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RESEARCH LETTER

Total and dissolved soil organic and inorganic carbon and their relationships in typical loess cropland of Fengu Basin

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Abstract

There is evidence of connections between soil organic carbon (SOC) and inorganic carbon (SIC) in dryland of north China. However, fractions of SOC and SIC and the relationship are not well understood in the Loess Plateau that undergoes profound erosion and redeposition. A study was conducted in low-elevation cropland of Loess Plateau across two distinctive basins: Linfen basin (LFB) with lower soil pH (< 8.4) and subject to erosion–redeposition, and Yuncheng basin (YCB) with higher soil pH (> 8.6) and under the influence of the Yellow River. Soil samples were collected from 30 sites over 100 cm. We determined SOC, SIC, dissolved organic carbon (DOC) and other properties. Above 100 cm, SOC stock is significantly higher in LFB (10.0 ± 2.6 kg C m^{-2}) than in YCB (6.9 ± 1.5 kg C m^{-2}), but SIC lower in LFB (14.0 ± 2.5 kg C m^{-2}) than in YCB (17.0 ± 5.7 kg C m^{-2}). We find a significantly negative correlation between SOC and SIC stocks in LFB, but no clear relationship in YCB. DOC:SOC ratio (an indicator for DOC desorption or SOC stability) is significantly higher below 40 cm in YCB (1.9%) than LFB (1.2%), indicating stronger DOC desorption in YCB that has stronger hydrological process due to the influence of the Yellow River. Overall, SOC has a negative correlation with SIC and soil pH, and DOC:SOC ratio has a significantly positive correlation with soil pH. Our analyses suggest that erosion/re-deposition of topsoil is partly responsible for the negative SIC-SOC relationship in LFB, and high soil pH and stronger hydrological processes are attributable to relatively lower levels of SOC in YCB. This study highlights that soil carbon fractions in the lowland of Loess Plateau are influenced by many drivers, which leads to complex relationships between major soil carbon pools.

Keywords: Soil organic carbon, Soil inorganic carbon, Dissolved carbon, Loess cropland, Fengu Basin

Introduction

The storage (~ 1500 Pg) of soil organic carbon (SOC) is greater than the sum of carbon stock in the atmosphere (~ 750 Pg) and terrestrial biosphere (~ 560 Pg), acting as both sources and sinks and contributing huge share to the regional and/or global carbon budgets (Amundson 2001; Jobbágy and Jackson 2000). The pool of soil inorganic carbon (SIC) is comparable to that of SOC in both the global land (Lal 2004) and China's land (Li et al. 2007). Although there are many studies that demonstrate some kinds of connection between SOC and SIC (Mehra et al. 2019; Monger et al. 2015; Zamanian et al. 2016), the relationship between SOC and SIC has not been well understood.

There are some studies addressing SIC-SOC relationship, which report inconsistent findings. While there is evidence of a positive correlation between SIC and SOC stocks in the cropland of north China (Guo et al. 2016; Shi et al. 2017b; Wang et al. 2015b), studies also report a negative SIC-SOC relationship under various land uses in the North China (Li et al. 2010; Zhao et al. 2016). In particular, Zhao et al. (2016) found that SOC had a negative relationship with SIC under mixed land uses (i.e., forest,

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grass, shrub lands) in the Loess Plateau that undergoes profound erosion.

The differences in SIC-SOC relationship may reflect the differences in the responses to changes in environmental conditions between SOC and SIC. For instance, there is evidence that high soil pH/salinity often leads to low levels of SOC (partly due to low stability of SOC) (Chen et al. 2017; Demoling et al. 2007), but high levels of SIC probably owing to high levels of Ca^{2+}/Mg^{2+} (Oste et al. 2002; Wang et al. 2015a). Recent studies suggest that hydrologic processes may have influences on various fractions of soil carbon (Lu et al. 2020; Zhang et al. 2020), particularly on dissolved organic carbon (DOC) and inorganic carbon (DIC), which could alter the SIC-SOC relationship. For example, low SOC stability (under high pH/salinity) often result in more desorption of DOC (Mavi et al. 2012) whereas hydrologic processes may enhance both desorption of DOC and the dissolution of SIC (Shi et al. 2017a; Zhang et al. 2020). On the other hand, there is also evidence that higher levels of $CaCO_3$ or Ca^{2+}/Mg^{2+} are beneficial for SOC stabilization (Tavakkoli et al. 2015; Virto et al. 2011) because of enhanced formation of soil aggregates (Rowley et al. 2018).

There have been some studies on soil carbon dynamics in the Loess Plateau, showing large variability in both SOC and SIC, which is influenced by many environmental factors such as climate (e.g., precipitation, temperature), and vegetation types (Han et al. 2018; Liu et al. 2011). The Loess Plateau has undergone severe soil erosions due to the poor structure of loess (Fu et al. 2011). Numerous studies have reported that erosion associated processes, including detachment, transport and deposition of soil materials, have large impacts on SOC distribution (Schiettecatte et al. 2008; Zhu et al. 2014).

There is a distinctive difference in vertical distribution between SOC and SIC in the north China's cropland: i.e., a sharp decrease in SOC but a general increase in SIC with depth (Shi et al. 2017b; Zhang et al. 2015). Erosion and redeposition of topsoil from highlands to lowlands could have influences on the storages of both SOC and SIC, thus altering the SOC-SIC relationship in the Loess Plateau. The Fengu Basin, consisting of Linfen Basin (LFB) and Yuncheng Basin (YCB), is located at the southeast edge of the Loess Plateau, which is subject to erosion–redeposition (in LFB) and under the influence of Yellow River (In YCB). We hypothesize that the relationship between SIC and SOC is more complex in the cropland of Fengu Basin (relative to other regions of north China, e.g., the North China Plain) because of different influences of erosion–redeposition and hydrological processes that have large impacts on soil carbon, particularly on DOC and DIC. The objectives of this work are to study the dynamics of SOC and SIC and their dissolved fractions in the low-elevation cropland of the Loess Plateau, to assess the relationship between these soil carbon fractions, and to explore the underlying mechanism responsible for the variability of SOC and SIC in a semiarid region.

Materials and methods

Characteristics of the study area

Our study area (110° 24′ 12″ − 111° 42′ 29″ E, 34° 54′ 43″ − 36° 15′ 52″ N, ~ 4000 km^2) is located at the southwest of Shanxi Province on the Loess Plateau in China (Fig. 1), which spans almost the entire Fengu Basin's cropland. The area is dominated by semiarid continental monsoon climate with noticeable seasonal changes: a severely dry spring, hot and rainy summer, and a cold and dry winter. Main soil type is identified as Calcareous cinnamon (Huang et al. 2007; Shi et al. 2006). The region has an agricultural history of thousands of years. At present, a double-cropping system, i.e., winter wheat and summer maize rotation is being practiced, with similar fertilization and tillage management. Irrigation is often applied using waters from the rivers.

Despite the similarity in climate and agricultural practice, there are some differences in other aspects between the LFB and YCB. LFB is a canyon basin with an elevation of 389–554 m and Fenhe river flowing from the north to the south, which is surrounded by mountains (> 1000 m a.s.l.). The parent material in the region is redeposited loess. Annual mean temperature is 8.9–12.9 °C. Annual mean precipitation ranges from 420 at a lower altitude to 550 mm at a higher altitude, with 70% during June–September. Annual average evaporation is ~ 1660 mm.

The parent material in the YCB is the alluvial loess. The elevation varies from 380 to 820 m. Annual mean temperature is ~ 13 °C, and annual mean evaporation is ~ 1800 mm. Annual precipitation has a range of ~ 500–750 mm, showing an increasing trend with an increase in elevation, and 69% during the period of June–September. The majority of YCB is influenced by the Yellow River, and the northern part is also influenced by Fenhe river.

Soil sampling and analyses

Soil samples were collected in late-August 2017 from 30 sites (Fig. 1) using a soil auger to a depth of 100 cm, at 20-cm intervals. At each site, four soil cores were randomly taken, and soils for each layer were mixed. Soil bulk density was determined for the 0–20, 20–40 and 40–60 cm at several representative sites. Soils were air-dried, crushed, mixed thoroughly and passed 2-mm screen. A portion of soil samples was crushed to < 0.25 mm, which were used for the measurements of total carbon (TC), SOC and total nitrogen (TN). We prepared soil–water mixtures (1:5) using 2-mm soils for

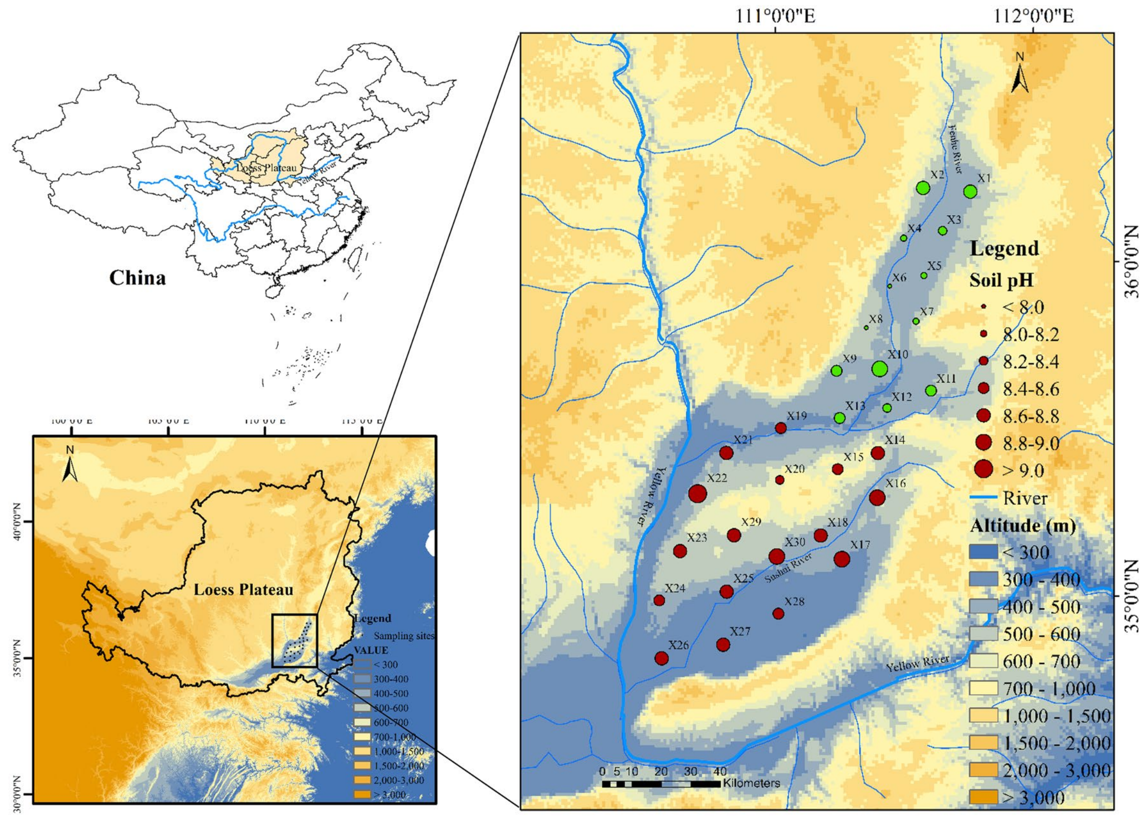

Fig. 1 Sampling locations with altitudes and soil pH in the Loess Plateau, China

measurements of soil pH, electrical conductivity (EC), and water-extractable Ca^{2+} and Mg^{2+} (using an Atomic Absorption Spectrophotometer). Contents of TC and TN were measured using a CNHS–O analyzer (Model EuroEA3000). SOC content was determined by $K_2Cr_2O_7$ oxidation titration (Walkley and Black 1934). Content of SIC was obtained by subtracting SOC from TC.

For the measurements of DOC and DIC, 6 g 2-mm soil was treated with 24 ml 0.05 M K_2SO_4 solution for 4 h at 25 °C, the mixture was shaken for one hour, and followed by centrifugation. The supernatant was filtered through a 0.45-µm membrane, then TC and DIC were determined by a TOC analyzer (TOC-VCPH, Shimadzu). Concentration of DOC was calculated by the difference between TC and IC.

Data calculation and statistical analyses

Stocks of SOC, SIC and DOC were calculated using the following equations:

$$X_{\text{stock}} = \sum_{i=1}^{n} X_i \times B_i \times \frac{D_i}{100} \tag{1}$$

where X_i is carbon content for layer i, D_i soil layer thickness (cm), B_i bulk density (g cm^{-3}), and n the number of soil layers.

The normality test of our data on organic and inorganic carbon shows a normal distribution. Two-way analyses of variance followed by the least significant differences (LSD) were performed to evaluate the differences of various soil indices between basins and layers. Linear regression analyses were employed to analyze the SOC-SIC relationship, and the relationship between DOC:SOC ratio and other soil properties. Statistical analysis was executed using SPSS 19.0.

Results

Basic soil properties and spatial variations of water-soluble Ca + Mg density

As presented in Fig. 1, soil pH had a small range in both LFB (7.9 ~ 8.9) and YCB (8.4 ~ 9.1); mean soil pH was significantly lower in the former (< 8.4) than in the latter (> 8.6) (Table 1). But EC value was observably high in the LFB (0.49–0.72 mS/cm) than in the YCB (0.19–0.29 mS/cm), with higher values in the subsoil. Soil C:N ratio was similar between LFB (9.2–13.4) and YCB (10.2–12.4)

Table 1 Basic soil properties in the Linfen basin (LFB) and Yuncheng basin (YCB)

Layer (cm)	BD		pH		EC (mS/cm)		C:N	
	LFB	YCB	LFB	YCB	LFB	YCB	LFB	YCB
0–20	1.19Ab	1.23Ab	8.20 Ba	8.64 Aa	0.48 Ab	0.19 Ba	13.4 Aa	12.3 Aa
20–40	1.35Aab	1.49Aa	8.38 Ba	8.70 Aa	0.51 Ab	0.22 Ba	11.2 Abc	12.4 Aa
40–60	1.42Aa	1.44Aa	8.38 Ba	8.72 Aa	0.59 Aab	0.25 Ba	10.2 Ac	10.2 Abc
60–80	1.43Aa	1.43Aa	8.37 Ba	8.73 Aa	0.69 Aa	0.27 Ba	9.2 Ac	10.3 Abc
80–100	1.44Aa	1.45Aa	8.38 Ba	8.78 Aa	0.72 Aa	0.29 Ba	7.3 Bc	9.3 Ac

Values followed by the same letter (capital letter between two basins and lowercase letter between layers) are not significantly different at $P < 0.05$ based on LSD test.

above 80 cm, but significantly lower in LFB (7.3) than in YCB (9.3) over 80–100 cm.

Figure 2 showed that water-soluble Ca + Mg (the sum of water-soluble Ca^{2+} and Mg^{2+}) was generally lower in topsoil (i.e., 98 to 341 g m^{-3}) than in subsoils (i.e., 133–450 g m^{-3} over 20–40 cm, and 134–465 g m^{-3} over 40–100 cm). Overall, water-soluble Ca + Mg was low at sites in the north of LFB, and at the sites close to the Yellow River in the YCB above 40 cm. Interestingly, water-soluble Ca + Mg showed similar spatial pattern and magnitudes over 40–100 cm to those over 20–40 cm in the YCB, but overall higher levels in the LFB. There were no significant differences in water-soluble Ca + Mg between two basins or over depth (Table 1).

Spatial variations of SOC, DOC density and DOC:SOC ratio

Figure 3 shows SOC had a larger range in topsoil (5.9–23.0 kg C m^{-3}) than in subsoils (4.3–16.7 kg C m^{-3} over 20–40 cm, and 3.1–12.1 kg C m^{-3} over 40–100 cm). Overall, SOC density was greater in LFB than in YCB, especially in subsoils, although there were a couple of sites (along the Fenhe river and Yellow River) showing high levels of SOC over 20–40 cm in YCB. It appeared that SOC density was lower at high-altitude sites, in particular over 0–20 cm.

DOC varied from 64 to 147 g C m^{-3} in LFB, and 45 to 118 g C m^{-3} in YCB over 0–20 cm (Fig. 3b), showing a similar spatial distribution with SOC (Fig. 3a). However, the spatial pattern of DOC was somehow different from that of SOC in subsoils. Overall, DOC level in subsoil was higher in the YCB than in the LFB. For example, DOC over 40–100 cm varied from 46 to 106 g C m^{-3} in LFB, but 48–144 g C m^{-3} in the YCB.

Ratio of DOC:SOC ranged from 0.37% to 0.98% over 0–20 cm, 0.49% to 1.87% over 20–40 cm, and 0.71% to 2.52% over 40–100 cm (Fig. 4). Despite a large spatial variability, DOC:SOC ratio showed a general higher values in YCB than in LFB in particular below 40 cm. As shown in Table 2, mean DOC:SOC ratio was slightly higher in the YCB (0.76–1.09%) than in the LFB (0.61–0.95%) above 40 cm, significantly higher in the YCB (1.24%) than in the LFB (1.88%) below 40 cm. It appeared that lower ratio of DOC:SOC was found at sites in high-altitude and far away from the Yellow River.

Spatial variations of SIC and DIC density

SIC also showed large spatial variation, with a range from 1.5 to 37.8 kg C m^{-3} above 20 cm, 7.7 to 25.5 kg C m^{-3} over 20–40 cm, and 5.3 to 28.2 kg C m^{-3} over 40–100 cm (Fig. 5a, c, e). Overall, lower levels of SIC were found in the north LFB; however, the lowest SIC (< 5 kg C m^{-3}) was at high-altitude sites in the YCB over 40–100 cm. Nevertheless, the highest levels of SIC (> 37 kg C m^{-3}) were found in the YCB for all soil layers. It appeared that the spatial variability of SIC was larger over 20–40 and 40–100 cm than over 0–20 cm.

The spatial pattern of DIC was markedly different between the three layers although the range was similar, i.e., from 34 to 85 g C m^{-3} over 0–20 cm, 37 to 96 g C m^{-3} over 20–40 cm, and 38 to 98 g C m^{-3} over 40–100 cm (Fig. 5b, d, f). Overall, the spatial distribution of DIC showed no similarity to that of SIC (Fig. 5). For the 0–20 cm layer, high DIC (> 50 g C m^{-3}) was found at sites in the north and south part of LFB and the southwest of YCB. However, DIC below 40 cm displayed high values (> 60 g C m^{-3}) at sites in the east of YCB. In general, low values of DIC were found at sites near the Yellow River below 20 cm (Fig. 5d, f).

The relationship between carbon fractions

Figure 6 shows a significant negative correlation between SIC and SOC stocks using the entire dataset (30 sites) over both 0–20 cm ($P < 0.05$) and 0–100 cm ($P < 0.01$). On a regional scale, there was a significantly negative correlation between SIC and SOC stocks in LFB over the 0–20 cm ($P < 0.01$) and 0–100 cm ($P < 0.05$), but weak or no significant correlation in YCB. Our analysis also showed a strong positive relationship ($P < 0.01$) between DOC and SOC over 0–20 cm in both LFB and YCB. However, for the 20–100 cm layer, DOC had a

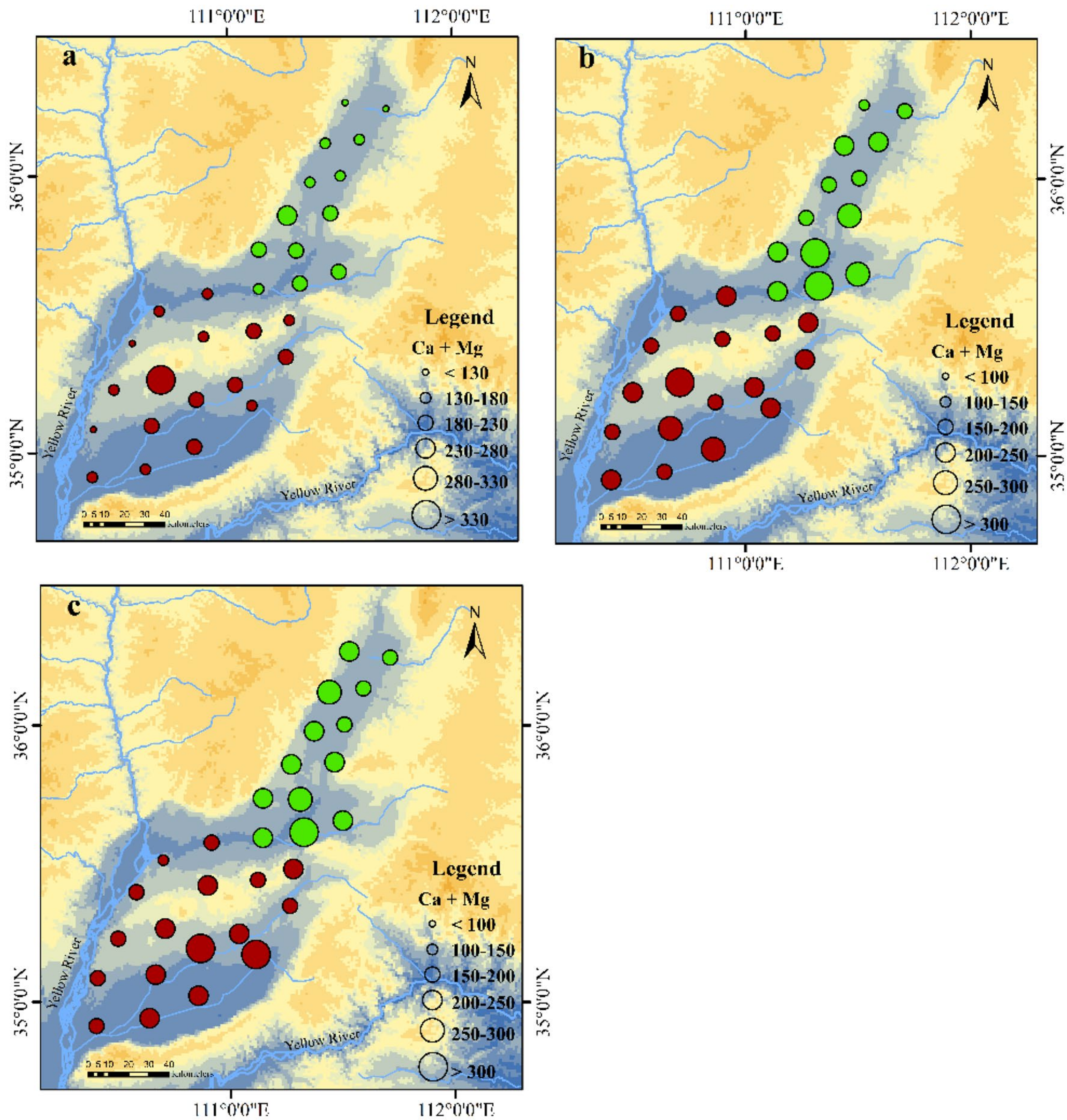

Fig. 2 Density (g m^{-3}) of water soluble Ca + Mg over (**a**) 0–20 cm, (**b**) 20–40 cm, and (**c**) 40–100 cm in the YCB (red) and LFB (green). The figure was generated using ArcMap 10.5 (https://www.esri.com/)

significantly positive correlation with SOC only in the YCB (Fig. 7).

Discussion

Variations of SOC and SIC in loess cropland

On average, SOC content is significantly higher in the whole soil profile in the LFB (4.35–15.1 g kg^{-1}) relative to YCB (3.14–10.3 g kg^{-1}) (Table 2). Previous studies have demonstrated that erosion can transport topsoil from highlands to lowlands, which leads to depositions of SOM/SOC in valleys and basins with lower elevation (Liu et al. 2011; Zheng et al. 2005; Zhong and Xu 2009). The LFB, as a valley, may have accumulated a thick layer of redeposited topsoil from surrounding highlands that contain high levels of SOC (Liu et al. 2011).

SOC content of the YCB (from 10.3 g kg^{-1} over 0–20 cm to 3.1 g kg^{-1} over 80–100 cm) is similar to those in loess cropland, e.g., from 9.7 to 2.7 g kg^{-1} in the Hebei Plain (Lu et al. 2020), and from 11.0 to 3 g kg^{-1} in the west part of Loess Plateau (Liu et al. 2018; Zhang et al. 2015). The relative low levels of SOC in those loess croplands may be largely related to the texture of loess that has less

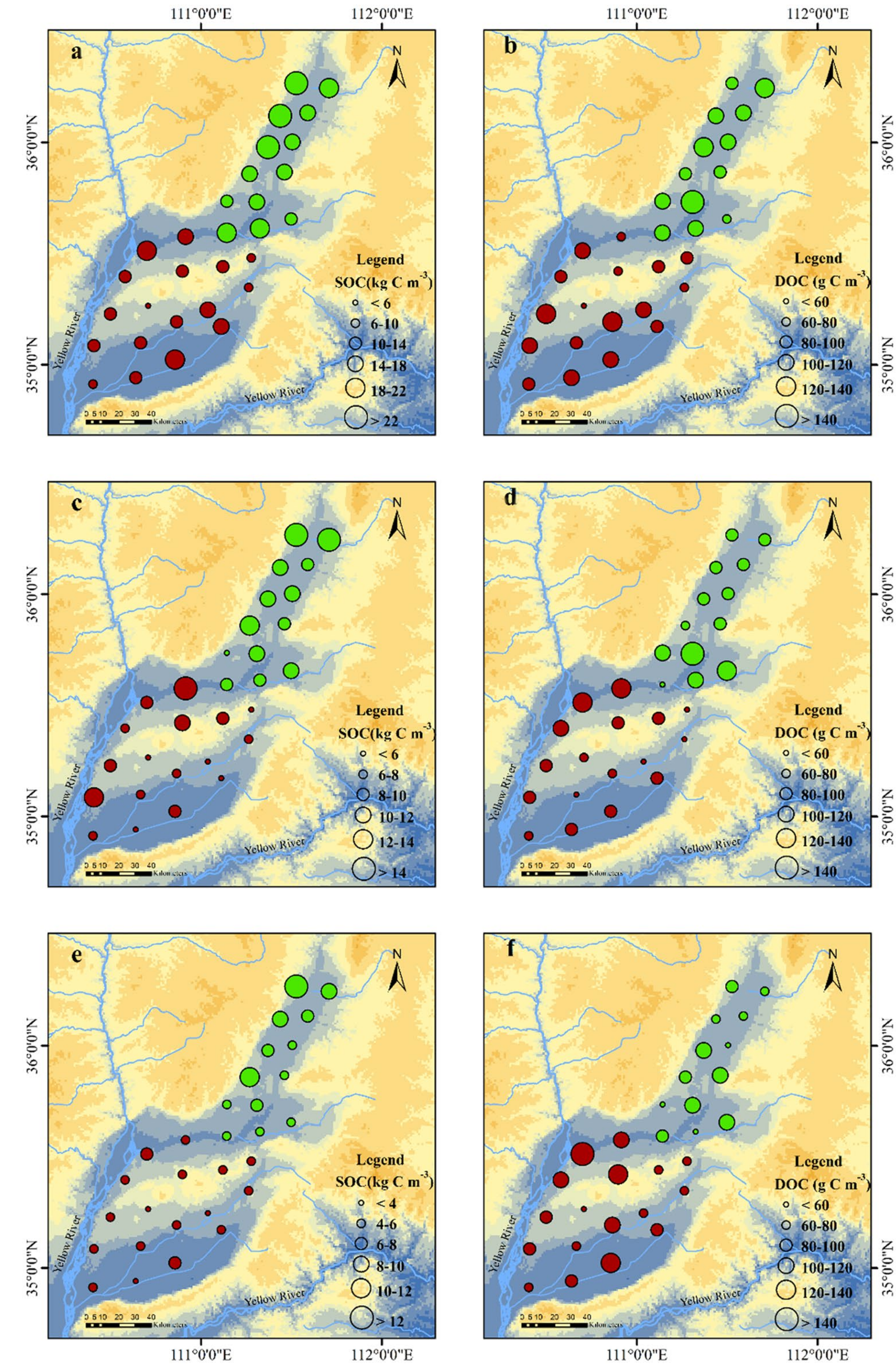

Fig. 3 Density of soil organic carbon (SOC) (left panel) and dissolved organic carbon (DOC) (right panel) over (**a**, **b**) 0–20 cm, (**c**, **d**) 20–40 cm, and (**e**, **f**) 40–100 cm in the YCB (red) and LFB (green). The figure was generated using ArcMap 10.5 (https://www.esri.com/)

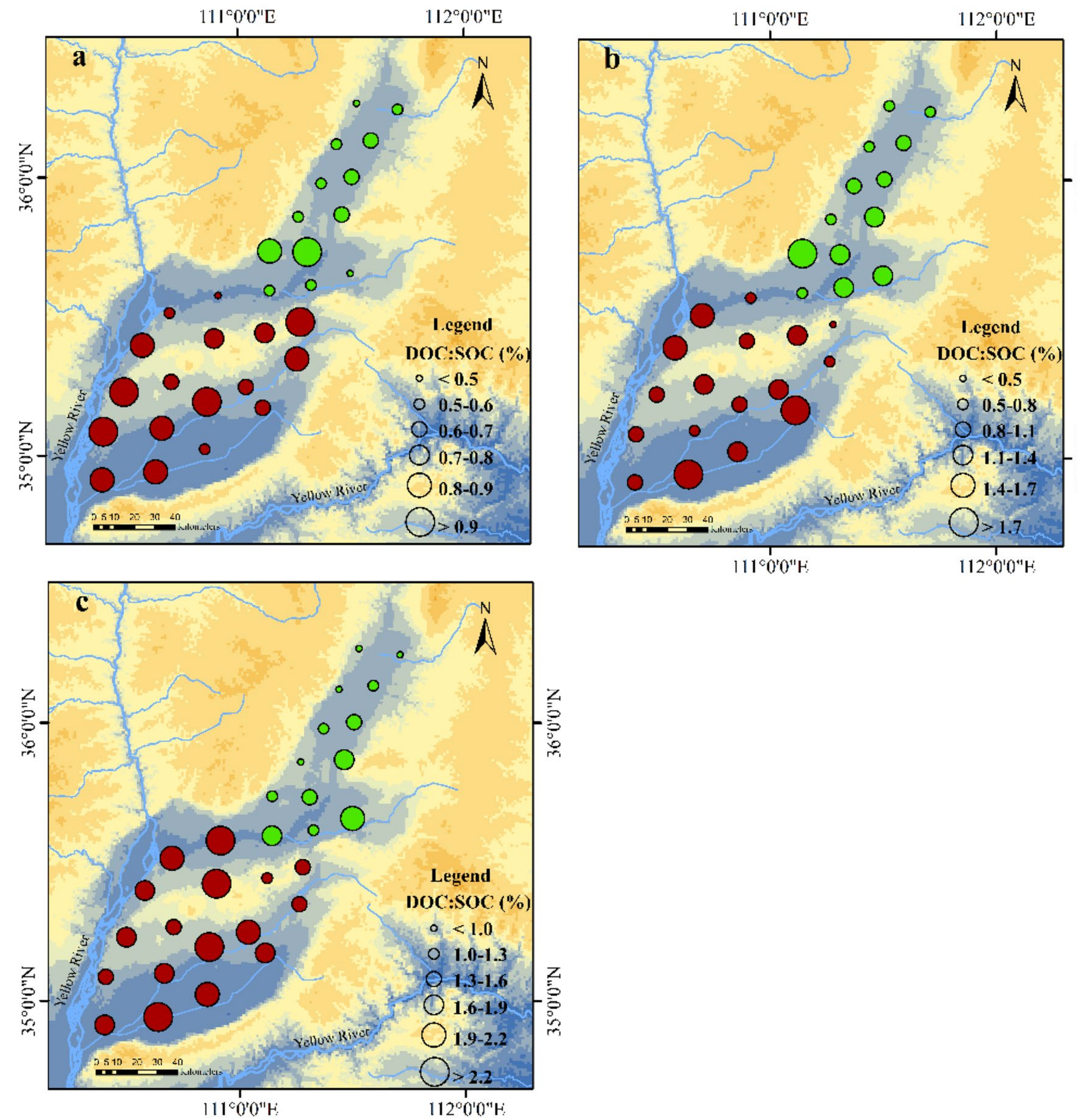

Fig. 4 Ratio of dissolved organic carbon and soil organic carbon (DOC:SOC, %) over (**a**) 0–20 cm, (**b**) 20–40 cm, and (**c**) 40–100 cm in the YCB (red) and LFB (green). The figure was generated using ArcMap 10.5 (https://www.esri.com/)

Table 2 Main soil carbon forms and their ratios in the Linfen basin (LFB) and Yuncheng basin (YCB)

Depth (cm)	SOC (g/kg)		SIC (g/kg)		DOC (mg/kg)		DIC (mg/kg)		DOC:SOC (%)		DIC:SIC (%)	
	LFB	YCB	LFB	YCB	LFB	YCB	LFB	YCB	LFB	YCB	LFB	YCB
0–20	15.1 Aa	10.3 Ba	9.17 Bb	12.1 Aab	90.1 Aa	75.2 Ba	43.1 Aa	41.3 Aa	0.61 Ac	0.76 Ac	0.91 Aa	0.39 Ba
20–40	8.02 Ab	5.75 Bb	9.69 Bb	11.4 Ab	71.1 Ab	59.3 Bb	37.4 Aa	42.2 Aa	0.95 Ab	1.09 Ab	0.43 Ab	0.39 Aa
40–60	5.73 Ac	3.91 Bc	9.29 Bb	12.2 Aab								
60–80	4.95 Ac	3.38 Bc	10.6 Bb	13.4 Aa	57.3 Ac	64.9 Ab	41.5 Aa	41.8 Aa	1.24 Ba	1.88 Aa	0.39 Ab	0.39 Aa
80–100	4.35 Ac	3.14 Bc	12.5 Aa	12.8 Aa								

Values followed by the same letter (capital letter between the basin and lowercase letter between layers) are not significantly different at $P < 0.05$ based on LSD test

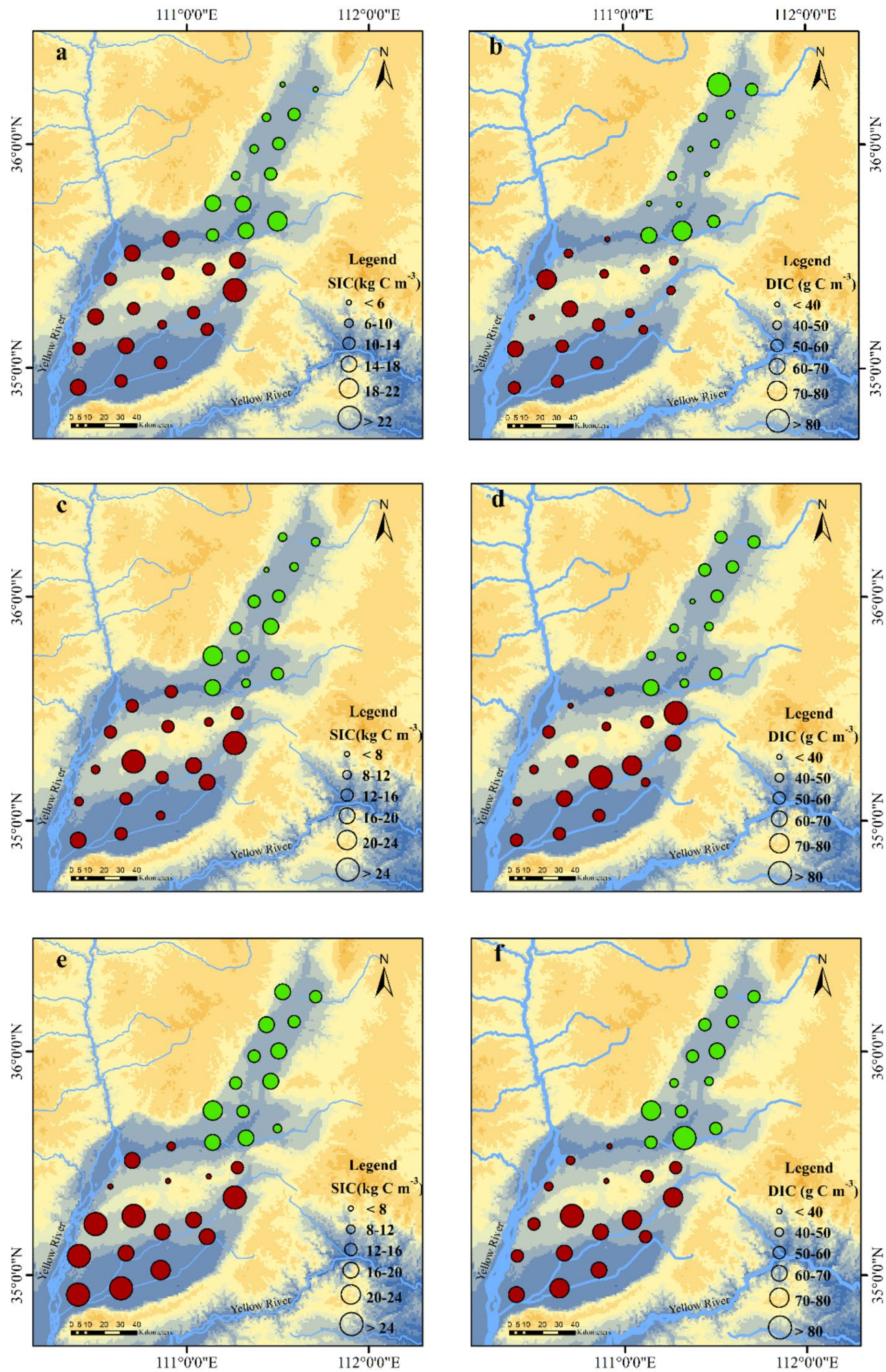

Fig. 5 Density of soil inorganic carbon (SIC) (left panel) and dissolved inorganic carbon (DIC) (right panel) over (**a**, **b**) 0–20 cm, (**c**, **d**) 20–40 cm, and (**e**, **f**) 40–100 cm in the YCB (red) and LFB (green). The figure was generated using ArcMap 10.5 (https://www.esri.com/)

clay thus less protection for SOM (Li et al. 2019, 2017). In addition, hydrological processes associated with the Yellow River may lead to enhanced desorption/removal of DOC from soil profile, which is partly responsible for the relatively lower SOC in the loess croplands (Shi et al. 2017a; Zhang et al. 2020).

Our study showed that SIC was significantly lower in LFB (9.2–10.6 g kg^{-1}) than in YCB (11.4–13.4 g kg^{-1})

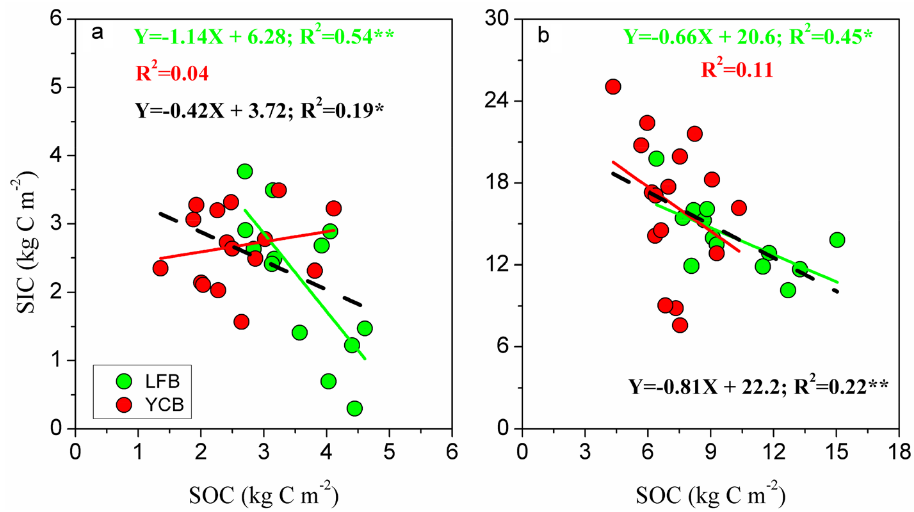

Fig. 6 Correlation between SIC and SOC stocks in LFB, YCB and combined data (black dash lines) over (**a**) 0–20 cm, (**b**) 0–100 cm. One asterisk indicates significance at $P<0.05$, and two asterisks at $P<0.01$

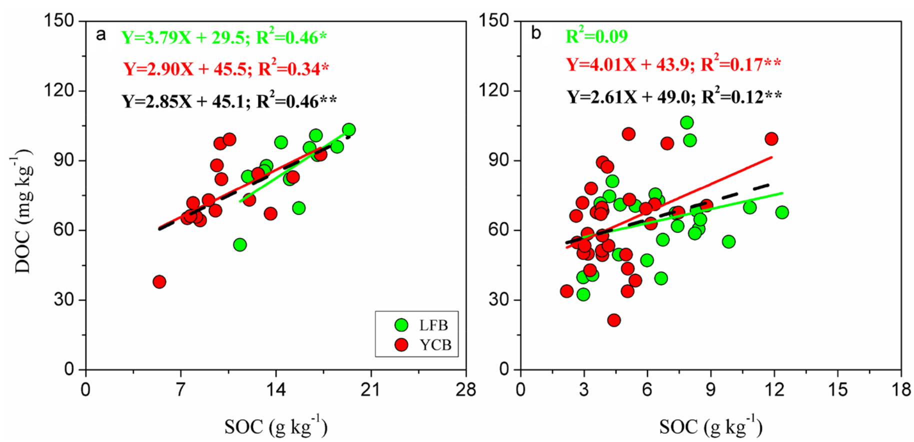

Fig. 7 Correlation between DOC and SOC content in the LFB, YCB and combined data (black dash lines) over (**a**) 0–20 cm and (**b**) 20–100 cm. One asterisk indicates significance at $P<0.05$, and two asterisks at $P<0.01$

above 80 cm, which corresponded with significantly higher DIC:SIC ratio in the LFB (0.91%) than in the YCB (0.39%) in the topsoil (Table 2). There were some studies on SIC dynamics in the croplands of north China that have the same or similar parent materials, such as in the Loess Plateau (Zhang et al. 2015) and the North China Plain (Guo et al. 2016; Shi et al. 2017b). Clearly, SIC content in the LFB (with redeposited topsoil) is much lower than that in the western highland (>15 g kg^{-1}) of Loess Plateau (Zhang et al. 2015) that has much drier climate and higher soil pH (Table 3). Interestingly, SIC levels in the YCB are close to those (10.5–12.7 g kg^{-1}) in the upper YRD (Guo et al. 2016), but modest higher than those (7.1–11.4 g kg^{-1}) in the North China Plain (Shi et al. 2017b) though all soils had same parent materials and similar climatic conditions (Table 3). Both the YCB and upper YRD are close to the Yellow River, thus experience strong influences of hydrological processes that could supply extra Ca and Mg ions over the past, which is beneficial for SIC formation (Guo et al. 2016).

The relationship between SIC and SOC in loess

Our analysis shows no clear relationship between SIC and SOC stocks in YCB, but a significant negative correlation between SIC and SOC stocks in the LFB. The overall negative correlation of SIC and SOC in this study area

Table 3 Comparisons of climate conditions and soil variables (mean and standard deviation) in different study areas under the same/similar parent material

Study area	Elevation (m)	parent material	Temperature (°C)	precipitation (mm)	Evaporation (mm)	pH	EC (mS/cm)	SOC (kg C m^{-2})	SIC (kg C m^{-2})
LZ[a]	1700–2000	Loess	9.6	250–350	1500	8.94 (0.22)	0.19 (0.06)	5.73 (1.68)	22.3 (3.13)
NCP[b]	6–112	Alluvial loess	12.5	500–600	1900	8.64 (0.21)	0.22 (0.09)	7.51 (1.47)	16.5 (2.04)
YRD[c]	11–35	Alluvial loess	13.4	530–640	2100	8.20 (0.08)	0.34 (0.16)	5.73 (1.31)	16.89 (2.52)
LFB[d]	389–554	Redeposited loess	8.9–12.9	420–550	1659	8.34 (0.19)	0.61 (0.28)	10.0 (2.56)	14.0 (2.51)
YCB[d]	380–820	Alluvial loess	13.3	500–750	1810	8.71 (0.21)	0.24 (0.14)	6.96 (1.50)	16.9 (5.71)

The numbers in brackets represent the standard deviation

LZ-Lanzhou, NCP-Northern China Plan, YRD-upper Yellow River Delta, LFB-Linfeng Basin, YCB-Yuncheng Basin

[a] (Zhang et al. 2015)

[b] (Shi et al. 2017b)

[c] (Guo et al. 2016)

[d] This study

disagrees with our previous findings of a positive correlation in the loess cropland of North China Plain (Guo et al. 2016; Shi et al. 2017b), and under various land uses in northwest China (Gao et al. 2018; Wang et al. 2015b). There is also evidence of a negative SIC-SOC relationship in the cropland of Hebei Plain (Li et al. 2010) and under various land use types in the Loess Plateau, north China (Zhao et al. 2016).

We found a negative SIC-SOC relationship in the LFB, which was consistent with a report for another part of the Loess Plateau (Zhao et al. 2016). Soil erosion and redeposition/redistribution are profound in the Loess Plateau (Zheng et al. 2005), which would move topsoil from highlands to lowlands, leading to enhanced SOC storage (but with lower SIC stock) in upper 100 cm (Table 3). In addition, elevated SOC level in the soil profile of LFB could also result in more CO_2 production thus lower pH (Table 1), which causes dissolution of soil carbonate (Chang et al. 2012; Raheb et al. 2017).

The non-significantly SIC-SOC relationship in YCB may reflect the complex influences of multi drivers. There is evidence that precipitation has large impacts on both SOC and SIC in arid/semi-arid lands (Li et al. 2007; Raheb et al. 2017; Wu et al. 2009), particularly in the Loess Plateau (Han et al. 2018). The YCB has a large spatial variation in both precipitation (500–750 mm) and elevation (380–820 m a.s.l.), which could have large impacts on the distributions of SOC and SIC, leading to alterations of the SIC-SOC relationship. Our analyses indicate that there is an increasing trend (from 1.0 to 5.8) in SIC:SOC ratio with increasing elevation in the YCB. In addition, the distance from the Yellow River is probably another factor that can alter the SIC-SOC relationship through the influences of hydrological processes on either SIC (Shi et al. 2017b) or SOC (Shi et al. 2017a). We further discuss the potential influence of hydrological processes on SOC below.

Regulating factors for SOC

The variability of SOC is large under the same cropping system in the loess of north China (Fig. 3 and Shi et al. 2017b), implying that "outputs" of SOC/SOM (e.g., decomposition of SOM), rather than "inputs", primarily regulate the dynamics of SOC, which is influenced by environmental conditions (Liu et al. 2011; Shirale et al. 2019). Given that subsoils are mainly subject to decomposition, we evaluate the relationships between soil carbon indices and other variables over 40–100 cm. Our analyses show that SOC has a positive correlation with EC and a negative correlation with soil pH (Fig. 6). There is evidence that high EC in saline soils can cause flocculation of clay particles into aggregates, which restricts substrate availability for microbial thus retards decomposition of SOM (Wong et al. 2010). Additionally, soils with high pH often have poor physical–chemical conditions that are harmful to crop growth and root system development, resulting in less organic carbon inputs into the soil (Kemmitt et al. 2006; Wong et al. 2010).

In addition to the decomposition process, desorption could also lead to lower SOC (Kalbitz et al. 2000; Mavi et al. 2012). Our analyses show that DOC:SOC ratio (representing desorption potential) is positively correlated with pH, and negatively correlated with EC in subsoils (Fig. 8). There are studies demonstrating that high soil pH can destroy soil aggregates, thus reduce the protection of SOM against degradation (Kalbitz et al. 2000; Tavakkoli et al. 2015) whereas high EC may be beneficial for

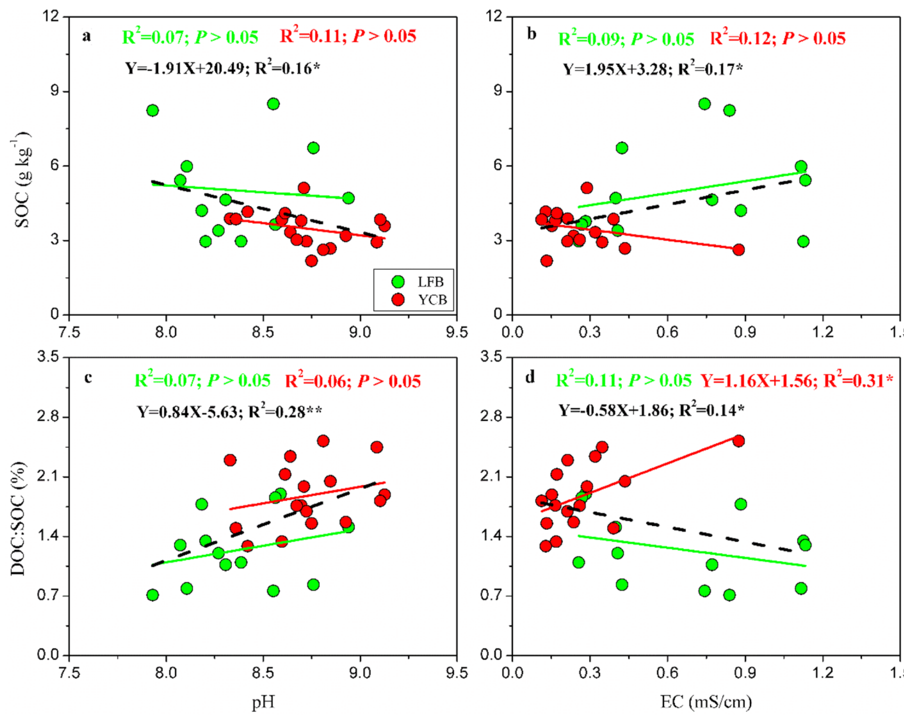

Fig. 8 Correlation between SOC (DOC:SOC) and pH or EC in the LFB, YCB and combined data (black dash lines) over 40–100 cm. One asterisk indicates significance at $P < 0.05$, and two asterisks at $P < 0.01$

the formation and stabilization of soil aggregates (Rahimi et al. 2000).

Our analyses show that DOC:SOC ratio is higher in YCB (0.76–1.88%) than in LFB (0.61–1.24%), with a significant difference below 40 cm (Table 2), which indicates stronger desorption of SOC in the subsoils of YCB. Similarly, Zhang et al. (2020) reported greater DOC:SOC ratio close to the Yellow River over 60–100 cm, relative to those in other parts of North China Plain. Apparently, the YCB and other regions that have a shorter distance to the Yellow River are influenced by stronger hydrological processes (such as water movements), which would result in more desorption and remove of DOC thus lower levels of SOC in subsoils (Zhang et al. 2020).

Conclusions

We evaluate the spatial variation, relationship and driving factors of soil carbon fractions over 0–100 cm in low-elevation cropland of the Loess Plateau, i.e., LFB and YCB. Our data show that SIC stock is significantly higher than SOC stock over 0–100 cm in the whole study area; SOC stock is negatively correlated with soil pH, but positively correlated with EC. SOC and SIC stocks reveal a significantly negative correlation in LFB, which is partly related to erosion and re-deposition/redistribution of topsoil. We find no clear relationship between SOC and SIC stocks in YCB, which may reflect the large spatial variations of elevation and precipitation.

Our data show a significantly positive correlation between DOC and SOC in both topsoil and subsoil of YCB, but only in the topsoil of LFB. We find that DOC:SOC ratio is significantly higher below 40 cm in YCB than LFB, and DOC:SOC ratio is positively correlated with soil pH, and negatively correlated with EC. Our analyses suggest that high soil pH and stronger hydrological processes are attributable to the relatively lower levels of SOC in YCB. Further studies are needed to investigate how soil properties and environmental conditions interplay to regulate the dynamics of SOC and SIC in the Loess Plateau.

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Authors' contributions
XW provided supervision and financial support for this study, and checked/corrected all the versions of the manuscript. TL collected soils, conducted laboratory measurements and data analyses, and prepared for the manuscript. WZ helped with sampling and analyses, and commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The research data of this study can be obtained upon by requesting the corresponding author.

Competing interests
The authors declare that they have no conflict of interests.

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