Response of the characteristics of organic carbon mineralization of soft rock and soil composed of sand to soil depth

Wanying Li¹,²,*, Zhen Guo²,³,*, Juan Li²,³ and Jichang Han¹,²,³

¹ College of Land Engineering, Chang’an University, Xi’an, Shaanxi, China
² Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi’an, Shaanxi, China
³ Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi’an, Shaanxi, China
* These authors contributed equally to this work.

ABSTRACT

The addition of soft rock to aeolian sandy soil can improve the level of fertility and ability of the soil to sequester carbon, which is of substantial significance to improve the ecological environment of the Mu Us sandy land and supplement newly added cultivated land. Soft rock and sand were combined using the ratio (v/v) of 0:1 (CK), 1:5 (S1), 1:2 (S2), and 1:1 (S3). The process of mineralization of organic carbon at different depths (0–10 cm, 10–20 cm, and 20–30 cm) in the combined soil was studied by 58 days of incubation indoors at a constant temperature. The content of soil nutrients increased significantly under the S2 and S3 treatments and was higher in the 0–10 cm soil depth. The mineralization of rate of soil organic carbon (SOC) of different combination ratios can be divided into three time periods: the stress mineralization stage (1–7 d), the rapid mineralization stage (7–9 d) and the slow mineralization stage (9–58 d). At the end of incubation, the rates of mineralization of SOC and accumulated mineralization amount (Ct) were relatively large in the 0–10 cm soil depth, followed by the 10–20 cm and 20–30 cm soil layers, indicating that the stability of SOC in the surface layer was poor, which is not conducive to the storage of carbon. The content of potentially mineralizable organic carbon (C0) in the soil was consistent with the trend of change of Ct. Compared with the CK treatment, the cumulative organic carbon mineralization rate (Cr) of the S2 and S3 treatments decreased by 7.77% and 6.05%, respectively; and the C0/SOC decreased by 22.84% and 15.55%, respectively. Moreover, the Cr and C0/SOC values in the 10–20 cm soil depth were small, which indirectly promoted the storage of organic carbon. With the process of SOC mineralization, the contents of soil microbial biomass carbon (SMBC) and dissolved organic carbon (DOC) tended to decrease compared with the initial contents, with larger amplitudes in the 20–30 cm and 10–20 cm soil depth, respectively. SOC, total nitrogen, available potassium, SMBC and DOC were all closely related to the process of mineralization of organic carbon. Therefore, the accumulation of soil carbon could be enhanced when the proportion of soft rock and sand composite soil was between 1:2 and 1:1, and the 10–20 cm soil depth was relatively stable. These results provide a theoretical basis for the improvement of desertified land.
INTRODUCTION

Soil organic carbon (SOC), an important component of soil, plays a critical role in soil fertility, ecological system balance, and sustainable agricultural development, although it only comprises a small part of the total soil quality (Bishwakarma et al., 2014). SOC refers to the total amount of organic matter in the soil that contains carbon, which is primarily composed of plant and animal residues, soil humus and soil microbial carbon (Martens, Reedy & Lewis, 2004; Gomez, Delgado & Gonzalez, 2021). The SOC pool is twice that of the atmospheric carbon pool and three times the total carbon pool of the earth’s vegetation, and approximately 80% of the total carbon involved in the carbon cycle of the earth’s land area exists in the soil in the form of SOC (Körschens, 2010; Ganjegunte et al., 2005). Small changes in the soil carbon pool can lead to significant changes in the concentration of atmospheric CO\(_2\), indicating that the fixation and mineralization of SOC play an important regulatory role in the concentration of global atmospheric CO\(_2\) (Kuzyakov, Friedel & Stahr, 2000; Guo et al., 2021). In this context, it is highly important to understand the dynamic changes in the global terrestrial ecosystem carbon pool to reduce the greenhouse effect and improve the quality of environment (Moore et al., 2020).

The mineralization of SOC is an important biochemical process in the soil, which not only reflects the stability and turnover rate of organic carbon but also directly relates to the release and supply of soil nutrients (Marinari et al., 2010). The process of SOC mineralization is affected by many factors, such as the chemical composition and existence of soil organic matter, soil microbial population composition and activity, soil physical and chemical properties, soil type, and soil depth thickness (Saggar, 2001; Huang et al., 2002). Among them, the thickness of soil depth is an important factor that affects the mineralization of organic carbon, and the rate of mineralization of organic carbon of the soil below the surface has a significant impact on the atmospheric circulation effect (Fontaine et al., 2007). Jobbagy & Jackson (2000) reported that in the global terrestrial ecosystem, the carbon content of soil at a depth of 20–300 cm is three times higher than that of the surface soil. In the context of global climate change, plant roots grow to deeper soils, and the production of root exudates and the input of animal and plant residues will change the carbon input at deeper soil depths, thereby triggering the mineralization and decomposition of carbon (Lal et al., 2007). Karhu et al. (2016) studied the ability of organic carbon to stimulate mineralization at different depths of boreal forest soils and showed that the mineralization of organic carbon in the lower soil is more sensitive to that of external carbon. However, Paterson & Sim (2013) found that the mineralization of organic carbon in the upper and lower layers of the soil responds to outside factors in the same way. When there is no stimulation, some recent studies have shown that deep soil organic carbon is more stable than surface organic carbon (Schimel et al., 2011). In farmland and woodland ecosystems, studies have shown that soil depth, sampling method, and cultivation time have significant effects on the mineralization of organic carbon, while temperature has no obvious effect (Fang et al., 2005). Thus, without the addition of external carbon sources, as the roots of crops gradually grow to the lower layer, the intensity of mineralization of the soil itself on the vertical scale merits further clarification.
In the semiarid Mu Us sandy land in northern China, the development of desertification has led to the fragmentation of habitats and patchy distribution of vegetation, as well as the depletion of nutrients and a high degree of spatial heterogeneity in their distribution (Liu et al., 2020). By studying the soft rock and aeolian sandy soil (sand) in the Mu Us sandy land, Han, Liu & Luo (2012) obtained a formula for the combination of soft rock and sand suitable for different crop growth needs. The use of soft rock to improve sandy soil not only enhances the air permeability and water retention of sand but also increases crop yields and promotes the development of sandy soil to loamy soil (Wang et al., 2016; Guo, Zhang & Wang, 2020; Li et al., 2019). Guo, Han & Li (2020) showed that non-dominant bacteria in the 0–30 cm soil depth play an important role in the fixation of organic carbon, but the influence of soil thickness on the mineralization of organic carbon in the compound soil has not been studied. The soft rock and sand composite soil is a mixed soil depth (0–30 cm) that is utilized in engineering measures, such as excavation and filling, crushing soft rock, and topsoil stripping. Since microorganisms in the mixed soil depth are affected by the external environment and root growth, there must be a gradient or differences (Sun & Han, 2018). However, in the 0–30 cm mixed soil depth, under the action of microorganisms, the degree of mineralization of organic carbon of the composite soil every 10 cm interval remains to be elucidated. Therefore, this study aimed to understand the potential of soft rock and sandy composite soil to undergo mineralization at different soil depths using laboratory soil incubation experiments and to understand the biological feedback mechanism of desertification from the perspective of soil carbon mineralization that affects nutrient cycling. Therefore, the purpose of this study was to (1) study the difference in gradients of contents of soil nutrients between mixed soil depths; (2) explore the intensity of mineralization of organic carbon in soft rock and sand composite soil at different soil depths; and (3) reveal the relationship between mineralization of organic carbon and nutrients at different soil depth. We hypothesized the following outcomes: (1) the compound soil at a depth of 0–10 cm had a higher nutrient content; (2) the compound soil was more stable and could sequester carbon more effectively at a depth of 10–20 cm, and (3) the turnover time of carbon pool was longer, and the content of nutrients was higher when the proportion of addition of soft rock to the sandy soil was between 33.33–50%.

**MATERIALS & METHODS**

**Study site**

The experimental plot was established in a pilot test base of the Shaanxi Provincial Land Engineering Technology Research Institute (Fuping county, China) (109°11'E, 34°42'N). The area is in the transition zone between the Guanzhong Plain and the northern Shaanxi Plateau and belongs to the gully region of the Weibei Loess Plateau. The terrain is high in the north and low in the south. It slopes from northwest to southeast. The elevation in the territory is 375.8–1, 420.7 m. The area belongs to the continental monsoon warm zone and has a semiarid climate. The annual total radiation is 5,187.4 MJ m⁻²; the annual average sunshine hours is approximately 2,389.6 h; the annual average temperature is 13.1 °C,
The annual average precipitation is 527.2 mm. The interannual precipitation varies substantially, and its coefficient of variation (CV) reaches 21.1%.

**Experimental design**

The test field was utilized to simulate the conditions of soft rock and sand mixed layer in the Mu Us sandy land. The design depth of the experimental field was 1 m, and it was filled with a mixture of soft rock and sand at a depth of 0–30 cm and filled with aeolian sandy soil at a depth of 30–70 cm. The test was conducted in 2009, and four treatments of soft rock and sand in a volume ratio of 0:1 (CK), 1:5 (S1), 1:2 (S2), and 1:1 (S3) were selected. Each treatment was repeated three times for a total of 12 trial plots (Fig. 1). The area of each plot was 2 m × 2 m. Based on the site conditions of the test plot, considering the uniformity of factors, such as illumination and microtopography, the test plot was arranged from south to north in a “one” shape. The experimental field was artificially sown with was maize (Jincheng 508) and wheat (Xiaoyan 22) with a rotation of two crops a year. The types of fertilizers tested in the experimental field were urea, including N 46.4%, diammonium phosphate; including N 16%, containing P₂O₅ 44%, potassium sulfate, including K₂O 52%, and the amount of fertilizer applied was 255 kg hm⁻² (N), 180 kg hm⁻² (P₂O₅) and 90 kg hm⁻² (K₂O). The mode of fertilization of each treatment was the same, and all three fertilizers were applied.

**Collection of soil samples**

After the wheat was harvested in May 2020, soil samples at a depth of 0–30 cm (0–10 cm, 10–20 cm and 20–30 cm) were collected from each plot. Soil samples were collected from five different points and mixed to make a composite sample for each plot. The animal and plant residues were removed from the collected soil samples, sieved through a 1-mm sieve, and then divided into two portions. One was placed at 4 °C for the mineralization incubation test, and one was naturally air-dried to determine the basic physical and chemical properties.

**Method of determination**

The soil organic carbon (SOC) was determined using the potassium dichromate-concentrated sulfuric acid external heating method as previously described (Nelson & Sommers, 1996). The total nitrogen (TN) was determined using Kjeldahl digestion; the available phosphorus (AP) was determined using molybdate blue colorimetry, and the concentrations of available potassium (AK) were measured using atomic absorption spectrometry (Qiu et al., 2014). The soil particle composition was determined using a Mastersizer 3000 laser diffraction particle size analyzer (Malvern Instruments, Worcestershire, UK) (Sun & Han, 2018).

The content of dissolved organic carbon (DOC) content was determined by extraction with deionized water as previously described (Ghani, Dexter & Perrott, 2003). The specific steps were as follows: the weight of fresh soil equivalent to that of 10 g of dry soil was placed in a 50 mL centrifuge tube, and 30 mL of deionized water was added. The mixture was shaken and extracted for 30 min at room temperature and centrifuged using a high-speed centrifuge (Allegra 64R; Beckman Coulter, New York City, NY, USA). After
centrifugation, the supernatant was passed through a 0.45-μm filter membrane, and the filtrate was measured with a Multi N/C 3100 total organic carbon/total nitrogen analyzer (AnalytikJena, Jena, Germany). The soil microbial biomass carbon (SMBC) was determined using the chloroform fumigation-potassium sulfate extraction method as previously described (Brookes et al., 1985).

The organic carbon mineralization test utilized the lye absorption method (Ribeiro et al., 2010), which entailed weighing 30 g of the soil stored at 4 °C into a 50 mL beaker, adjusting the water content with deionized water to maintain the amount of water at approximately 65%, and weighing the beaker as a constant value at this time. Lye and the soil-filled beaker were placed in an incubation bottle to be sealed and cultured in the dark. The lye was a solution of 0.1 mol L\(^{-1}\) NaOH. The lye was removed and titrated with dilute acid at 1, 3, 5, 7, 9, 16, 23, 30, 37, 44, 51, and 58 days of incubation respectively. The dilute acid was a solution of 0.1 mol L\(^{-1}\) HCl. A volume of two mL of one mol L\(^{-1}\) BaCl\(_2\) solution and 2 drops of phenolphthalein indicator were added to the lye before each titration. After the dilute acid titration had been completed, a new lye solution was replaced. At this time, the beaker that contained the soil was removed and weighed, and deionized water was added to keep it at a constant weight before incubation.
Data analysis
The rate of soil organic carbon (SOC) mineralization was calculated as described by Wang et al. (2014). After the indoor incubation was completed, the first-order kinetic equation in Origin 2017 software (OriginLab, Northampton, MA, USA) was used to fit the SOC cumulative mineralization parameters to obtain the potential mineralizable organic carbon ($C_0$) and turnover rate constant ($k$) (Stanford & Smith, 1972). The formula for first-order kinetic model is shown as follows:

$$C_t = C_0(1 - e^{-kt})$$

where $C_t$ is the cumulative mineralization of SOC (mg kg$^{-1}$); $C_0$ is the potential mineralizable organic carbon (mg kg$^{-1}$), and $k$ is the turnover rate constant (d$^{-1}$).

The semi-turnover period was $T_{1/2} = \ln2/k$ (d).

The soil depth and compound ratio were the two factors in this study. The data from soil physical and chemical properties and mineralization were subjected to a Duncan multiple comparison and analysis of variance (ANOVA) using Microsoft Excel 2010 (Redmond, WA, USA) and SPSS 20.0 (IBM, Inc., Armonk, NY, USA).

RESULTS
Soil physical and chemical properties
The combined effect of the two factors of soil depth and compound ratio had a significant impact on the SOC, AK, sand, clay and texture (Table 1). The SOC, TN and clay contents of the S1, S2, and S3 treatments were significantly higher in the 0–10 cm soil depth than those of the CK treatment ($P < 0.05$), and there was no significant difference in the content of AP between treatments ($P > 0.05$). The contents of AK and silt in the S2 and S3 treatments were significantly higher than those in the CK treatment, and the content of sand was lower in the S2 and S3 treatments. There was no significant difference between the contents of SOC and AP in the 10–20 cm soil depth treatment, and the contents of TN and AK of the S3 treatment were significantly higher than those of the CK. The content of sand decreased significantly with the increase in proportion of soft rock, while the contents of silt and clay increased significantly in the 10–20 cm soil depth treatment. During the 20–30 cm soil depth, there was no significant difference in the contents of SOC, TN, AP and AK among the treatments. The sand content of S2 treatment decreased significantly, and the clay content increased significantly. All of the nutrients were found at higher concentrations in the 0–10 cm soil depth. With the change in composition of soil particles in the compound soil, the trend of change of soil texture was sand-loamy sand-sandy loam. It was apparent that the content of soil nutrients increased significantly under the S2 and S3 treatments, with a higher content in the 0–10 cm soil depth. The soil texture developed benign.

Rate of SOC mineralization
The rate of mineralization of different types of organic carbon in the compound soils changed with the incubation time, revealing clear differences in their characteristics depending on the stage. During the early stage of incubation, the rate of SOC mineralization was unstable, and it first decreased and then increased (Fig. 2). The rate of mineralization
| Soil depth (cm) | Compound ratio | SOC (g kg\(^{-1}\)) | TN (g kg\(^{-1}\)) | AP (mg kg\(^{-1}\)) | AK (mg kg\(^{-1}\)) | Sand (%) | Silt (%) | Clay (%) | Texture |
|----------------|----------------|---------------------|---------------------|---------------------|---------------------|----------|----------|----------|---------|
| 0–10           | CK             | 2.95 ± 0.14 bA      | 0.20 ± 0.02 bA      | 18.4 ± 0.40 aA      | 50.00 ± 5.00 cA     | 100 ± 0 aA| 0 ± 0 cA | 0 ± 0 bB | Sand    |
|                | S1             | 5.57 ± 1.71 aA      | 0.48 ± 0.14 aA      | 20.43 ± 2.74 aA    | 65.00 ± 10.66 bcA  | 84.42 ± 4.20 bA| 14.80 ± 2.91 bA| 0.78 ± 0.29 a A| Loamy sand |
|                | S2             | 4.54 ± 0.81 aA      | 0.48 ± 0.04 aA      | 17.33 ± 2.98 aA    | 111.67 ± 4.62 aA   | 79.83 ± 5.35 bcA| 19.13 ± 4.01 abA| 1.04 ± 0.34 a A| Loamy sand |
|                | S3             | 5.13 ± 0.74 aA      | 0.55 ± 0.08 aA      | 16.57 ± 3.01 aA    | 100.00 ± 6.00 abA  | 72.32 ± 5.20 CB  | 26.14 ± 4.83 aA| 1.54 ± 0.38 a A| Loamy sand |
| 10–20          | CK             | 3.98 ± 0.06 aA      | 0.34 ± 0.06 aA      | 11.93 ± 1.05 aA    | 44.00 ± 5.00 hA     | 90.95 ± 0.05 abA| 8.93 ± 0.12 dB  | 0.12 ± 0.03 dB | Sand    |
|                | S1             | 4.38 ± 0.12 aA      | 0.38 ± 0.12 abAB    | 14.77 ± 0.68 aAB   | 58.00 ± 12.49 abA  | 84.72 ± 1.44 bA   | 14.41 ± 1.32 cA| 0.87 ± 0.13 c A| Loamy sand |
|                | S2             | 4.42 ± 0.17 aA      | 0.38 ± 0.11 abAB    | 13.67 ± 2.99 aA    | 60.33 ± 5.51 abB   | 75.87 ± 0.76 cA   | 22.66 ± 0.81 bA| 1.47 ± 0.07 b A| Loamy sand |
|                | S3             | 4.59 ± 0.82 aA      | 0.54 ± 0.10 aA      | 13.76 ± 2.62 aA    | 69.00 ± 5.57 ab    | 68.63 ± 3.66 db    | 29.33 ± 3.37 aA| 2.04 ± 0.30 a A| Sandy loam |
| 20–30          | CK             | 4.01 ± 0.02 aA      | 0.26 ± 0.04 aA      | 9.10 ± 0.60 aA     | 50.01 ± 3.25 aA    | 87.34 ± 0.65 aB   | 11.96 ± 1.05 abA| 0.70 ± 0.20 c A| Sand    |
|                | S1             | 2.50 ± 0.96 aB      | 0.24 ± 0.06 aB      | 6.80 ± 0.61 aB     | 41.33 ± 8.50 aB    | 86.53 ± 5.11 aB   | 12.42 ± 0.92 abB| 1.05 ± 0.28 abB| Sand    |
|                | S2             | 2.87 ± 0.21 aB      | 0.32 ± 0.07 aB      | 7.50 ± 2.09 aB     | 38.67 ± 4.04 aB    | 81.53 ± 4.15 aB   | 15.01 ± 3.81 aA| 1.46 ± 0.30 a A| Loamy sand |
|                | S3             | 2.58 ± 0.58 aB      | 0.30 ± 0.15 aB      | 7.57 ± 1.35 aB     | 40.00 ± 5.58 aC    | 83.42 ± 6.20 abA  | 15.57 ± 2.84 aA| 1.01 ± 0.31 bcB| Loamy sand |

Notes. SOC refers to soil organic carbon; TN refers to soil total nitrogen; AP refers to soil available phosphorus; AK refers to soil available potassium. Mean ± standard deviation, lowercase letters indicate significant differences between different treatments under the same soil depth, capital letters indicate significant differences between different soil depth under the same treatment (P < 0.05).
Figure 2  SOC mineralization rate under different soil layers. CK represents the volume ratio of soft rock to sand is 0:1; S1 represents a volume ratio of soft rock to sand of 1:5; S2 represents a volume ratio of soft rock to sand of 1:2; S3 represents the volumetric ratio of soft rock to sand is 1:1.

The rate of mineralization of SOC slowly declined and gradually stabilized during the latter period of experiment. At the end of culture, the rates of SOC mineralization of S1, S2, and S3 treatments in the 0–10 cm soil depth were 22.51 mg kg\(^{-1}\) d\(^{-1}\), 12.80 mg kg\(^{-1}\) d\(^{-1}\), and 17.83 mg kg\(^{-1}\) d\(^{-1}\), respectively. The rates of mineralization of the CK and S2 were basically the same, while those of S1 and S3 increased by 12.71% and 33.96%, respectively, compared with those of the CK. The average values of rate of SOC mineralization in the 10–20 cm and 20–30 cm soil depths were basically the same, but both were less than that in the 0–10 cm soil depth. In the 10–20 cm soil depth, the rate of SOC mineralization of S1, S2, and S3 treatments increased by 288.36%, 133.33%, and 351.72%, respectively, compared with that of the CK. At the 20–30 cm soil depth, the rates of mineralization of SOC of the S1, S2, and S3 treatments were lower than that of the CK treatment.
Figure 3  SOC cumulative mineralization of each treatment under different soil layers. CK represents the volume ratio of soft rock to sand is 0:1; S1 represents a volume ratio of soft rock to sand of 1:5; S2 represents a volume ratio of soft rock to sand of 1:2; S3 represents the volumetric ratio of soft rock to sand is 1:1.

**SOC cumulative mineralization (C_t)**

The C_t in each soil depth increased exponentially with the incubation time, and the average value gradually decreased as the soil depth deepened. The specific performance was 0–10 cm (843.72 mg kg$^{-1}$) > 10–20 cm (659.16 mg kg$^{-1}$) > 20–30 cm (612.30 mg kg$^{-1}$) (Fig. 3).

In the same soil depth, the C_t differed between treatments with different compound ratios. In the 0–10 cm soil depth, the S1 treatment had the largest C_t, which was 1,125.17 mg kg$^{-1}$, followed by the CK, S3, and S2 treatments. In the 10–20 cm soil depth, the S3 treatment had the largest C_t, which was 781.91 mg kg$^{-1}$, followed by those of the S1, S2, and CK treatments. In the 20–30 cm soil depth, the CK treatment had the largest C_t, which was 796.49 mg kg$^{-1}$, followed by the S3, S2, and S1 treatments. When all the soil depths were factored into account, the average cumulative mineralization of organic carbon was the largest in S1 treatment, which was 806.62 mg kg$^{-1}$, followed by the S3, CK and S2 treatments, and the cumulative mineralization of organic carbon was 721.30 mg kg$^{-1}$, 697.14 mg kg$^{-1}$, and 595.19 mg kg$^{-1}$, respectively.

**Cumulative rate of SOC mineralization**

The accumulated rate of mineralization (C_r) of the SOC in compound soils of different soil depths differed to some extent. The C_r in the 0–10 cm (26.01%) soil depth was significantly higher than that at the 10–20 cm (19.08%) and 20–30 cm (19.52%) soil depths (Fig. 4).
In the 0–10 cm soil depth, the ratios of S1, S2, and S3 were reduced by 1.61-, 2.49-, and 2.44-fold compared with the CK, respectively. Compared with the S1 treatment, the C\(_r\) of SOC under S2 and S3 treatments was significantly reduced by 1.55- and 1.52-fold. In the 10–20 cm soil depth, the C\(_r\) of SOC treated by S1, S2 and S3 did not differ significantly but increased to some extent compared with that treated by the CK. In the 20–30 cm soil depth, there was no significant difference in the C\(_r\) of SOC treated by S1, S2, and S3, but it was significantly reduced by 1.17–1.29-fold compared with that treated by the CK. It was apparent that the S2 and S3 treatments had a lower C\(_r\), which is beneficial to carbon storage, and the effect at the 10–20 cm soil depth was even better.

**SOC mineralization kinetic equation fitting**

Based on the CO\(_2\)-C release measured at each stage of incubation in the 58 d constant room temperature, the C\(_t\) in soil depth with different compound ratios of 0–10 cm, 10–20 cm and 20–30 cm was fitted using a first-order kinetic equation (C\(_t\) = C\(_0\)[1–e\(^{-kt}\)]. The results showed that the fitting effect was excellent (R\(^2\) > 0.96), and fitting parameters, such as C\(_0\), k and T\(_{1/2}\), were obtained (Table 2). Among all the soil depths, the 0–10 cm soil depth has the largest C\(_0\). The C\(_0\) and C\(_t\) of 0–10 cm and 10–20 cm soil depths have the same tendency to change, and the C\(_0\) value of the 20–30 cm soil depth was the largest when treated with S1 and S3. The k value was the largest in the 10–20 cm soil depth, and there was no significant difference between the 0–10 cm and 20–30 cm soil depths. The k value of the S1 treatment in the 0–10 cm and 20–30 cm soil depths was significantly lower than
Table 2 Parameters of the first-order kinetics for the SOC mineralization.

| Soil depth (cm) | Compound ratio | C₀ (mg kg⁻¹) | k (× 10⁻³ d⁻¹) | T₁/₂(d) | C₀/SOC (%) | R²     |
|----------------|----------------|--------------|----------------|---------|------------|--------|
| 0–10           | CK             | 1561.71 ± 136.72 bA | 27.10 ± 0.33 cB | 25.5 ± 2.13 aA | 77.19       | 0.9971 |
|                | S1             | 2242.29 ± 207.55 aA | 23.05 ± 0.55 cB | 30.10 ± 1.26 aA | 52.93       | 0.9911 |
|                | S2             | 684.04 ± 46.13 dAB | 63.52 ± 0.85 aA | 10.92 ± 0.08 bcA | 19.21       | 0.9835 |
|                | S3             | 1048.51 ± 119.79 cB | 41.46 ± 0.76 bB | 16.75 ± 0.09 bB | 23.78       | 0.9840 |
| 10–20          | CK             | 454.49 ± 18.64 dB | 99.28 ± 0.11 aA | 6.98 ± 0.21 bcB | 13.16       | 0.9813 |
|                | S1             | 912.92 ± 46.96 bB | 59.07 ± 0.82 aA | 11.73 ± 0.10 bB | 26.20       | 0.9917 |
|                | S2             | 785.99 ± 65.68 bC | 53.84 ± 0.58 bB | 12.87 ± 0.63 bA | 22.76       | 0.9824 |
|                | S3             | 1362.71 ± 73.93 aA | 27.57 ± 0.876 cC | 25.14 ± 0.73 aA | 39.79       | 0.9826 |
| 20–30          | CK             | 1499.94 ± 214.65 aA | 24.56 ± 0.47 bB | 28.22 ± 0.15 aA | 42.61       | 0.9931 |
|                | S1             | 1008.93 ± 181.87 bB | 22.68 ± 1.21 bB | 30.56 ± 0.61 aA | 34.28       | 0.9610 |
|                | S2             | 637.18 ± 62.45 cB | 54.30 ± 0.97 aB | 12.77 ± 0.71 bA | 22.48       | 0.9754 |
|                | S3             | 717.43 ± 62.57 cC | 56.72 ± 0.93 aA | 12.22 ± 0.75 bBC | 22.74      | 0.9778 |

Notes.
Mean ± standard deviation, lowercase letters indicate significant differences between different treatments under the same soil layer, capital letters indicate significant differences between different soil depth under the same treatment (P < 0.05).

those of the S2 and S3 treatments. The tendency of T₁/₂ to change was opposite to the value of k, and the T₁/₂ of 0–10 cm and 20–30 cm soil depths were larger. The C₀/SOC in the 10–20 cm soil depth was the smallest (25.47%), and the C₀/SOC in the S2 and S3 treatments was small (21.48% and 28.27%, respectively). In summary, the mineralization of the 10–20 cm soil depth was relatively small, and the ability of the S2 and S3 treatments to sequester carbon was relatively strong.

Characteristics of the variation of DOC and SMBC during SOC mineralization
Before and after the incubation, the average DOC content decreased with the deepening of the soil depth and increased with the increase in the proportion of soft rock. The average content of SMBC was the largest in the 10–20 cm soil depth before and after incubation, and the increase paralleled that of the proportion of soft rock. With the extension of the incubation time, the contents of DOC and SMBC tended to decrease compared with the initial content. After the incubation, the contents of DOC in the 0–10 cm, 10–20 cm, and 20–30 cm soil depth decreased by 17.76–23.21%, 19.86–24.46%, and 14.99–20.58%, respectively, compared with those before incubation. The contents of SMBC were reduced by 14.55–21.54%, 12.69–20.01% and 19.34–20.99%, respectively, compared with before incubation (Table 3). In the 0–10 cm soil depth, there was no significant difference in the content of DOC between the treatments before and after the incubation, and the content of SMBC was the largest in the S3 treatment. In the 10–20 cm soil depth, the contents of DOC of the S1, S2, and S3 treatments before and after the incubation were significantly higher than that of the CK treatment, and the content of SMBC was the highest in S2 treatment. In the 20–30 cm soil depth, the changes of DOC and SMBC before and after the incubation...
Table 3 The initial content of DOC and SMBC in different compound ratios, depth and its changes after incubation.

| Soil depth (cm) | Compound ratio | DOC (mg kg\(^{-1}\)) | SMBC (mg kg\(^{-1}\)) |
|----------------|----------------|------------------------|------------------------|
|                | Before incubation | After incubation | Decrease value |
|                | Before incubation | After incubation | Decrease value |
| 0–10           | CK              | 5.01 ± 0.93 aA | 4.12 ± 0.53 aA | 0.89 ± 0.06 bA |
|                | S1              | 5.60 ± 1.61 aA | 4.30 ± 0.75 aA | 1.30 ± 0.32 aA |
|                | S2              | 5.84 ± 1.13 aA | 4.57 ± 0.31 aA | 1.27 ± 0.13 aA |
|                | S3              | 5.82 ± 1.32 aA | 4.68 ± 1.06 aA | 1.15 ± 0.08 aA |
| 10–20          | CK              | 3.53 ± 0.82 bB | 2.79 ± 0.75 bB | 0.74 ± 0.04 bA |
|                | S1              | 5.56 ± 0.44 aA | 4.20 ± 1.52 aA | 1.36 ± 0.03 aA |
|                | S2              | 5.19 ± 0.15 aA | 4.07 ± 1.31 aA | 1.12 ± 0.09 aA |
|                | S3              | 5.89 ± 0.36 aA | 4.72 ± 0.47 aA | 1.17 ± 0.21 aA |
| 20–30          | CK              | 3.50 ± 0.62 bB | 2.78 ± 0.29 bB | 0.72 ± 0.22 abA |
|                | S1              | 3.87 ± 0.96 bB | 3.29 ± 0.62 bB | 0.58 ± 0.07 bB |
|                | S2              | 5.07 ± 1.51 aA | 4.16 ± 1.14 aA | 0.91 ± 0.13 aAB |
|                | S3              | 5.27 ± 1.31 aA | 4.39 ± 0.86 aA | 0.87 ± 0.05 aAB |

Notes. Mean ± standard deviation, lowercase letters indicate significant differences between different treatments under the same soil depth, capital letters indicate significant differences between different soil depth under the same treatment (\(P < 0.05\)).

were the same, and the contents of both S2 and S3 treatments were higher. It is apparent that the contents of DOC and SMBC of the S2 and S3 treatments have a greater tendency to change, and the mineralization was stronger, particularly in the 10–20 cm soil depth.

Relationship between the parameters of SOC mineralization and physicochemical properties

Through the correlation analysis of the \(C_0\) and \(k\) values of three soil depths and four soils with different compound ratios and soil physicochemical properties, the results showed that there was no significant correlation between the \(C_0\) and \(k\) values at the 0–10 cm soil depth and the soil physicochemical properties (Table 4). As the soil depth deepened, the correlation became clearer. At the 10–20 cm soil depth, the \(C_0\) value had no significant correlation with the soil physicochemical properties, but the \(k\) value had a significant negative correlation with the contents of SOC and silt and an extremely significant negative correlation with the AK content. In the 20–30 cm soil depth, the \(C_0\) value significantly positively correlated with the AK content. The \(k\) value significantly positively correlated with the contents of TN and DOC and was extremely significantly positively correlated with the content of SMBC. It showed that the influence of soil depth and compound ratio on \(C_0\) and \(k\) of the 0–10 cm soil depth was not significant and had little effect on mineralization, while the influence of 10–20 cm and 20–30 cm soil depths on the mineralization of organic carbon was higher.
Table 4  Correlation analysis of soil $C_0$, k and soil physicochemical properties.

| Soil depth | Items | SOC  | TN   | AP   | AK   | Sand  | Silt  | Clay  | DOC   | SMBC  |
|------------|-------|------|------|------|------|-------|-------|-------|-------|-------|
| 0–10 cm    | $C_0$ | 0.1737 | −0.2162 | 0.9132 | −0.8016 | 0.4236 | −0.4225 | −0.4404 | −0.4414 | −0.6304 |
|            | k     | 0.0623 | 0.3904 | −0.6876 | 0.8958 | −0.5115 | 0.5120 | 0.5013 | 0.6317 | 0.5740 |
| 10–20 cm   | $C_0$ | 0.9189 | 0.9412 | 0.6180 | 0.9450 | −0.8682 | 0.8655 | 0.8917 | 0.8932 | 0.6163 |
|            | k     | −0.9925 | −0.8484 | −0.6912 | −0.9997$^*$ | 0.9406 | −0.9372$^*$ | −0.9704 | −0.9477 | −0.8252 |
| 20–30 cm   | $C_0$ | 0.8130 | −0.7206 | 0.7116 | 0.9742$^*$ | −0.1229 | −0.517 | −0.5488 | −0.9181 | −0.8531 |
|            | k     | −0.4104 | 0.9552$^*$ | −0.2057 | −0.6785 | 0.5830 | 0.8442 | 0.8487 | 0.9761 | 0.9987$^{**}$ |

Notes.

$^*$Significance level at < 0.05.

$^{**}$Significance level at < 0.01.

**DISCUSSION**

With the extension of incubation time, the $C_t$ content increased continuously. The process of mineralization of SOC of different compound ratios can be roughly divided into three stages: stress change stage (1–7 d), rapid mineralization stage (7–9 d) and slow mineralization stage (9–58 d), which was similar to the results of previous research (Marinari et al., 2010). In this study, the mineralization rate was higher on the first day of incubation, primarily because the water added to the soil at the initial stage of incubation stimulated the soil microorganisms (Tang et al., 2017). Studies have confirmed the following: water stimulates soil microorganisms, which will affect the soil microbial community structure and microbial activity, and then affect the dynamic process of SOC mineralization (Wang et al., 2011). In the latter period of incubation, as the content of easily mineralizable carbon decreases, the rate of SOC mineralization decreases, and the microorganisms begin to decompose relatively stable organic carbon components (Guo, Han & Li, 2020). Therefore, the SOC mineralization rate gradually decreases and then stabilizes.

Different soil physical and chemical properties have mineralization levels that vary. This study found that the $C_t$ value of S1 treatment was the largest, followed by S3, and the S2 treatment was the smallest. This difference was owing to the higher proportion of soil nutrient content and active organic carbon the S1 treatment. The rate of SOC mineralization was consistent with the change in $C_t$. Zha et al. (2014) pointed out that SOC was the main driving factor of soil fertility and has a significant impact on the mineralization process. The results of this study also showed that there was a significant negative correlation between SOC and the k value (Table 4), indicating that the content of SOC was one of the main factors that affected the difference in SOC mineralization (Zhang et al., 2016). Among the many factors that affected the intensity of SOC mineralization, the contents of TN and AK also had a substantial influence on the mineralization of SOC, and it had a significant correlation with the $C_0$ and k values. This was consistent with the conclusion that the organic carbon mineralization studied by Li et al. (2011) had a significant positive correlation with the initial content of TN. Both $C_r$ and $C_0$/SOC were the ratio of soil easily decomposable organic carbon to total organic carbon, which can...
visually demonstrate the relative stability of SOC (Yang et al., 2019). The results of this study indicated that the $C_r$ and $C_0$/SOC values treated by CK and S1 were relatively large, with a strong ability for mineralization and minimal storage of organic carbon. Under the premise of maintaining a certain SOC content, the higher ability to mineralize SOC indicated that the organic carbon was more unstable, which was not conducive to SOC fixation (Qiu et al., 2021). The intensity of SOC mineralization generally decreased with the deepening of the soil depth, i.e., the ability of the 0–10 cm soil depth to mineralize SOC was high, followed by 10–20 cm and 20–30 cm. The lower $C_r$ and $C_0$/SOC values in the 10–20 cm soil depth indicated that the active organic carbon in the surface layer was higher, and the SOC in the bottom layer was more stable. This could be because the 10–30 cm bottom soil was more stable than the 0–10 cm surface soil, and the short-term changes were small. In addition to the effects of mineralization of organic carbon, there are many other factors that affect the ability of soil to sequester carbon, including land use patterns, vegetation types and human disturbances (Ghimire & Khanal, 2020). Therefore, the factors that influence the sequestration of soil carbon urgently merit further study.

With the increase in soil depth, the DOC and SMBC exhibited a trend that was closely related to the $k$ value. Since the DOC can be more easily decomposed and utilized by microorganisms, organic carbon must enter the soil solution to be converted into DOC before it is converted to CO$_2$, and the soil moisture moves downward along with it (Tang et al. 2017). Therefore, the 20–30 cm soil depth showed a correlation between DOC and SMBC with the mineralization of SOC. Li, Zhang & Chen (2004) also found that the DOC was closely related to the mineralization of SOC and proposed that increasing the content of soil water can increase the content of DOC in the soil and increase the substrates available to soil microorganisms, thereby promoting the mineralization of SOC. Therefore, the dynamics and turnover of DOC content were closely related to the mineralization of SOC. SMBC is an important carbon source that composes soil humus, and it is substantially significant to the turnover of SOC and the ecological environment (Guo, Han & Li, 2020). With the extension of the incubation time, the contents of SMBC and DOC in different treatments and soil depth decreased to varying degrees. This phenomenon indicates that during the process of cultivation, soil active organic carbon is used as a carbon source for SOC mineralization, which is decomposed and utilized by microorganisms and releases CO$_2$ during respiration, resulting in a decrease in the active organic carbon content in the soil, which directly affects the cumulative release of CO$_2$. In summary, the mineralization of SOC was affected by soil depth, compound ratio and active organic carbon, and changes under the combined action of these factors. In the future, it will be necessary to continue to strengthen the research on functional microorganisms and reveal the microbial mechanism of organic carbon mineralization.

**CONCLUSIONS**

The trend of change of soil organic carbon (SOC) mineralization rate curve and cumulative mineralization curve at different soil depths of soft rock and sand compound soil was basically the same, and both showed the characteristics of first decreasing, then increasing. 
and finally stabilizing at a certain level. However, with the deepening of soil depth, the rate of mineralization of SOC and the cumulative mineralization of compound soil gradually decreased. These characteristics may be affected by soil properties, such as organic carbon vertical input, soil active organic carbon composition, and the contents of total nitrogen (TN) and available potassium (AK). In concert with the process of SOC mineralization, the soil microbial biomass carbon and dissolved organic carbon content of different treatments decreased compared with the initial content, and the amplitude of change was larger in the 20–30 cm and 10–20 cm soil depths. The surface soil stability was poor, and the rate of mineralization of SOC and \( C_r \) decreased with the increase in soil depth, and the \( C_r \) and \( C_0/SOC \) values in the 10–20 cm soil depth were smaller. Compared with the other treatments, those of S2 and S3 can reduce the loss of carbon. Deep SOC has a slow rate of mineralization and a small amount of accumulated mineralization. This process was affected by the contents of TN and AK, which may become a carbon sink or a carbon source. Therefore, when conducting research on the global carbon cycle, deep SOC and surface SOC should be placed in an equally important position.

ACKNOWLEDGEMENTS

The authors thank the editor and anonymous reviewers for their constructive comments, which helped to improve the manuscript.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding
This study is financially supported by Shaanxi Provincial Natural Science Basic Research Program (2021JZ-57), funded by the Technology Innovation Center for Land Engineering and Human Settlements, Shaanxi Land Engineering Construction Group Co., Ltd. and Xi’an Jiaotong University (2021WHZ0087), and the Fund Project of Shaanxi Key Laboratory of Land Consolidation (2018-JC18, 2019-JC07, 2019-JC08). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Grant Disclosures
The following grant information was disclosed by the authors:
Shaanxi Provincial Natural Science Basic Research Program: 2021JZ-57.
Xi’an Jiaotong University: 2021WHZ0087.
Shaanxi Key Laboratory of Land Consolidation: 2018-JC18, 2019-JC07, 2019-JC08.

Competing Interests
The authors declare there are no competing interests. Wanying Li, Zhen Guo, Juan Li and Jichang Han are employed by Shaanxi Provincial Land Engineering Construction Group Co., Ltd.
Author Contributions

• Wanying Li performed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.
• Zhen Guo performed the experiments, prepared figures and/or tables, and approved the final draft.
• Juan Li conceived and designed the experiments, prepared figures and/or tables, and approved the final draft.
• Jichang Han conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw data are available in the Supplemental File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.11572#supplemental-information.

REFERENCES

Bishwakarma BK, Dahal NR, Allen R, Rajbhandari NP, Dhital BK, Gurung DB, Bajracharya RM, Baillie IC. 2014. Effects of improved management and quality of farmyard manure on soil organic carbon contents in small-holder farming systems of the Middle Hills of Nepal. *Climate and Development* 7:426–436.

Brookes PC, Landman A, Pruden G, Jenkinson DS. 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biology and Biochemistry* 17:837–842 DOI 10.1016/0038-0717(85)90144-0.

Fang C, Smith P, Moncrieff JB, Smith JU. 2005. Similar response of labile and resistant soil organic matter pools to changes in temperature. *Nature* 433:57–59 DOI 10.1038/nature03138.

Fontaine S, Barot S, Barré P, Bdioui N, Mary B, Rumpel C. 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450:277–280 DOI 10.1038/nature06275.

Ganjegunte GK, Vance GF, Preston CM, Schuman GE, Ingram LJ, Stahl PD, Welker JM. 2005. Soil organic carbon composition in a northern mixed-grass prairie. *Soil Science Society of America Journal* 69:1746–1756 DOI 10.2136/sssaj2005.0020.

Ghani A, Dexter M, Perrott KW. 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilization, grazing and cultivation. *Soil Biology and Biochemistry* 35:1231–1243 DOI 10.1016/S0038-0717(03)00186-X.

Ghimire R, Khanal BR. 2020. Soil organic matter dynamics in semiarid agroecosystems transitioning to dryland. *PeerJ* 8:e10199 DOI 10.7717/peerj.10199.
Gomez EJ, Delgado JA, Gonzalez JM. 2021. Influence of water availability and temperature on estimates of microbial extracellular enzyme activity. PeerJ 9:e10994 DOI 10.7717/peerj.10994.

Guo Z, Han JC, Li J. 2020. Response of organic carbon mineralization and bacterial communities to soft rock additions in sandy soils. PeerJ 8:e8948 DOI 10.7717/peerj.8948.

Guo Y, Yin W, Chai Q, Fan ZL, Hu FL, Fan H, Zhao C, Yu AZ, Coulter JA. 2021. No tillage with previous plastic covering increases water harvesting and decreases soil CO₂ emissions of wheat in dry regions. Soil and Tillage Research 208:104883 DOI 10.1016/j.still.2020.104883.

Guo Z, Zhang HO, Wang HY. 2020. Soft rock increases the colloid content and crop yield in sandy soil. Agronomy Journal 112:1–8 DOI 10.1002/agj2.20001.

Han JC, Liu YS, Luo LT. 2012. Research on the core technology of remixing soil by soft rock and sand Mu Us sand land region. Chinesea Land Science 26:87–94.

Huang Y, Liu SL, Shen QR, Zong LG. 2002. Influence of environmental factors on the decomposition of organic carbon in agricultural soils. Chinese Journal of Applied Ecology 13:709–714.

Jobbagy EG, Jackson RB. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10:423–436 DOI 10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2.

Körschens M. 2010. Der organische kohlenstoff im boden (corg)–bedeutung, bestimmung, bewertung soil organic carbon (corg)–importance, determination, evaluation. Archives of Agronomy and Soil Science 56:375–392 DOI 10.1080/03650340903410246.

Kuzyakov Y, Friedel JK, Stahr K. 2000. Review of mechanisms and quantification of priming effects. Soil Biology and Biochemistry 32:1485–1498 DOI 10.1016/S0038-0717(00)00084-5.

Lal R, Follett RF, Stewart BA, Kimble JM. 2007. Soil carbon sequestration to mitigate climate change and advance food security. Soil Science 172:943–956 DOI 10.1097/ss.0b013e31815cc498.

Li J, Han JC, Wang YK, Ge L, Tian C, Shi CD, Wang HY, Guo H. 2019. Effect of mixing ratio and planting years on the micro structure of soft rock and sand compound soil: a scanning electron microscope study. Applied Ecology and Environmental Research 17:10599–10610.

Li YC, Song CC, Hou CC, Wang XW, Sun XX. 2011. Effects of exogenous nitrogen availability on carbon mineralization of different wetlands soil types in northeast China. Scientia Geographical Science 31:1480–1486.

Li ZP, Zhang TL, Chen BY. 2004. Dynamics of soluble organic carbon and its relation to mineralization of soil organic carbon. Acta Pedologica Sinica 41:544–552.

Liu DY, Song CC. 2008. Effects of phosphorus enrichment on mineralization of organic carbon and contents of dissolved carbon in a freshwater marsh soil. China Environmental Science 28:769–774.
Liu QF, Zhang Q, Yan YZ, Zhang XF, Niu JM, Svenning JC. 2020. Ecological restoration is the dominant driver of the recent reversal of desertification in the Mu Us Desert (China). *Journal of Cleaner Production* **268**:1–12.

Marinari S, Lagomarsino A, Moscatelli MC, Di Tizio A, Campiglia E. 2010. Soil carbon and nitrogen mineralization kinetics in organic and conventional three-year cropping systems. *Soil and Tillage Research* **109**:161–168 DOI 10.1016/j.still.2010.06.002.

Martens DA, Reedy TE, Lewis DT. 2004. Soil organic carbon content and composition of 130-year crop, pasture and forest land-use managements. *Global Change Biology* **10**:65–78 DOI 10.1046/j.1529-8817.2003.00722.x.

Moore CE, Berardi DM, Blanc-Betes E, Dracup EC, Egenriether S, Gomez-Casanovas N, Hartman MD, Hudiburg T, Kantola I, Masters MD, Parton WJ, Allen RV, Haden AC, Yang WH, DeLuca EH, Bernacchi CJ. 2020. The carbon and nitrogen cycle impacts of reverting perennial bioenergy switchgrass to an annual maize crop rotation. *GCB Bioenergy* **12**:941–954 DOI 10.1111/gcbb.12743.

Paterson E, Sim A. 2013. Soil-specific response functions of organic matter mineralization to the availability of labile carbon. *Global Change Biology* **19**:1562–1571 DOI 10.1111/gcb.12140.

Qiu LP, Zhu HS, Liu J, Yao YF, Wang X, Rong GH, Zhao XN, Shao MG, Wei XR. 2021. Soil erosion significantly reduces organic carbon and nitrogen mineralization in a simulated experiment. *Agriculture, Ecosystems & Environment* **307**:107232 DOI 10.1016/j.agee.2020.107232.

Qiu SJ, Xie JG, Zhao SC, Xu XP, Hou YP, Wang XF, Zhou W, He P, Johnston AM, Christie P, Jin JY. 2014. Long-term effects of potassium fertilization on yield, efficiency, and soil fertility status in a rain-fed maize system in northeast China. *Field Crops Research* **163**:1–9 DOI 10.1016/j.fcr.2014.04.016.

Ribeiro HM, Fanguiero D, Alves F, Vasconcelos E, Coutinho J, Bol R, Cabral F. 2010. Carbon-mineralization kinetics in an organically managed Cambic Arenosol amended with organic fertilizers. *Journal of Plant Nutrition and Soil Science* **173**:39–45 DOI 10.1002/jpln.200900015.

Saggar S. 2001. Cultivation effects on soil biological properties, microfauna and organic matter dynamics in Eutric Gleysol and Gleyic Luvisol soils in New Zealand. *Soil and Tillage Research* **58**:55–68 DOI 10.1016/S0167-1987(00)00184-7.

Schimel JP, Wetterstedt JAM, Holden PA, Trumbore SE. 2011. Drying-rewetting cycles mobilize old C from deep soils from a California annual grassland. *Soil Biology & Biochemistry* **43**:1101e1103.

Stanford G, Smith SJ. 1972. Nitrogen mineralization potentials of soils. *Soil Science Society of America Journal* **36**:190–196.
Sun ZH, Han JC. 2018. Effect of soft rock amendment on soil hydraulic parameters and crop performance in Mu Us Sandy Land, China. *Field Crops Research* 222:85–93 DOI 10.1016/j.fcr.2018.03.016.

Tang SR, Cheng WG, Hu RG, Nakajima M, Guigue J, Kimani SM, Sato S, Tawaraya K, Xu XK. 2017. Decomposition of soil organic carbon influenced by soil temperature and moisture in Andisol and Inceptisol paddy soils in a cold temperate region of Japan. *Journal of Soils and Sediments* 17:1843–1851 DOI 10.1007/s11368-016-1607-y.

Wang HY, Han JC, Tong W, Cheng J, Zhang HO. 2016. Analysis of water and nitrogen use efficiency for maize (*Zea mays* L.) grown on soft rock and sand compound soil. *Journal of the Science of Food and Agriculture* 97:2553–2560.

Wang YH, Su YR, Li Y, Wu JS, Zheng H, Zhu HH, Hu LN. 2011. Characteristics of mineralization of soil organic carbon in paddy and upland with rice straw incorporated and differences between the two. *Acta Pedologica Sinica* 48:979–987.

Wang Q, Wang S, He T, Liu L, Wu J. 2014. Response of organic carbon mineralization and microbial community to leaf litter and nutrient additions in subtropical forest soils. *Soil Biology and Biochemistry* 71:13–20 DOI 10.1016/j.soilbio.2014.01.004.

Yang H, Mo BQ, Zhou MX, Zhu TB, Cao JH. 2019. Effects of plum plantation ages on soil organic carbon mineralization in the karst rocky desertification ecosystem of southwest China. *Forests* 10:1107 DOI 10.3390/f10121107.

Zha Y, Wu XP, He XH, Zhang HM, Gong FF, Cai DX, Zhu P, Gao HJ. 2014. Basic soil productivity of spring maize in black soil under long-term fertilization based on DSSAT model. *Journal of Integrative Agriculture* 13:577–587 DOI 10.1016/S2095-3119(13)60715-7.

Zhang M, Dong LG, Fei SY, Zhang JW, Jiang XM, Wang Y, Yu X. 2021. Responses of soil organic carbon mineralization and microbial communities to leaf litter addition under different soil layers. *Forests* 12:170 DOI 10.3390/f12020170.

Zhang YS, Xu MX, Chen G, Wang CH. 2016. Modelling the dynamics of soil organic carbon mineralization on water-eroded sloping land in the Loess Hilly region. *Science of Soil and Water Conservation* 14:9–17.