Fractions of soil organic and inorganic carbon and their relationships in typical loess cropland of Fenggu Basin

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Research Letter

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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: Lingfeng 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. On average, DOC:SOC ratio 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, SIC 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.

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 & 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, 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 of environmental conditions between SOC and SIC. For instance, there is evidence that high soil pH often leads to low levels of SOC but high levels of SIC (Oste et al. 2002, Tavakkoli et al. 2015, Wang et al. 2015a). Recent studies suggest that hydrologic process may have influences on various fractions of soil carbon, including dissolved organic (DOC) and inorganic carbon (DIC) that result from the desorption of organic matter and the dissolution of inorganic carbon, respectively (Shi et al. 2017b, Zhang et al. 2020). There is 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 Fenggu Basin, consisting of Linfeng 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 Fenggu Basin relative to other regions of
north China (e.g., the North China Plain). The objectives of this work are to study the dynamics of SOC and SIC in the low-elevation cropland of the Loess Plateau, to assess the relationship between major soil carbon fractions, and to explore the underlying mechanism responsible for the variability of SOC and SIC in semi-arid region.

**Materials And Methods**

**Characteristics of the study area**

Our study area (110°24¢12²-111°42¢29²E, 34°54¢43²-36°15¢52²N, ~4000 km²) 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 of a double cropping system, i.e., winter wheat and summer maize rotation, with similar fertilization and tillage management. Irrigation is often applied using waters from the rivers.

Despite of 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 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 lower altitude to 550 mm at 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 m 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**

In August 2017, during mature stage of maize, soil samples were collected from 30 sites (Figure 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 were 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 measurements of soil pH, electrical conductivity (EC), and water extractable Ca²⁺ and Mg²⁺ (by using an Atomic Absorption Spectrophotometer). Contents of TC and TN were measured using a CNHS–O analyzer (Model EuroEA3000). SOC content was determined by K₂Cr₂O₇ oxidation titration (Walkley & Black 1934). Content of SIC was obtained by subtracting SOC from TC.

For the measurements of DOC and dissolved inorganic carbon (DIC), 6 g 2-mm soil was treated with 24 ml 0.05 M K₂SO₄ solution for 4 hours at 25°C, the mixture was shaken for one hour, then centrifugation. The supernatant was filtered through a 0.45-μm membrane, followed by analyses of DOC and DIC by a TOC analyzer (TOC-VCPH, Shimadzu).

**Data calculation and Statistical analyses**

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

\[
X_{stock} = \sum_{i=2}^{n} X_i \times D_i \times \frac{B_i}{100}
\]

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

Fig. 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

Fig. 3 shows SOC had a large 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 to 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 of a large spatial variability, DOC:SOC ratio showed general higher values in YCB than in LFB in particular below 40 cm. As showed 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) above 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. 5ace). 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. 5bdf). 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. 5df).

The relationship between carbon fractions

Fig. 6 shows a significantly negative correlation between SIC and SOC stocks using 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 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 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 & 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 clay thus less protection for SOM (Li et al. 2019, Li et al. 2017).

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\(^{-1}\)) 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).

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 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 re-deposition/redistribution is profound in the Loess Plateau (Zheng et al. 2005), which would move topsoil from highland to lowland, 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.

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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 soil (Kemmitt et al. 2006, Wong et al. 2010).

In addition to 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 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 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 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.

Declarations

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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Author contributions
Xiujun Wang provided supervision and financial support for this study, and checked/corrected all the versions of the manuscript. Tongping Lu collected soils, conducted laboratory measurements and data analyses, and prepared for the manuscript. Wenxi Zhang 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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**References**

Amundson R (2001): The carbon budget in soils. Annual Review of Earth and Planetary Sciences 29, 535-562

Chang R, Fu B, Liu G, Wang S, Yao X (2012): The effects of afforestation on soil organic and inorganic carbon: A case study of the Loess Plateau of China. Catena 95, 145-152

Fu B, Liu Y, Lü Y, He C, Zeng Y, Wu B (2011): Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecological Complexity 8, 284-293

Gao Y, Dang P, Zhao Q, Liu J, Liu J (2018): Effects of vegetation rehabilitation on soil organic and inorganic carbon stocks in the Mu Us Desert, northwest China. Land Degradation & Development 29, 1031-1040

Guo Y, Wang X, Li X, Wang J, Xu M, Li D (2016): Dynamics of soil organic and inorganic carbon in the cropland of upper Yellow River Delta, China. Scientific Reports 6, 36105. doi: 10.1038/srep36105

Han X, Gao G, Chang R, Li Z, Ma Y, Wang S, Wang C, Lü Y, Fu B (2018): Changes in soil organic and inorganic carbon stocks in deep profiles following cropland abandonment along a precipitation gradient across the Loess Plateau of China. Agriculture, Ecosystems & Environment 258, 1-13

Huang C, Cong Y, Chen Y, Yang Z, Hou Q, Zhou J, Wang J, Li D, Wang H, Zhang M, Li W (2007): Fluorine content in soils of the Linfen- Yuncheng basin, southern Shanxi, China, and its influence factors. Geological Bulletin of China 26, 878-885

Jobbágy EG, Jackson RB (2000): The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10, 423-436

Kalbitz K, Solinger S, Park J-H, Michalzik B, Matzner E (2000): Controls on the dynamics of dissolved organic matter in soils: a review. Soil Science 165, 277-304

Kemmitt SJ, Wright D, Goulding KW, Jones DL (2006): pH regulation of carbon and nitrogen dynamics in two agricultural soils. Soil Biology and Biochemistry 38, 898-911

Lal R (2004): Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science (New York, N.Y.) 304, 1623

Li GT, Zhang CL, Zhang HJ, Gilkes RJ, Prakongkep N (2010): Soil inorganic carbon pool changed in long-term fertilization experiments in north China plain, World Congress of Soil Science: Soil Solutions for A Changing World, Brisbane, Australia, 1-6 August 2010. Congress Symposium 4: Greenhouse Gases From Soils, pp. 220-223

Li M, Han X, Du S, Li L-J (2019): Profile stock of soil organic carbon and distribution in croplands of Northeast China. Catena 174, 285-292

Li Z, Nie X, He J, Chang X, Liu C, Liu L, Sun L (2017): Zonal characteristics of sediment-bound organic carbon loss during water erosion: A case study of four typical loess soils in Shaanxi Province. Catena 156, 393-400
Li ZP, Han FX, Su Y, Zhang TL, Sun B, Monts DL, Plodinec MJ (2007): Assessment of soil organic and carbonate carbon storage in China. Geoderma 138, 119-126

Liu C, Li Z, Chang X, He J, Nie X, Liu L, Xiao H, Wang D, Peng H, Zeng G (2018): Soil carbon and nitrogen sources and redistribution as affected by erosion and deposition processes: A case study in a loess hilly-gully catchment, China. Agriculture, Ecosystems & Environment 253, 11-22

Liu Z, Shao Ma, Wang Y (2011): Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China. Agriculture, Ecosystems & Environment 142, 184-194

Lu T, Wang X, Xu M, Yu Z, Luo Y, Smith P (2020): Dynamics of pedogenic carbonate in the cropland of the North China Plain: Influences of intensive cropping and salinization. Agriculture, Ecosystems & Environment 292, 106820

Mavi MS, Marschner P, Chittleborough DJ, Cox JW, Sanderman J (2012): Salinity and sodicity affect soil respiration and dissolved organic matter dynamics differentially in soils varying in texture. Soil Biology and Biochemistry 45, 8-13

Mehra P, Sarkar B, Bolan N, Chowdhury S, Desbiolles J (2019): Impact of carbonates on the mineralisation of surface soil organic carbon in response to shift in tillage practice. Geoderma 339, 94-105

Monger HC, Kraimer RA, Khresat Se, Cole DR, Wang X, Wang J (2015): Sequestration of inorganic carbon in soil and groundwater. Geology 43, 375-378

Oste LA, Temminghoff EJ, Riemsdijk WV (2002): Solid-solution partitioning of organic matter in soils as influenced by an increase in pH or Ca concentration. Environmental Science & Technology 36, 208-214

Raheb A, Heidari A, Mahmoodi S (2017): Organic and inorganic carbon storage in soils along an arid to dry sub-humid climosequence in northwest of Iran. Catena 153, 66-74

Rahimi H, Pazira E, Tajik F (2000): Effect of soil organic matter, electrical conductivity and sodium adsorption ratio on tensile strength of aggregates. Soil and Tillage Research 54, 145-153

Rowley MC, Grand S, Verrecchia ÉP (2018): Calcium-mediated stabilisation of soil organic carbon. Biogeochemistry 137, 27-49

Schiettecatte W, Gabriels D, Cornelis W, Hofman G (2008): Impact of deposition on the enrichment of organic carbon in eroded sediment. Catena 72, 340-347

Shi H, Wang X, Xu M, Zhang H, Luo Y (2017a): Characteristics of soil C:N ratio and δ13C in wheat-maize cropping system of the North China Plain and influences of the Yellow River. Scientific Reports 7, 16854

Shi HJ, Wang XJ, Zhao YJ, Xu MG, Li DW, Guo Y (2017b): Relationship between soil inorganic carbon and organic carbon in the wheat-maize cropland of the North China Plain. Plant and Soil 418, 423-436

Shi X, Yu D, Warner E, Sun W, Petersen G, Gong Z, Lin H (2006): Cross-reference system for translating between genetic soil classification of China and soil taxonomy. Soil Science Society of America Journal 70, 78-83

Shirale AO, Meena BP, Gurav PP, Srivastava S, Biswas AK, Thakur JK, Somasundaram J, Patra AK, Rao AS (2019): Prospects and challenges in utilization of indigenous rocks and minerals as source of potassium in farming. Journal of Plant Nutrition 42, 2682-2701

Tavakkoli E, Rengasamy P, Smith E, McDonald G (2015): The effect of cation–anion interactions on soil pH and solubility of organic carbon. European Journal of Soil Science 66, 1054-1062

Virto I, Gartzia-Bengoetxea N, Femández-Ugalde O (2011): Role of organic matter and carbonates in soil aggregation estimated using laser diffractometry. Pedosphere 21, 566-572
Walkley A, Black IA (1934): An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science 37, 29-38

Wang JP, Wang XJ, Zhang J, Zhao CY (2015a): Soil organic and inorganic carbon and stable carbon isotopes in the Yanqi Basin of northwestern China. European Journal of Soil Science 66, 95-103

Wang XJ, Wang JP, Xu MG, Zhang WJ, Fan T, Zhang J (2015b): Carbon accumulation in arid croplands of northwest China: pedogenic carbonate exceeding organic carbon. Scientific Reports 5, 11439

Wong VNL, Greene RSB, Dalal RC, Murphy BW (2010): Soil carbon dynamics in saline and sodic soils: a review. Soil Use and Management 26, 2-11

Wu H, Guo Z, Gao Q, Peng C (2009): Distribution of soil inorganic carbon storage and its changes due to agricultural land use activity in China. Agriculture, Ecosystems & Environment 129, 413-421

Zamanian K, Pustovoytov K, Kuzyakov Y (2016): Pedogenic carbonates: Forms and formation processes. Earth-Science Reviews 157, 1-17

Zhang F, Wang X, Guo T, Zhang P, Wang J (2015): Soil organic and inorganic carbon in the loess profiles of Lanzhou area: implications of deep soils. Catena 126, 68-74

Zhang W, Wang X, Lu T, Shi H, Zhao Y (2020): Influences of soil properties and hydrological processes on soil carbon dynamics in the cropland of North China Plain. Agriculture, Ecosystems & Environment 295

Zhao W, Zhang R, Huang C, Wang B, Cao H, Koopal LK, Tan W (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

Zheng F, He X, Gao X, Zhang C-e, Tang K (2005): Effects of erosion patterns on nutrient loss following deforestation on the Loess Plateau of China. Agriculture, Ecosystems & Environment 108, 85-97

Zhong B, Xu YJ (2009): Topographic effects on soil organic carbon in Louisiana watersheds. Environmental Management 43, 662-672

Zhu H, Wu J, Guo S, Huang D, Zhu Q, Ge T, Lei T (2014): Land use and topographic position control soil organic C and N accumulation in eroded hilly watershed of the Loess Plateau. Catena 120, 64-72

Tables

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

| Layer (cm) | BD     | pH    | EC (mS/cm) | Ca+Mg (mg/kg) | C:N   |
|-----------|--------|-------|------------|----------------|-------|
|           | LFB    | YCB   | LFB        | YCB            | LFB   | YCB   | LFB   | YCB   | LFB   | YCB   |
| 0-20      | 1.19Ab | 1.23Ab| 8.20Ba     | 8.64Ba         | 0.48Ab| 0.19Ba| 143   | 149   | 13.4  | 12.3  |
| 20-40     | 1.35Aab| 1.49Aa| 8.38Ba     | 8.70Aa         | 0.51Ab| 0.22Ab| 166   | 165   | 11.2  | 12.4  |
| 40-60     | 1.42Aa | 1.44Aa| 8.38Ba     | 8.72Aa         | 0.59Aab| 0.25Ba| 161   | 144   | 10.2  | 10.2  |
| 60-80     | 1.43Aa | 1.43Aa| 8.37Ba     | 8.73Aa         | 0.69Aa| 0.27Ba| 153   | 145   | 9.2   | 10.3  |
| 80-100    | 1.44Aa | 1.45Aa| 8.38Ba     | 8.78Aa         | 0.72Aa| 0.29Ba| 151   | 162   | 7.3   | 9.3   |
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.

### Table 2 Main carbon forms and their ratios in the LFB and 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         |
| 0-20       | 15.1       | 10.3       | 9.17        | 12.1        | 90.1        | 75.2        | 43.1        | 41.3        | 0.61        | 0.76        | 0.91        | 0.39        |
|            | Aa         | Ba         | Ab          | Aab         | Ba          |            | Ac          | Ac          |            |            |            |            |
| 20-40      | 8.02       | 5.75       | 9.69        | 11.4        | 71.1        | 59.3        | 37.4        | 42.2        | 0.95        | 1.09        | 0.43        | 0.39        |
|            | Ab         | Bb         | Ab          | Aab         | Ab          |            | Ab          | Ab          |            |            |            |            |
| 40-60      | 5.73       | 3.91       | 9.29        | 12.2        | 57.3        | 64.9        | 41.5        | 41.8        | 1.24        | 1.88        | 0.39        | 0.39        |
|            | Ac         | Bc         | Ac          | Aab         | Aa          |            | Aa          | Aa          |            |            |            |            |
| 60-80      | 4.95       | 3.38       | 10.6        | 13.4        |             |             |             |             |             |             | 0.39        | 0.39        |
|            | Ac         | Bc         | Bc          | Aa          |             |             |             |             |             |            |            |            |
| 80-100     | 4.35       | 3.14       | 12.5        | 12.8        |             |             |             |             |             |             |             |            |
|            | Ac         | Bc         | Aa          | Aa          |             |             |             |             |             |            |            |            |

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

### Table 3 Comparisons of climate and soil variable 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 | 0.19       | 5.73 (1.68)           | 22.3 (3.13)            |
| NCP\(^b\)  | 6-112         | Alluvial Loess  | 12.5             | 500-600            | 1900             | 8.64 | 0.22       | 7.51 (1.47)           | 16.5 (2.04)            |
| YRD\(^c\)  | 11-35         | Alluvial Loess  | 13.4             | 530-640            | 2100             | 8.20 | 0.34       | 5.73 (1.31)           | 16.89 (2.52)           |
| LFB\(^d\)  | 389-554       | Redeposited Loess | 8.9-12.9   | 420-550            | 1659             | 8.34 | 0.61       | 10.0 (2.56)           | 14.0 (2.51)            |
| YCB\(^d\)  | 380-820       | Alluvial Loess  | 13.3             | 500-750            | 1810             | 8.71 | 0.24       | 6.96 (1.50)           | 16.9 (5.71)            |

Note: the numbers in brackets represent the standard deviation. \(^a\)Zhang et al., (2015); \(^b\)Shi et al., (2017b); \(^c\)Guo et al., (2016); \(^d\)this study. LZ-Lanzhou, NCP-Northern China Plan, YRD-upper Yellow River Delta, LFB-Linfeng Basin, YCB-Yuncheng Basin.

**Figures**
Figure 1

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

Figure 2
Water soluble Ca+Mg density (g m⁻³) 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 (http://www.esri.com/).

Figure 3

Soil organic carbon (SOC) (left panel) and dissolved organic carbon (DOC) stocks (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 (http://www.esri.com/).
Figure 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 (http://www.esri.com/).
Figure 5
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 (http://www.esri.com/).

Figure 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 $P < 0.01$.

Figure 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 $P < 0.01$. 

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 $P < 0.01$. 

Figure 8