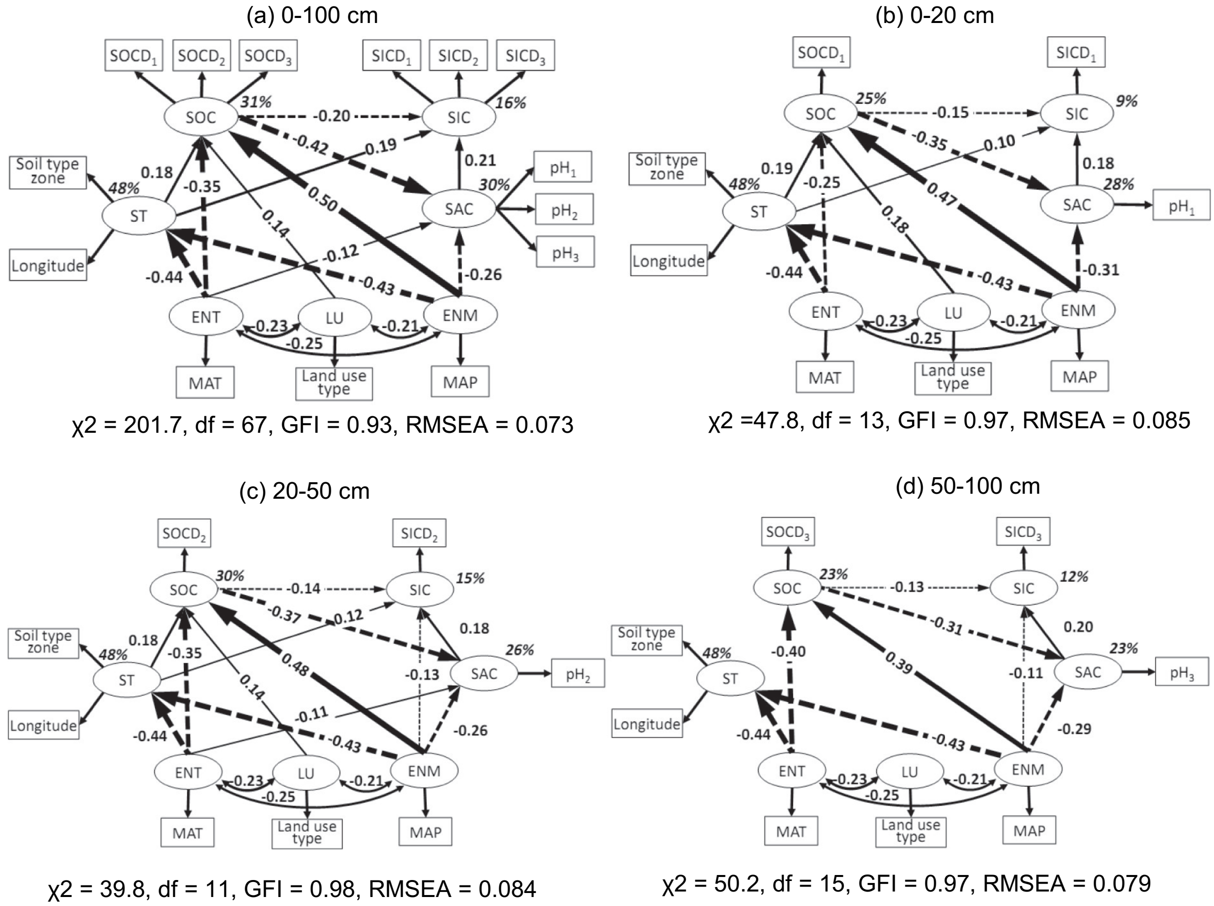

Fig. 2. Structural equation model relating environmental temperature, moisture, soil type, and land use to carbon accumulation in soil depths of 0–100 cm (a), 0–20 cm (b), 20–50 cm (c), and 50–100 cm (d). Rectangles represent observed variables; ovals represent latent variables. A single arrow indicates the direct effect of a variable assumed to be a cause on another variable assumed to be an effect, and a bottom arc double-headed arrows denotes a correlation between two exogenous variables. Only significant direct effects are plotted ($P < 0.05$; see a priori model in Fig. S1). Solid arrows denote positive relationships, whilst dashed arrows correspond to negative ones. Arrow thickness represents the magnitude of the path coefficient. Numbers in bold on arrows are standardized path coefficients ($P < 0.05$). Percentages in italic on ovals indicate the variance explained by the model (R^2). For the single-indicator latent variables, the error variance associated with the observed variable was fixed to zero to indentify the model. Error variables for the unexplained variance in all endogenous variables are not included in the figure. Non-significant pathways are not included in the model. ENT, environmental temperature; ENM, environmental moisture; ST, soil type; LU, land use; SAC, soil acidity; SOC, soil organic carbon accumulation; SIC, soil inorganic carbon accumulation.

3.4. Structural equation modeling

Our a priori model was successfully fitted to our data at the 0–100, 0–20, 20–50, and 50–100 cm soil layer and the goodness-of-fit metrics were satisfied (RMSEA ≤ 0.085, GFI ≥ 0.93; Fig. 2). Together, the measured factors explained 31%, 25%, 30%, and 23% of the variations in SOC accumulation and 16%, 9%, 15%, and 12% of the variations in SIC accumulation at the 0–100, 0–20, 20–50, 50–100 cm depths, respectively (Fig. 2).

Decomposition of correlations into standardized direct, indirect and total effects are shown in Table 7 for the environmental variables in the model. Total effects are the sum of indirect and direct effects. For the SOC densities in the 0–100 cm soil layers (Fig. 2a), environmental temperature (−0.43) and moisture (0.43) have about equally strong total effects on the variations in SOCD and acted as more important controlling factors than did soil type (0.18) and land use (0.14). The total effect of environmental temperature on SOCD was close in magnitude to that of environmental moisture, however, the total effect of the former on SOCD was negative, and that of the latter was positive. The direct effects of environmental temperature and moisture on SOCD were far larger than their indirect effects. Table 7 shows that the direct effect of environmental temperature (−0.35) on SOCD was four times larger than its indirect effect (−0.078), and the direct effect of environmental moisture (0.50) was six times larger than its indirect effect (−0.076). The weak, indirect, and negative effects of environmental temperature (−0.078) and moisture (−0.076) on SOCD were mediated through their impacts on soil type (Fig. 2a; Table 7). The total effects of soil type (0.18) and land use (0.14) on SOCD were less than half of those of environmental temperature (−0.43) and moisture (0.43). And soil type and land use mainly directly affected SOCD. In addition, with soil depth the direct and negative effect of environmental temperature increased from −0.25 to −0.40, and the direct and positive effect of environmental moisture decreased from 0.47 to 0.39 (Fig. 2b, c, d, and Table 7). And with soil depth the direct and positive effect of soil type decreased from 0.19 to 0, and the direct and positive effect of land use decreased from 0.18 to 0 (Fig. 2b, c, d, and Table 7).

For the SIC densities in the 0–100 cm soil layers (Fig. 2a), SOC content acted as the most important factor (−0.29) controlling the variations in SICD, followed by environmental moisture (−0.26) and soil type (0.14). The direct effect of SOC content on SICD (−0.20) was two times larger than its indirect effect (−0.088). The weak, indirect, and negative effect of SOC (−0.088) on SICD was mediated through its impact on soil acidity (Fig. 2a). The total effect of environmental moisture (−0.26) on SICD was close in magnitude to that of SOC (−0.29). Environmental moisture mainly indirectly affected SICD by impacting soil type, SOC, and soil acidity (Fig. 2a). The total effect of

Table 7
Standardized total, direct and indirect effects of influencing factors on soil carbon concentration analyzed by structural equation modeling[a].

	Effect on SOC				Effect on SIC					
	ENT	ENM	ST	LU	ENT	ENM	ST	LU	SOC	SAC
Total effect										
0–100 cm	−0.43	0.43	0.18	0.14	0.014	−0.26	0.14	−0.040	−0.29	0.21
0–20 cm	−0.33	0.39	0.19	0.18	0.029	−0.18	0.057	−0.040	−0.22	0.18
20–50 cm	−0.42	0.40	0.18	0.14	0.013	−0.32	0.085	−0.029	−0.21	0.18
50–100 cm	−0.40	0.39	0	0	0.076	−0.25	0	0	−0.19	0.20
Direct effect										
0–100 cm	−0.35	0.50	0.18	0.14	0	0	0.19	0	−0.20	0.21
0–20 cm	−0.25	0.47	0.19	0.18	0	0	0.098	0	−0.15	0.18
20–50 cm	−0.35	0.48	0.18	0.14	0	−0.13	0.12	0	−0.14	0.18
50–100 cm	−0.40	0.39	0	0	0	−0.11	0	0	−0.13	0.20
Indirect effect										
0–100 cm	−0.078	−0.076	0	0	0.014	−0.26	−0.051	−0.040	−0.088	0
0–20 cm	−0.082	−0.080	0	0	0.029	−0.18	−0.041	−0.040	−0.065	0
20–50 cm	−0.077	−0.076	0	0	0.013	−0.18	−0.036	−0.029	−0.066	0
50–100 cm	0	0	0	0	0.076	−0.13	0	0	−0.063	0

[a] ENT, environmental temperature; ENM, environmental moisture; ST, soil type; LU, land use; SOC, soil organic carbon; SAC, soil acidity. Direct effects are simple paths and are equal to the path coefficients in Fig. 2. Indirect effects are the sum of the products of the chain of path coefficients for all compound paths for which the independent variable is connected to the dependent variable while maintaining the causal direction of the arrows. Total effects are the sum of direct and indirect effects. The values indicate changes of soil carbon concentration per standardized-unit change of influencing factors.

soil type (0.14) on SICD was close in magnitude to half of that of environmental moisture (−0.26) or SOC (−0.29). A weak, indirect, and negative effect of soil type (−0.051) on SICD occurred and was mediated through its influence on SOC (Fig. 2a; Table 7). And environmental temperature and land use mainly indirectly affected SICD via their influences on SOC (Fig. 2a). In addition, with soil depth the direct and negative effect increased from 0 to −0.13, and the indirect and negative effect of environmental moisture on SICD decreased from −0.18 to −0.13 (Fig. 2b, c, d, and Table 7). And with soil depth the indirect and negative effect of land use on SICD decreased from −0.040 to 0 (Fig. 2b, c, d, and Table 7).

4. Discussion

SOC and SIC are affected by various factors, such as environmental temperature, moisture, soil type, and land use, which result in potential effects on soil carbon sequestration. Because of the underlying interactions and covariance among the potential factors, a simple comparison of correlations could lead to erroneous or indecisive conclusions about the relative importance of each factor in this system. By using path analysis, we are able to separate the direct and indirect causal components from the noncausal components of these strong correlations; this allows us to evaluate the relative contributions of various potential factors to soil carbon accumulation.

4.1. Soil carbon densities in the topsoils and subsoils

The correlations between SOC densities in the different soil layers indicate that a higher SOC in topsoils can cause a higher SOC input into subsoils, which may result from three main reasons. One is the leaching of dissolved organic matter (DOM) from topsoils into subsoils. Another is the migration of particulate organic matter (POM) into subsoils via colloidal transport (Rumpel et al., 2012). And the other is the contribution of vegetation roots to SOC. Because vertical distribution of root biomass and soil organic carbon is similar, both exponentially decreasing with soil depth (Ojeda et al., 2018), soil organic carbon can be derived from the decomposition of root litter (Mazzilli et al., 2015).

Significantly positive correlations were found between SICD in the topsoil and that in the subsoil, which mainly results from the transfer of carbonate from topsoils into subsoils. Soils on the Loess Plateau were developed directly from the wind-deposited parent material. The parent minerals have higher carbonate contents. The carbonates include primary carbonates and secondary carbonates. And secondary carbonates in soil depths account for > 75% total carbonates (Li et al., 2013). In the topsoil, a high soil water content, together with the higher CO_2 partial pressures, could increase the dissolution and leaching of carbonate. The leached SIC may subsequently reprecipitate in the subsoil with the lower CO_2 partial pressure and the rapid decrease in soil water (Chang et al., 2012). When the mean annual precipitation is high enough the SIC will be leached completely out of the soil profile. Therefore, carbonates in certain 0–100 cm soil profiles were unobserved as Table 2 shown. Negative correlations occurred between the SOC and the SIC densities in the 0–100 cm soil depths, especially for those in the 0–50 cm ($P < 0.05$), which is consistent with the previous study by Zhao et al. (2016). SIC formation is closely related to SOC dynamics, and the higher SOC often results in looser soil structures and higher soil permeability, which could increase the dissolution and leaching of carbonate (Mi et al., 2008; Sartori et al., 2007).

4.2. Factor contribution to soil organic carbon accumulation

Environmental factors, especially temperature and moisture, are the most important determinants of SOCD (Alvarez and Lavado, 1998; Homann et al., 1995), due to their effects on the quantity and quality of organic residue soil inputs and on the rates of soil organic matter mineralization and litter decomposition (Hevia et al., 2003; Quideau et al., 2001). The effect of environmental temperature on SOC accumulation is complicated. Environmental temperature has a relatively large, direct, negative effect on SOCD. Environmental temperature decreased from the southeast to the northwest in our study region (Yang and Shao, 2000). Lower temperatures could result in reduced SOC breakdown, thereby increasing SOC accumulation (Trumbore et al., 1996). Lower temperatures could also reduce SOC turnover rates, leading to increases in SOC levels (Leifeld et al., 2005). Moreover, temperature sensitivity in subsoils is higher than in topsoils (Li et al., 2018), which leads to the enhancing direct and negative effect of environmental temperature on SOCD with soil depth, as shown in Fig. 2b, c, d, and Table 7. In addition, temperature can negatively affect SOC accumulation through its effect on soil development for different soil type zone (Fig. 2). The relatively cold climate does not contribute to soil development, which leads to more carbonate being present in the 0–100 cm soil layers. Carbonates decrease aggregate porosity in the nanometer range and thus, decrease the accessibility of intra-micro-aggregate SOC to decomposers (Rowley et al., 2018). Environmental moisture would be expected to influence SOCD because higher moisture is conducive to stronger microbial activity, which results in the formation of relatively high SOC (Zhao et al., 2016). Moreover, water content in subsoils is less than that in topsoils during infiltration under the similar rainfall condition (Wang et al., 2015), which leads to the decreasing direct and positive effect of environmental moisture on SOCD with soil depth, as shown in Fig. 2b, c, d, and Table 7. In addition, moisture can negatively affect SOC accumulation through its effect on soil development for different soil type zone, which is similar to the effect of environmental temperature. Interaction effects of environmental temperature (negative total effect) and moisture (positive total effect) on SOCD will lead to an uncertain difference in soil organic accumulation between areas. As reported by Liu et al. (2011), on the Chinese Loess Plateau, relatively higher SOCD in areas with temperatures > 5 °C and < 10 °C could be attributed to the slower breakdown of SOC due to the lower temperatures, as well as the drier conditions. However, with temperatures < 5 °C or > 10 °C the interaction effects of moisture and temperature on SOCD can result in insignificant differences between different areas.

Table 7 shows that soil types in the northwest can contribute to more SOC accumulation. Soils are weakly developed under the relatively cold and dry climates for soil types in the northwest compared to the southeast (Dixon et al., 2016). More calcium carbonates are present in the weakly developed soils in the northwest than in soils in the southeast. More Ca^{2+} released from calcium carbonates can form more complexes with high-molecular weight organic compounds derived from roots and microbes to bind aggregates, which is helpful for stability of aggregate and soil structure. Carbonate ions are also capable of reprecipitation with Ca^{2+} under the right environmental conditions and form secondary $CaCO_3$ crystals to cement aggregates, which also contributes to aggregate and soil structural stability. These improvements in the stability of aggregates increase the SOC stability and accumulation (Rowley et al., 2018). In addition, deeper soil layers (50–100 cm) under different soil types contribute little to SOC accumulation (Fig. 2d and Table 7), which possibly results from the relatively small difference in soil development for deeper soil layers compared with that for the 0–50 cm soil layers. The 0–50 cm soil layers are affected strongly by external environments, including temperature, precipitation, and vegetation, which results likely in large differences in soil development.

Vegetation cover under different land use produces different amounts of biomass with varying decomposability, which results in different SOM levels (Osman, 2013). Croplands do not favor the accumulation of organic matter due to tillage. However, forestland and grassland soils are particularly rich in organic matter due to ground litter in the forestland and much of the root litter in the grassland (Weil and Brady, 2016). In our study, grassland contributed to the most SOC sequestration, followed by forestland and then cropland. The other studies also obtained similar results on the Loess Plateau, i.e., cropland soils had lower SOC contents than that under forestland and grassland (Li et al., 2005; Wang et al., 2001). It has also been reported that SOC could be depleted by the conversion of natural vegetation to cropland due to reduced organic matter inputs and tillage effects that increase decomposition rates (Post and Kwon, 2000). Wei et al. (2012) reported that the SOC in the 0- to 100-cm layer of restored grasslands was more than twice that of restored forests, and the SOC in each soil layer below 10 cm in grassland was also higher than that in forestland. Moreover, in our study, the contribution of land use to SOC accumulation decreases with soil depth (Table 7), which may be related to the root distribution of vegetation.

4.3. Factor contribution to soil inorganic carbon accumulation

Environmental temperature mainly has a small and positive indirect effect on SICD, which is mediated through its impacts on soil type and SOC. The increase in the environmental temperature impairs SOC accumulation, which leads to a relatively low CO_2 partial pressure resulting from SOC mineralization. The lower CO_2 partial pressure will move the equilibrium (Eq. (3)) towards more precipitation of carbonates (Nordt et al., 2000), which enhances the SIC accumulation.

$$Ca^{2+} + 2HCO_3^{-} \leftrightarrow CaCO_3 + H_2O + CO_2 \quad (3)$$

In addition, the decrease in SOC accumulation with increasing environmental temperature often results in a relatively high soil acidity (SAC) (Table 3 and Fig. 2). Higher soil acidity, which corresponds to lower H^+ content in soil solutions, will move the equilibrium (Eq. (4)) towards more precipitation of carbonates (Lal and Kimble, 2000; Suarez, 2000).

$$CaCO_3 + 2H^+ \leftrightarrow Ca^{2+} + H^+ + HCO_3^{-} \leftrightarrow Ca^{2+} + CO_2 + H_2O \quad (4)$$

Environmental moisture has a negative total effect on SICD. No direct effect of environmental moisture on SCID in the 0–100 cm soil layer possibly due to the offset of precipitation and evapotranspiration in the 0–20 cm soil layer as shown in Fig. 2a, b. Though soil water can directly transfer dissolved carbonates to deeper soil layers, much evapotranspiration in the 0–20 cm soil depth possibly conduces inadequate soil water transferring dissolved carbonates to deeper soil layers. The negative indirect effect of environmental moisture on SICD is mediated through its impacts on soil type, SOC, and soil acidity. The increase in environmental moisture contributes to SOC accumulation, which leads to a relatively high CO_2 partial pressure resulting from SOC mineralization. The higher CO_2 partial pressure will move the equilibrium (Eq. (3)) towards less precipitation of carbonates (Nordt et al., 2000), which decreases the SIC accumulation. Moreover, the increase in SOC accumulation with increasing environmental moisture often results in a relatively low soil acidity (Table 3). Lower soil acidity corresponds to higher H^+ content in soil solutions, which will move the equilibrium (Eq. (4)) towards less precipitation of carbonates (Lal and Kimble, 2000; Suarez, 2000).

The relatively high environmental temperature and moisture in the southeast compared to that in the northwest increase the soil development for the soil type zone in the southeast (Dixon et al., 2016). Along with soil development lithogenic and pedogenic carbonates dissolute and leach into depths below 100 cm, which leads to the decrease of Ca^{2+}/Mg^{2+} ions in the 0–100 cm soil layers. The lack of Ca^{2+}/Mg^{2+} ions in the soils in the southeast impairs the formation of SIC (Eq. (3)). On the other hand, the weaker soil development results in more calcium carbonates being present in soils, which contributes to more SOC accumulation as discussed in Section 4.2. Subsequently, the enhanced SOC works against SIC accumulation. In addition, due to the relatively small difference in soil development for deeper soil layers (50–100 cm) compared with that for the 0–50 cm soil layers, deeper soil layers under different soil type zone likely contribute little to SIC accumulation (Fig. 2d and Table 7).

Land use affects SIC accumulation indirectly by its influence on SOC. Compared with forestland and cropland, organic matter in surface soil is relatively abundant in grassland, which leads to more SOC sequestration. The accumulation of SOC under restored grass could induce an increase in carbonic and organic acid production, which reduces the availability of soil Ca^{2+} through cation exchange in soils (McLaughlin and Wimmer, 1999; Sartori et al., 2007). This scenario would increase the dissolution and leaching of carbonate in the topsoil based on Eq. (4) and decrease the SIC concentration, thereby reducing the SICD. Furthermore, with soil depth the contribution of land use to SIC accumulation decreases (Table 7), which is possibly due to the decreased difference in SOC profile distribution under different vegetation cover.

4.4. Unexplained variation in soil carbon accumulation

In this study, < 40% of variation in soil carbon accumulation for 0–100 cm soil depth is explained explicitly in the model, rather than through simple correlation relations or qualitative statements. This is an important step in better supporting the attribution of the causes of changes in soil carbon accumulation. Conversely, > 60% of the variance remains unexplained. For the explanation of the variation in SOC, this may be due to the lack of data related to finer soil particle content. The proportion of finer soil particles (clay and silt) is an important control of soil carbon concentration variation, especially in the deeper soil layers. Soil carbon is subjected to physical preservation by clay and silt particles (Six et al., 2002; Xu et al., 2016). It also may be due to the quantity and quality of organic carbon inputs. The organic carbon inputs from the aboveground litter and fine root biomass partly contribute to the greater SOC content (Chang et al., 2012). And the lower ratio of carbon to nitrogen results in lower SOC content since the SOC with a lower C to N ratio is suggested to be more highly decomposed relative to the SOC with a higher C to N ratio (Zhao et al., 2016). In addition, the unexplained variation in SOC accumulation may be due to the lack of data related to the microbial community. Most soil microbes are heterotrophic and depend on soil organic matter as their energy and carbon source. Variation in decomposition could be attributed to specific properties of the soil-residing microbial community, including their structural and functional diversity (Jackson et al., 2003).

For the explanation of the variation in SIC, this may be due to the lack of data related to soil texture. Soil texture and structure control the accumulation depth of pedogenic carbonates because they affect water holding capacity, water penetration, and movement (Chadwick et al., 1989). The unexplained variation in SIC accumulation also may be due to the lack of data related to physicochemical properties of rhizosphere soils. In the presence of active roots, carbonate dissolution increases largely. Carbonate dissolution increases near roots because of (1) up to 100 times higher CO_2 concentration in the rhizosphere than that in atmosphere and (2) up to two units lower local pH in rhizosphere soils than that in non-rhizosphere soils due to H^+ and carboxylic acid release by roots (Andrews and Schlesinger, 2001; Gocke et al., 2011). Moreover, the unexplained variation in SIC accumulation may be due to the lack of data related to soil microorganisms. Soil microorganisms, such as bacteria, are active in pedogenic carbonate formation. If Ca^{2+} ions are available in solution, bacteria can produce a visible accumulation of carbonates within a few days (Monger et al., 1991).

5. Conclusions

SOC and SIC are affected by various factors, such as environmental temperature, moisture, soil type, and land use, which result in potential effects on soil carbon sequestration. SEM with latent variables is a useful tool for assessing the relative contribution of the influencing factors to soil carbon accumulation in the 0–100 cm soil layers. The presented models show that for the SOCD in the 0–100 cm soil layers, environmental temperature and moisture acted as more important factors controlling the variations in SOCD. The total effects of soil type and land use on SOCD were less than half of those of environmental temperature and moisture. The weak, indirect, and negative effects of environmental temperature and moisture on SOCD were mediated through their impacts on soil type. In addition, the direct and negative effect of environmental temperature on SOCD increased, and the direct and positive effects of environmental moisture and land use on SOCD decreased with soil depth.

For the SIC densities in the 0–100 cm soil layers, SOC content acted as the most important factor controlling the variation in SICD, followed by environmental moisture and soil type. The total effect of environmental moisture on SICD was close in magnitude to that of SOC content. The total effect of soil type on SICD was close in magnitude to half of that of environmental moisture and SOC content. The weak and indirect effects of environmental temperature and moisture on SICD were mediated through its impact on soil type, SOC content, or soil pH. In addition, the indirect and negative effect of land use on SICD decreased with soil depth. < 40% of variation in soil carbon accumulation for 0–100 cm soil depth is explained in the model. The unexplained variance highlights the need for the data on soil physicochemical properties, quality of organic carbon inputs, and soil microorganisms. The current study provides more insights into the mechanisms of soil carbon sequestration.

Acknowledgements

This work was funded jointly by the National Natural Science Foundation of China (Nos. 41877037, 41425006, and 41101218), the Western Light Project of Chinese Academy of Sciences (No. K318001103).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2019.06.005.

References

Alidoust, E., Afyuni, M., Hajabbasi, M.A., Mosaddeghi, M.R., 2018. Soil carbon sequestration potential as affected by soil physical and climatic factors under different land uses in a semiarid region. Catena 171, 62–71.
Alvarez, R., Lavado, R.S., 1998. Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina. Geoderma 83, 127–141.
Andrews, J.A., Schlesinger, W.H., 2001. Soil CO_2 dynamics, acidification, and chemical weathering in a temperate forest with experimental CO_2 enrichment. Glob. Biogeochem. Cycles 15, 149–162.
Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47, 151–163.
Berthrong, S.T., Piñeiro, G., Jobbágy, E.G., Jackson, R.B., 2012. Soil C and N changes with afforestation of grasslands across gradients of precipitation and plantation age. Ecol. Appl. 22, 76–86.
Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc. Natl. Acad. Sci. U. S. A. 104, 18866–18870.
Chadwick, O.A., Sowers, J.M., Amundson, R.G., 1989. Morphology of calcite crystals in clast coatings from four soils in the Mojave Desert Region. Soil Sci. Soc. Am. J. 53, 211–219.
Chang, R.Y., Fu, B.J., Liu, G.H., Wang, S., Yao, X.L., 2012. The effects of afforestation on soil organic and inorganic carbon: a case study of the Loess Plateau of China. Catena 95, 145–152.
Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.
Dixon, J.L., Chadwick, O.A., Vitousek, P.M., 2016. Climate-driven thresholds for chemical weathering in postglacial soils of New Zealand. J. Geophys. Res. Earth 121, 1619–1634.
Field, A., 2009. Discovering Statistics Using SPSS. Sage Publications Ltd, London.
Gocke, M., Pustovoytov, K., Kuzyakov, Y., 2011. Carbonate recrystallization in root-free soil and rhizosphere of Triticum aestivum and Lolium perenne estimated by 14C labeling. Biogeochemistry 103, 209–222.
Grace, J., 2006. Structural Equation Modeling Natural Systems. Cambridge University Press, New York.
Grace, J.B., Anderson, T.M., Olff, H., Scheiner, S.M., 2010. On the specification of structural equation models for ecological systems. Ecol. Monogr. 80, 67–87.
Hair, J.F., Anderson, R.E., 2010. Multivariate Data Analysis. Prentice-Hall Inc, Upper Saddle River (785 pp).
He Nan Soil Survey Office, 2004. Soils of Henan Province in China. China Agricultural Press, Beijing.
He, X., Li, Z., Hao, M., Tang, K., Zheng, F., 2003. Down-scale analysis for water scarcity in response to soil–water conservation on Loess Plateau of China. Agric. Ecosyst. Environ. 94, 355–361.
Hevia, G.G., Buschiazzo, D.E., Hepper, E.N., Urioste, A.M., Antón, E.L., 2003. Organic matter in size fractions of soils of the semiarid Argentina. Effects of climate, soil texture and management. Geoderma 116, 265–277.
Homann, P.S., Sollins, P., Chappell, H.N., Stangenberger, A.G., 1995. Soil organic carbon in a mountainous, forested region: relation to site characteristics. Soil Sci. Soc. Am. J. 59, 1468–1475.
Hooper, D., Coughlan, J., Mullen, M.R., 2008. Structural equation modelling: guidelines for determining model fit. Electron. J. Bus. Res. Methods 6, 53–60.
Hu, P.L., Liu, S.J., Ye, Y.Y., Zhang, W., Wang, K.L., Su, Y.R., 2018. Effects of environmental factors on soil organic carbon under natural or managed vegetation restoration. Land Degrad. Dev. 29, 387–397.

Huang, M., Fredlund, D.G., Fredlund, M.D., 2010. Comparison of measured and PTF predictions of SWCCs for loess soils in China. Geotech. Geol. Eng. 28, 105–117.
Inner Mongolia Autonomous Region's Soil Survey Office, 1994. Soil Species of Inner Mongolia Autonomous Region's in China. China Agricultural Press, Beijing.
Integrated Survey Team of Chinese Academy of Sciences on the Loess Plateau, 1991. Soil Resources and its Reasonable Utilization on the Loess Plateau Region China. Science and Technology Press, Beijing.
IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014. World Soil Resources Reports No. 106. FAO, Rome.
Jackson, L.E., Calderon, F.J., Steenwerth, K.L., Scow, K.M., Rolston, D.E., 2003. Responses of soil microbial processes and community structure to tillage events and implications for soil quality. Geoderma 114, 305–317.
Jia, X.X., Yang, Y., Zhang, C.C., Shao, M.A., Huang, L.M., 2017. A state-space analysis of soil organic carbon in China's Loess Plateau. Land Degrad. Dev. 28, 983–993.
Jin, Z., Dong, Y.S., Wang, Y.Q., Wei, X.R., Wang, Y.F., Cui, B.L., Zhou, W.J., 2014. Natural vegetation restoration is more beneficial to soil surface organic and inorganic carbon sequestration than tree plantation on the Loess Plateau of China. Sci. Total Environ. 485, 615–623.
Kirschbaum, M.U.F., Guo, L.B., Gifford, R.M., 2008. Why does rainfall affect the trend in soil carbon after converting pastures to forests?: a possible explanation based on nitrogen dynamics. For. Ecol. Manag. 255, 2990–3000.
Lai, R., 2004. Soil carbon sequestration in natural and managed tropical forest ecosystems. J. Sustain. For. 21, 1–30.
Lal, R., Kimble, J., 2000. Pedogenic carbonates and the global carbon cycle. In: Lal, R., Kimble, J.M., Eswaran, H., Stewart, B.A. (Eds.), Global Climate Change and Pedogenic Carbonates. CRC Press, Boca Raton, Florida, pp. 1–14.
Leifeld, J., Bassin, S., Fuhrer, J., 2005. Carbon stocks in Swiss agricultural soils predicted by land-use, soil characteristics, and altitude. Agric. Ecosyst. Environ. 105, 255–266.
Lewis, T., Verstraten, L., Hogg, B., Wehr, B.J., Swift, S., Tindale, N., Menzies, N.W., Dalal, R.C., Bryant, P., Francis, B., Smith, T.E., 2019. Reforestation of agricultural land in the tropics: the relative contribution of soil, living biomass and debris pools to carbon sequestration. Sci. Total Environ. 649, 1502–1513.
Li, Z., Zhao, Q.G., 2001. Organic carbon content and distribution in soils under different land uses in tropical and subtropical China. Plant Soil 231, 175–185.
Li, Y.Y., Shao, M.A., Zheng, J.Y., Zhang, X.C., 2005. Spatial-temporal changes of soil organic carbon during vegetation recovery at Ziwuling, China. Pedosphere 15, 601–610.
Li, G.J., Chen, J., Chen, Y., 2013. Primary and secondary carbonate in Chinese loess discriminated by trace element composition. Geochim. Cosmochim. Acta 103, 26–35.
Li, J., Yan, D., Pendall, E., Pei, J., Noh, N.J., He, J.-S., Li, B., Nie, M., Fang, C., 2018. Depth dependence of soil carbon temperature sensitivity across Tibetan permafrost regions. Soil Biol. Biochem. 126, 82–90.
Liu, Y.Z., Zhang, J.Y., 1992. Soils of Shaanxi Province. Science Press, Beijing.
Liu, Z.P., Shao, M.A., Wang, Y.Q., 2011. Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China. Agric. Ecosyst. Environ. 142, 184–194.
Mazzilli, S.R., Kemanian, A.R., Ernst, O.R., Jackson, R.B., Piñeiro, G., 2015. Greater humification of belowground than aboveground biomass carbon into particulate soil organic matter in no-till corn and soybean crops. Soil Biol. Biochem. 85, 22–30.
McLaughlin, S.B., Wimmer, R., 1999. Tansley review no. 104 calcium physiology and terrestrial ecosystem processes. New Phytol. 142, 373–417.
Mi, N., Wang, S.Q., Liu, J.Y., Yu, G.R., Zhang, W.J., JobbÁGy, E., 2008. Soil inorganic carbon storage pattern in China. Glob. Chang. Biol. 14, 2380–2387.
Monger, H.C., Daugherty, L.A., Lindemann, W.C., Liddell, C.M., 1991. Microbial precipitation of pedogenic calcite. Geology 19, 997–1000.
National Soil Survey Office, 1995a. Soil Species of China, Vol. V. Chinese Agriculture Press, Beijing, China.
National Soil Survey Office, 1995b. Soil Species of China, Vol. IV. Chinese Agriculture Press, Beijing, China.
National Soil Survey Office, 1998. Soils of China. China Agricultural Press, Beijing (in Chinese).
Nordt, L.C., Wilding, L.P., Drees, L.R., 2000. Pedogenic carbonate transformations in leaching soil system: implication for the global C cycle. In: Lal, R., Kimble, J.M., Eswaran, H., Stewart, B.A. (Eds.), Global Climate Change and Pedogenic Carbonates. CRC Press, Boca Raton, Florida.
Nunnally, J.C., Bernstein, I.H., 1994. Psychometric Theory. McGraw-Hill, New York.
Ojeda, J.J., Caviglia, O.P., Agnusdei, M.G., 2018. Vertical distribution of root biomass and soil carbon stocks in forage cropping systems. Plant Soil 423, 175–191.
Osman, K.T., 2013. Soils. Principles, Properties and Management. Springer, Netherlands.
Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. Glob. Chang. Biol. 6, 317–327.
Prober, S.M., Wiehl, G., 2012. Relationships among soil fertility, native plant diversity and exotic plant abundance inform restoration of forb-rich eucalypt woodlands. Divers. Distrib. 18, 795–807.
Qinghai Agricultural Resources and Regional Planning Office, 1995. Soil Species of Qinghai. China Agricultural Press, Beijing.
Qiu, L.P., Wei, X.R., Zhang, X.C., Cheng, J.M., Gale, W., Guo, C., Long, T., 2012. Soil organic carbon losses due to land use change in a semiarid grassland. Plant Soil 355, 299–309.
Quideau, S.A., Chadwick, O.A., Benesi, A., Graham, R.C., Anderson, M.A., 2001. A direct link between forest vegetation type and soil organic matter composition. Geoderma 104, 41–60.
Rowley, M.C., Grand, S., Verrecchia, É.P., 2018. Calcium-mediated stabilisation of soil organic carbon. Biogeochemistry 137, 27–49.
Rumpel, C., Chabbi, A., Marschner, B., 2012. Carbon storage and sequestration in subsoil horizons: knowledge, gaps and potentials. In: Lal, R., Lorenz, K., Hüttl, R.F., Schneider, B.U., von Braun, J. (Eds.), Recarbonization of the Biosphere: Ecosystems and the Global Carbon Cycle. Springer Netherlands, Dordrecht, pp. 445–464.
Sachs, L., 1992. Angewandte Statistik. Anwendung Statistischer Methoden. Springer-Verlag, Berlin.
Sartori, F., Lal, R., Ebinger, M.H., Eaton, J.A., 2007. Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. Agric. Ecosyst. Environ. 122, 325–339.
Scholes, R.J., Noble, I.R., 2001. Storing carbon on land. Science 294, 1012–1013.
Shi, H., Shao, M.G., 2000. Soil and water loss from the Loess Plateau in China. J. Arid Environ. 45, 9–20.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176.
Suarez, D.L., 2000. Impact of agriculture on CO_2 as affected by changes in inorganic carbon. In: Lal, R., Kimble, J.M., Eswaran, H., Stewart, B.A. (Eds.), Global Climate Change and Pedogenic Carbonates. CRC Press, Boca Raton, Florida, pp. 257–272.
Tan, W.F., Zhang, R., Cao, H., Huang, C.Q., Yang, Q.K., Wang, M.K., Koopal, L.K., 2014. Soil inorganic carbon stock under different soil types and land uses on the Loess Plateau region of China. Catena 121, 22–30.
Trumbore, S.E., Chadwick, O.A., Amundson, R., 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. Science 272, 393–396.
Wang, J., Fu, B., Qiu, Y., Chen, L., 2001. Soil nutrients in relation to land use and landscape position in the semi-arid small catchment on the loess plateau in China. J. Arid Environ. 48, 537–550.
Wang, L., Zhong, C., Gao, P., Xi, W., Zhang, S., 2015. Soil infiltration characteristics in agroforestry systems and their relationships with the temporal distribution of rainfall on the Loess Plateau in China. PLoS One 10, e0124767.
Wang, Y., Han, X., Jin, Z., Zhang, C., Fang, L., 2016. Soil organic carbon stocks in deep soils at a watershed scale on the Chinese Loess Plateau. Soil Sci. Soc. Am. J. 80, 157–167.
Wei, J., Cheng, J., Li, W., Liu, W., 2012. Comparing the effect of naturally restored forest and grassland on carbon sequestration and its vertical distribution in the Chinese Loess Plateau. PLoS One 7, e40123.
Weil, R.R., Brady, N.C., 2016. The Nature and Properties of Soils. Pearson.
Wu, G.L., Liu, Y., Tian, F.P., Shi, Z.H., 2017. Legumes functional group promotes soil organic carbon and nitrogen storage by increasing plant diversity. Land Degrad. Dev. 28, 1336–1344.
Xu, X., Shi, Z., Li, D., Rey, A., Ruan, H., Craine, J.M., Liang, J., Zhou, J., Luo, Y., 2016. Soil properties control decomposition of soil organic carbon: results from data-assimilation analysis. Geoderma 262, 235–242.
Yang, W.Z., Shao, M.A., 2000. Soil Water Research on the Loess Plateau. Science Press, Beijing (in Chinese with English abstract).
Zhao, W., Zhang, R., Huang, C.Q., Wang, B.Q., Cao, H., Koopal, L.K., Tan, W.F., 2016. Effect of different vegetation cover on the vertical distribution of soil organic and inorganic carbon in the Zhifanggou Watershed on the loess plateau. Catena 139, 191–198.