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Effects of land-use types on the vertical distribution of fractions of oxidizable organic carbon on the Loess Plateau, China

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Abstract: The oxidizability of soil organic carbon (SOC) influences soil quality and carbon sequestration. Four fractions of oxidizable organic carbon (very labile (C_1), labile (C_2), less labile (C_3) and non-labile (C_4)) reflect the status and composition of SOC and have implications for the change and retention of SOC. Studies of the fractions of oxidizable organic carbon (OC) have been limited to shallow soil depths and agroecosystems. How these fractions respond at deep soil depths and in other types of land-use is not clear. In this study, we evaluated the vertical distributions of the fractions of oxidizable organic carbon to a soil depth of 5.0 m in 10 land-use types in the Zhifanggou Watershed on the Loess Plateau, China. Along the soil profile, C_1 contents were highly variable in the natural grassland and shrubland I (*Caragana microphylla*), C_2 and C_4 contents were highly variable in the natural grassland and two terraced croplands, respectively, and C_3 contents varied little. Among the land-use types, natural grassland had the highest C_1 and C_2 contents in the 0–0.4 m layers, followed by shrubland I in the 0–0.1 m layer. Natural grassland had the highest C_4 contents in the 1.0–4.5 m layers. Natural grassland and shrubland I thus contributed to improve the oxidizability of SOC in shallow soil, and the deep soil of natural grassland has a large potential to sequester SOC on the Loess Plateau.

Keywords: land-use types; deep soil; oxidizable organic-carbon fractions; Loess Plateau

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The Loess Plateau is known for its long agricultural history and serious soil erosion (Hessel et al., 2003; Ritsema, 2003), which covers an area of approximately 62.4×10^4 km^2 (Fu et al., 2010) with a deep loess layer of 50–100 m (Mu et al., 2003). Loess is a highly erosion-prone soil that is susceptible to the forces of wind and water; in fact, the soil of this region has been called the most highly erodible soil on Earth. A series of ecological programs have been launched during the past few decades to control the erosion. The effects of afforestation on soil organic carbon (SOC) and soil quality have been investigated not only at individual sites (Zhang et al., 2011; Jia et al., 2012) but also at regional scales (Chang et al., 2011; Liu et al., 2011). However, previous studies mainly focused on the shallow soil layers at the depth of 0–2 m (Zhong and Zhao, 2001; Liu et al., 2011; Chang et al., 2012; Jia et al., 2012). This shallow sampling depth may introduce a bias of SOC

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storage underestimation and fail to include SOC changes in deeper layers (Shi et al., 2013).

The oxidation process of SOC releases mineral soil nutrients and drives CO_2 fluxes from soil to atmosphere and then influences soil quality and carbon sequestration (Majumder et al., 2007; Mosquera et al., 2012). Methods that preferentially extract the more-labile fractions could be useful for the characterization of SOC (Chan et al., 2001; Majumder et al., 2007). Based on a classical method of oxidizable organic carbon (OC) determination developed by Walkley and Black (1934), Chan et al. (2001) proposed a modification to split SOC into four fractions (C_1, C_2, C_3 and C_4) by lability level. The C_1 and C_2 fractions are comprised largely of relatively labile carbon compounds that are mainly derived from litter fall, root biomass and root exudates (Benbi et al., 2012). These labile OC compounds can be easily oxidized and decomposed by soil microbes with energy and available mineral nutrients such as nitrogen (N) and phosphorus (P) released during the decomposition (Majumder et al., 2007; Guareschi et al., 2013). Some microbial products of decomposition can bind to soil particles through organic binding agents and promote aggregation (Cotrofo et al., 2013; Tripathi et al., 2014). The C_1 and C_2 fractions associated with the availability of nutrients and the formation of macroaggregates and strongly influenced nutrient cycling for maintaining soil quality (Janzen, 1987; Maia et al., 2007). The C_3 and C_4 fractions associated with compounds of greater chemical stability and higher molecular weight, which are slowly altered by microbial activity (Sherrod et al., 2005; Guareschi et al., 2013). C_3 and C_4 belonged to a "passive pool" of SOC used in the Century Model (Parton et al., 1992), with a turnover period of 2,000 years (Chan et al., 2001) and thus contribute greatly to the sequestration of SOC in the soil.

Land-use and cultivation significantly influence soil quality and carbon sequestration (Chen et al., 2007a; Zhang, 2010). The distribution of carbon in labile or stable forms has implications for the changes in the physical, chemical, and biological properties of the soil and for its effect on atmospheric carbon retention (Barreto et al., 2011), therefore, it is necessary to understand the response of characteristics and vertical distributions of the fractions of oxidizable OC to different types of land-use and soil depth. Previous studies mainly focused on agroecosystems (Maia et al., 2007; Majumder et al., 2008; Benbi et al., 2012; Guareschi et al., 2013) and shallow soil depths (Barreto et al., 2011). However, few studies examined the response of oxidizable OC fractions to land-use conversion and deep soil.

A previous study by our group demonstrated that land-use significantly affected the SOC content down to a depth of 5.0 m and suggested that natural grassland was the optimal choice for SOC sequestration (Zhang et al., 2013). However, it was not clear about the reason for the high SOC sequestration. We hypothesized that land-use type would affect the fractions of oxidizable OC and their distribution in a soil profile. The objectives of this study were to: (1) evaluate the effects of 10 land-use types on the vertical distribution of oxidizable OC fractions to a depth of 5.0 m, and (2) analyze the capability of carbon sequestration of these land-use types from the perspective of carbon oxidizability.

1 Materials and methods

1.1 Study area

The study was conducted in the Zhifanggou watershed (36°46′28″–36°46′42″N, 109°13′03″–109°16′46″E; 1,010–1,431 m asl), Ansai county, Shaanxi province, China. The topography is featured as a representative Loess Plateau with an area of 8.27 km^2. The climate is typical semi-arid with an annual mean temperature of 8.8°C and a mean annual precipitation of 549.1 mm (Zhu et al., 2010). Seasonal rain is unevenly distributed during a year with 74.3% of the annual precipitation falling in June to September (Wang et al., 2012). The soils are classified as Calcic Cambisols (FAO/UNESCO, 1988), which mostly originated from wind-deposited loessial parent material, and are characterized with yellow particles, absence of bedding, looseness, macroporosity and wetness-induced collapsibility (Zhu et al., 2010). The soil texture and bulk density are presented in Table 1.

This area has suffered serious soil erosion with SOC contents decreased sharply (Shi and Shao, 2000; Zheng, 2006; Chen et al., 2007b; Fu et al., 2009) over the last century due to improper land uses, such as excessive cultivation, pasturing, and deforestation. To reduce the erosion and improve land quality, China initiated a state-funded project, Grain for Green, in 1999, which proposed the conversion of all croplands with the slope greater than 15° to undisturbed green land, with local farmers receiving compensations paid by the government for income loss due to the decrease in cropland. The current major land-use types in this region are forest land, shrubland, grassland (natural and artificial), cropland, orchards and abandoned cropland. Abandoned cropland, *Robinia pseudoacacia*, *Caragana microphylla*, *Hippophae rhamnoides* and *Medicago sativa* have been developed for vegetational restoration (Zhang et al., 2013).

1.2 Experimental design and soil sampling

In August 2011, ten study sites were selected in this region (Table 1), which were a forested land (*R. pseudoacacia*), two shrublands (*C. microphylla* and *H. rhamnoides*), a natural grassland, an artificial grassland (*M. sativa*), an orchards, a check-dam cropland (*Zea mays*), two terraced croplands (*Setaria italica* and *Z. mays*) and a sloped cropland (*S. italica*). Three replicated 20 m×20 m plots with similar slopes, gradients, and altitudes were established at each site, which were considered true replicates, since the distance between them exceeded the spatial dependence of 13.5 m for most soil chemical and microbial variables (Marriott et al., 1997; Zhang et al., 2013). Soil samples were collected from four randomly selected points in each plot using a soil auger in 4-cm diameter. The samples were separately collected from 14 layers at depths of 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5, 2.5–3.0, 3.0–3.5, 3.5–4.0, 4.0–4.5, and 4.5–5.0 m. Corresponding samples from the four points were mixed and then gravel and large pieces of living plant material were removed from the mixture, which were then air-dried, manually homogenized, crushed, and sifted with a 0.25-mm sieve for determining the oxidizable OC fractions and total organic carbon (TOC). Detailed site descriptions are provided by Zhang et al. (2013) (Table l).

Table 1 Parameters of the land-use types

Land-use	Altitude (m)	Restoration age (a)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	TOC (g/kg)	Vegetation
Forest land	1,242	30	30.0±1.1	61.4±0.8	8.6±0.3	1.27±0.07	2.81±1.49	*Robinia pseudoacacia.*
Chard	1,205	30	20.6±3.1	68.1±2.4	11.2±0.8	1.35±0.14	2.81±1.07	*Malus domestica*
Shrubland I	1,281	30	30.0±0.6	61.7±0.2	8.2±0.7	1.29±0.09	2.88±1.70	*Caragana microphylla*
Shrubland II	1,184	30	16.2±0.8	70.9±1.0	12.9±1.6	1.39±0.09	2.71±1.15	*Hippophae rhamnoides*
Artificial grassland	1,264	15	24.1±1.7	66.6±1.5	9.3±0.2	1.23±0.07	3.42±0.65	*Medicago sativa*
Natural grassland	1,203	30	22.4±0.9	65.9±1.2	11.7±1.1	1.37±0.10	4.41±3.83	*Artemisia sacrorum* *Stipa bungeana*
Terraced cropland I	1,296	30	26.6±3.7	64.3±3.0	9.1±0.7	1.35±0.14	1.80±0.72	*Setaria italica*
Terraced cropland II	1,205	30	19.7±2.0	68.0±2.1	12.4±0.4	1.42±0.13	2.55±1.30	*Zea mays*
Check-dam cropland	1,179	30	16.0±4.1	69.3±2.3	14.7±3.8	1.42±0.04	2.82±1.07	*Zea mays*
Sloped cropland	1,286	30	19.9±4.6	68.1±1.9	12.1±3.0	1.30±0.07	2.47±0.33	*Setaria italica*

Note: TOC means total organic carbon.

1.3 Laboratory analysis

TOC content was determined by wet combustion with a mixture of potassium dichromate and sulfuric acid, following the method by Nelson and Sommers (1982).

The oxidizable OC fractions were estimated through a modified Walkley and Black method by Chan et al. (2001). Briefly, three 0.5 g soils were added to three 500-mL Erlenmeyer flasks containing 10 mL of $K_2Cr_2O_7$ (0.167 mol/L), then added 5, 10, and 20 mL of concentrated H_2SO_4

(18 mol/L), producing three acid-aqueous solutions with ratios of 0.5:1, 1:1, and 2:1, respectively (corresponding to 6, 9, and 12 mol/L H_2SO_4, respectively). Oxidation was carried out by dichromate in the acidic medium without external heating. The amount of dichromate remained at the end of the reaction was determined by titrating against 0.5 mol/L $FeSO_4$. The amounts of TOC were categorized into four fractions with decreasing labilities: C_1, very labile, OC oxidizable under 6 mol/L H_2SO_4; C_2, labile, the difference in oxidizable OC extracted between 6 and 9 mol/L H_2SO_4; C_3, less labile, the difference inoxidizable OC extracted between 9 and 12 mol/L H_2SO_4 (12 mol/L H_2SO_4 is equivalent to the standard Walkley and Black method); C_4, non-labile, residual OC after reaction with 12 mol/L H_2SO_4 relative to TOC.

1.4 Statistical analysis

The effect of land-uses and soil depth on oxidizable OC fractions was evaluated by one-way analysis of variance and the averages were tested by Tukey's test at $P<0.05$. Multidimensional scaling (MDS) allows the display of n-dimensional data in two dimensions to illustrate similarities or dissimilarities between objects (Rooney and Clipson, 2009). Kruskal's stress measures how well the configuration matches the data, with the best-fitting configuration having minimum stress, and values <20% represent an acceptable goodness of fit (Kruskal, 1964). Effects of land-uses on TOC and the oxidizable OC fractions in various soil layers were analyzed by MDS. All analyses were conducted using SPSS ver. 18.0 (SPSS Inc., Chicago, IL, USA).

2 Results

2.1 Vertical distribution of oxidizable OC fractions

C_1 contents sharply decreased in the 0–0.2 m soil layers for most types of land-use except for check-dam cropland, and then unchanged from 0.2 to 5.0 m (Table 2). C_2 contents in forested land, two shrublands and artificial grassland significantly decreased in the 0–0.2 m soil layers, and maintained below 0.2 m for all land-use types (Table 3). The C_4 contents in the two terraced croplands were significantly lower in the 1.0–5.0 m relative to the 0–1.0 m soil layers. Change of C_3 contents along soil depth was small compared to C_1, C_2 and C_4 (Tables 4 and 5).

The coefficients of variability of C_1 contents across soil layers were >80% for the forested land, shrubland I, and the natural grassland. The coefficients of variability of C_2 content were highest for the natural grassland (87.00%), and the coefficients of variability of C_4 content were highest for the two terraced croplands (94.48% and 94.41%). The coefficients of variability of C_3 contents were less than 50% for all land-use types.

2.2 Oxidizable OC fractions in different land-use types

Land-use type had a similar effect on C_1 and C_2 contents. Natural grassland had significant higher C_1 and C_2 contents in the 0–0.4 m soil layers relative to the sloped cropland. The next highest C_1 and C_2 contents in the 0–0.1 m layer were observed in shrubland I, followed by forested land, orchard, shrubland II, artificial grassland, terraced cropland II, and check-dam cropland, compared to terraced cropland I and the sloped cropland. C_1 and C_2 contents in the 0.4–1.0 m layers had no significant difference compared with the sloped cropland. C_1 and C_2 contents in the 1.5–5.0 m layers in the artificial grassland were significantly higher than in shrubland II and the natural grassland.

C_3 contents significantly differed among land-use types only in the 0.1–0.2 and 3.5–4.0 m soil layers. The highest C_4 contents appeared in the 0–0.2 and 1.0–4.5 m layers in natural grassland. Compared with the sloped cropland, C_4 contents were relatively lower in the 1.0–3.0 m layers in the two terraced croplands.

2.3 Changes of the proportion of each fraction relative to TOC with soil depth

In the 0–1.5 m soil layers, C_1/TOC was significantly higher than C_2/TOC, while C_3/TOC and C_4/TOC were the lowest (Fig. 1). The proportions of fractions of oxidizable OC relative to TOC in the 2.0–5.0 m layers followed the order C_1/TOC and C_4/TOC>C_2/TOC>C_3/TOC. The proportion of C_1 decreased in the 0–0.6 m layers, slightly increased in the 0.6–1.5 m, and remained uniform at depths of 1.5–5.0 m. The proportions of C_2 and C_3 remained unchanged throughout the soil profile. The proportion of C_4 tended to increase with soil depth to 2.5 m and kept unchanged in the soil depth deeper than 2.5 m.

Table 2 Distribution of very labile oxidizable organic carbon (C_1) with soil depths

Depth (m)	Forest land	Orchard	Shrubland I	Shrubland II	Artificial grassland	Natural grassland	Terraced cropland I	Terraced cropland II	Check-dam cropland	Slope cropland
	(g/kg)									
0–0.1	4.30^{Abc}	2.48^{Abc}	4.87^{Ab}	3.05^{Abc}	2.32^{Abc}	8.41^{Aa}	1.69^{Ac}	2.67^{Abc}	2.37^{Abc}	1.46^{Ac}
0.1–0.2	1.43^{Bb}	1.64^{Bb}	2.34^{Bb}	1.79^{Bb}	1.48^{Bb}	4.78^{Ba}	1.11^{Bb}	1.80^{Bb}	2.08^{Ab}	0.98^{Bb}
0.2–0.4	0.65^{Bc}	1.16^{BCbc}	0.99^{BCbc}	1.16^{BCbc}	0.95^{Ebc}	2.22^{Ca}	0.70^{Cbc}	1.28^{BCbc}	1.60^{ABab}	0.83^{Bbc}
0.4–0.6	0.65^{Bb}	0.85^{BCab}	0.78^{Cab}	0.61^{Cb}	0.98^{DEab}	1.27^{Ca}	0.67^{Cb}	0.93^{CDab}	1.11^{BCab}	0.85^{Bab}
0.6–0.8	0.53^{B}	0.71^{BC}	0.67^{C}	0.71^{C}	1.01^{DE}	0.80^{C}	0.70^{C}	1.13^{CD}	0.97^{BC}	0.88^{B}
0.8–1.0	0.61^{Bb}	0.77^{BCab}	0.64^{Cb}	0.79^{Cab}	0.95^{DEab}	0.92^{Cab}	0.67^{Cb}	0.99^{CDab}	1.13^{BCa}	0.82^{Bab}
1.0–1.5	0.77^{Bb}	0.84^{BCb}	0.62^{Cb}	0.86^{Cb}	1.05^{CDEb}	2.35^{Ca}	0.50^{Cb}	0.88^{CDb}	0.67^{BCb}	0.80^{Bb}
1.5–2.0	0.85^{Bab}	0.90^{BCab}	0.48^{Cb}	0.58^{Cb}	1.28^{BCDa}	0.62^{Cb}	0.45^{Cb}	0.77^{CDb}	0.65^{BCb}	0.81^{Bb}
2.0–2.5	0.91^{Bab}	0.71^{BCb}	0.54^{Cb}	0.55^{Cb}	1.36^{BCa}	0.39^{Cb}	0.42^{Cb}	0.86^{CDab}	0.65^{BCb}	0.68^{Bb}
2.5–3.0	0.90^{Bab}	0.84^{BCab}	0.61^{Cb}	0.51^{Cb}	1.24^{BCDEa}	0.52^{Cb}	0.46^{Cb}	0.83^{CDab}	0.79^{BCab}	0.68^{Bab}
3.0–3.5	0.87^{Bab}	0.79^{BCab}	0.67^{Cab}	0.39^{Cb}	1.07^{CDEa}	0.49^{Cb}	0.53^{Cab}	0.79^{CDab}	0.86^{BCab}	0.73^{Bab}
3.5–4.0	1.12^{Ba}	1.16^{BCa}	0.75^{Cab}	0.54^{Cb}	1.14^{CDEa}	0.43^{Cb}	0.45^{CEb}	0.59^{CDab}	0.46^{Cb}	0.79^{Bab}
4.0–4.5	1.06^{Bab}	0.72^{BCabc}	0.78^{Cabc}	0.53^{Cbc}	1.15^{CDEa}	0.46^{Cc}	0.65^{Cabc}	0.59^{CDbc}	0.76^{BCabc}	0.70^{Babc}
4.5–5.0	1.06^{Babc}	0.40^{Ce}	1.25^{BCa}	0.52^{Cde}	1.14^{CDEab}	0.46^{Cde}	0.66^{Ccde}	0.55^{Dde}	0.92^{BCabcd}	0.74^{Bbcde}
CV (%)	84.15	51.52	102.69	79.56	28.93	132.09	48.94	54.10	52.48	23.43

Note: Values followed by uppercase letters in the same column and by lowercase letters in the same row indicate significant differences at $P<0.05$ level. CV means coefficient of variation.

Table 3 Distribution of labile oxidizable organic carbon (C_2) at various soil depths

Depth (m)	Forest land	Orchard	Shrubland I	Shrubland II	Artificial grassland	Natural grassland	Terraced cropland I	Terraced cropland II	Check-dam cropland	Sloped cropland
	(g/kg)									
0–0.1	2.13^{Aabc}	1.53^{Abc}	2.38^{Aab}	1.98^{Aabc}	1.63^{Abc}	2.97^{Aa}	1.07^{Ac}	1.65^{Abc}	1.50^{Abc}	1.11^{Ac}
0.1–0.2	1.09^{Bb}	1.18^{ABb}	1.36^{Bb}	1.25^{Bb}	0.97^{Bb}	3.13^{Aa}	0.89^{ABb}	1.39^{ABb}	1.36^{ABb}	0.96^{ABb}
0.2–0.4	0.61^{BCb}	1.02^{ABCb}	0.76^{BCb}	0.99^{BCb}	0.89^{Bb}	1.75^{BCa}	0.62^{BCb}	1.07^{BCb}	1.17^{ABCb}	0.80^{ABb}
0.4–0.6	0.60^{BC}	0.93^{ABC}	0.68^{BC}	0.66^{CD}	0.87^{B}	1.08^{BCD}	0.50^{BC}	0.90^{CD}	0.88^{ABCD}	0.82^{AB}
0.6–0.8	0.47^{BCb}	0.64^{BCab}	0.69^{BCab}	0.57^{CDab}	0.82^{Bab}	0.72^{BDab}	0.59^{BCab}	0.96^{BCDab}	1.08^{ABCDa}	0.70^{ABab}
0.8–1.0	0.30^{C}	0.71^{BC}	0.51^{C}	1.00^{BC}	0.82^{B}	0.82^{BCD}	0.56^{BC}	0.92^{CD}	0.46^{D}	0.79^{AB}
1.0–1.5	0.59^{BCb}	0.81^{BCb}	0.68^{BCb}	0.76^{CDb}	0.85^{Bb}	1.95^{Ba}	0.60^{BCb}	0.81^{CDb}	0.62^{CDb}	0.70^{ABb}
1.5–2.0	0.67^{BCab}	0.82^{BCab}	0.54^{BCb}	0.50^{CDb}	1.05^{Ba}	0.51^{CDb}	0.40^{Cb}	0.75^{CDab}	0.58^{CDb}	0.63^{ABab}
2.0–2.5	0.69^{BCb}	0.62^{BCb}	0.66^{BCb}	0.42^{Db}	1.20^{ABa}	0.31^{Db}	0.48^{Cb}	0.64^{CDb}	0.69^{BCDb}	0.56^{Bb}
2.5–3.0	0.82^{BCab}	0.65^{BCab}	0.67^{BCab}	0.28^{Db}	1.22^{ABa}	0.44^{CDab}	0.44^{Cab}	0.49^{Dab}	0.64^{CDab}	0.58^{ABab}
3.0–3.5	0.78^{BCab}	0.72^{BCab}	0.78^{BCab}	0.34^{Db}	1.01^{Ba}	0.39^{CDb}	0.52^{BCb}	0.62^{CDab}	0.71^{BCDab}	0.56^{Bb}
3.5–4.0	0.93^{BCab}	0.62^{BCc}	0.73^{BCbc}	0.44^{Dc}	1.08^{Ba}	0.49^{CDc}	0.65^{BCbc}	0.47^{Dc}	0.47^{Dc}	0.58^{ABc}
4.0–4.5	0.86^{BCab}	0.55^{BCb}	0.81^{BCab}	0.47^{Db}	1.05^{Ba}	0.47^{CDb}	0.53^{BCb}	0.62^{CDab}	0.77^{BCDab}	0.61^{ABab}
4.5–5.0	0.87^{BCab}	0.42^{Cc}	1.08^{BCa}	0.45^{Dc}	1.02^{Ba}	0.44^{CDc}	0.65^{BCbc}	0.57^{CDbc}	0.44^{Dc}	0.78^{ABab}
CV (%)	52.63	35.94	54.77	63.27	20.83	87.13	29.33	40.37	41.92	22.60

Note: Values followed by uppercase letters in the same column and by lowercase letters in the same row indicate significant differences at $P<0.05$ level.

Table 4 Distribution of less labile oxidizable organic carbon (C_3) at various soil depths

Depth (m)	Forested land	Orchard	Shrubland I	Shrubland II	Artificial grassland	Natural grassland	Terraced cropland I	Terraced cropland II	Check-dam cropland	Sloped cropland
	(g/kg)									
0–0.1	0.68	0.95^{A}	0.61^{A}	0.59	0.53	0.81^{AB}	0.41^{A}	0.56^{A}	0.61^{A}	0.53
0.1–0.2	0.37^{b}	0.46^{Bab}	0.54^{ABab}	0.35^{b}	0.33^{b}	0.87^{Aa}	0.39^{ABb}	0.56^{Aab}	0.49^{ABab}	0.44^{b}
0.2–0.4	0.25	0.39^{B}	0.25^{BC}	0.25	0.37	0.52^{ABC}	0.30^{AB}	0.38^{ABC}	0.36^{AB}	0.42
0.4–0.6	0.32	0.32^{B}	0.20^{BC}	0.19	0.29	0.48^{ABC}	0.27^{AB}	0.48^{AB}	0.26^{AB}	0.30
0.6–0.8	0.31	0.33^{B}	0.18^{BC}	0.34	0.30	0.41^{BC}	0.21^{AB}	0.46^{ABC}	0.18^{B}	0.31
0.8–1.0	0.37	0.34^{B}	0.17^{BC}	0.18	0.30	0.23^{C}	0.26^{AB}	0.49^{AB}	0.24^{AB}	0.28
1.0–1.5	0.29^{b}	0.31^{Bb}	0.16^{Cb}	0.18^{b}	0.48^{ab}	0.66^{ABCa}	0.21^{ABb}	0.14^{BCb}	0.24^{ABb}	0.37^{ab}
1.5–2.0	0.43^{ab}	0.42^{Bab}	0.29^{ABCabc}	0.21^{bc}	0.53^{a}	0.36^{BCabc}	0.30^{ABabc}	0.14^{BCc}	0.25^{ABabc}	0.37^{abc}
2.0–2.5	0.35	0.37^{B}	0.23^{BC}	0.17	0.45	0.34^{BC}	0.24^{AB}	0.14^{BC}	0.21^{B}	0.32
2.5–3.0	0.36	0.33^{B}	0.25^{BC}	0.27	0.50	0.35^{BC}	0.28^{AB}	0.27^{ABC}	0.29^{AB}	0.34
3.0–3.5	0.29^{ab}	0.32^{Bab}	0.19^{BCb}	0.21^{b}	0.53^{a}	0.45^{ABCab}	0.21^{ABb}	0.19^{ABCb}	0.29^{ABab}	0.45^{ab}
3.5–4.0	0.39^{b}	0.33^{Bb}	0.25^{BCbc}	0.31^{b}	0.42^{b}	0.66^{ABCa}	0.19^{ABc}	0.31^{ABCb}	0.23^{ABbc}	0.40^{b}
4.0–4.5	0.46	0.33^{B}	0.29^{ABC}	0.38	0.52	0.36^{BC}	0.25^{AB}	0.17^{BC}	0.33^{AB}	0.48
4.5–5.0	0.43^{ab}	0.27^{Bb}	0.34^{ABCab}	0.44^{Ab}	0.43^{ab}	0.64^{ABCa}	0.20^{ABb}	0.24^{ABCb}	0.52^{ABab}	0.48^{ab}
CV (%)	27.68	43.10	48.03	42.26	21.66	37.28	25.48	49.68	39.61	20.14

Note: Values followed by uppercase letters in the same column and by lowercase letters in the same row indicate significant differences at $P<0.05$ level.

Table 5 Distribution of non-labile oxidizable organic carbon (C_4) at various soil depths

Depth (m)	Forested land	Orchard	Shrubland I	Shrubland II	Artificial grassland	Natural grassland	Terraced cropland I	Terraced cropland II	Check-dam cropland	Sloped cropland
	(g/kg)									
0–0.1	0.53^{b}	0.98^{b}	0.36^{BCb}	0.37^{Cb}	0.57^{ABb}	3.12^{Aa}	0.58^{Ab}	0.94^{Ab}	0.89^{b}	0.23^{b}
0.1–0.2	0.25^{b}	0.89^{ab}	0.24^{Cb}	0.55^{Cab}	0.63^{ABab}	1.31^{ABa}	0.43^{Ab}	0.62^{ABab}	0.67^{ab}	0.51^{ab}
0.2–0.4	0.50	0.52	0.50^{ABC}	0.33^{C}	0.45^{B}	0.58^{AB}	0.43^{A}	0.35^{BC}	0.85	0.57
0.4–0.6	0.30	0.54	0.54^{ABC}	0.44^{C}	0.57^{AB}	0.71^{AB}	0.51^{A}	0.74^{AB}	0.61	0.65
0.6–0.8	0.21	0.51	0.44^{ABC}	0.64^{C}	0.49^{AB}	0.32^{B}	0.56^{A}	0.64^{AB}	0.40	0.54
0.8–1.0	0.23	0.43	0.39^{BC}	0.62^{C}	0.60^{AB}	0.24^{B}	0.44^{A}	0.61^{AB}	0.39	0.47
1.0–1.5	0.59^{b}	0.61^{b}	0.60^{ABCb}	0.89^{BCab}	0.88^{ABab}	1.05^{ABa}	0.08^{Bc}	0.09^{Cc}	0.61^{b}	0.56^{b}
1.5–2.0	0.66^{ab}	0.56^{b}	0.60^{ABCb}	0.80^{Cab}	0.90^{ABab}	1.03^{ABa}	0.06^{Bc}	0.10^{Cc}	0.61^{b}	0.62^{b}
2.0–2.5	0.63^{b}	0.56^{b}	0.52^{ABCb}	0.76^{Cb}	0.89^{ABb}	1.49^{ABa}	0.05^{Bc}	0.08^{Cc}	0.56^{b}	0.75^{b}
2.5–3.0	0.69^{b}	0.74^{b}	0.60^{ABCb}	0.67^{Cb}	0.65^{ABb}	1.18^{ABa}	0.09^{Bc}	0.14^{Cc}	0.67^{b}	0.53^{b}
3.0–3.5	0.67^{ab}	0.80^{ab}	0.83^{Aab}	0.74^{Cab}	0.89^{ABa}	1.03^{ABa}	0.02^{Bc}	0.11^{Cc}	0.70^{ab}	0.41^{bc}
3.5–4.0	0.59^{abc}	0.43^{bcd}	0.83^{Aab}	0.87^{Cab}	1.00^{Aa}	0.84^{ABab}	0.03^{Bd}	0.09^{Cd}	0.61^{abc}	0.40^{cd}
4.0–4.5	0.56^{bc}	0.62^{bc}	0.81^{Ab}	1.48^{ABa}	0.89^{ABb}	1.27^{ABa}	0.04^{Bd}	0.07^{Cd}	0.84^{b}	0.38^{cd}
4.5–5.0	0.57^{bc}	0.47^{bcd}	0.75^{ABb}	1.72^{Aa}	0.86^{ABb}	0.90^{ABb}	0.07^{Bd}	0.05^{Cd}	0.20^{cd}	0.60^{bc}
CV (%)	34.79	27.73	32.11	50.52	25.24	64.20	94.48	94.41	31.00	25.34

Note: Values followed by uppercase letters in the same column and by lowercase letters in the same row indicate significant differences at $P<0.05$ level.

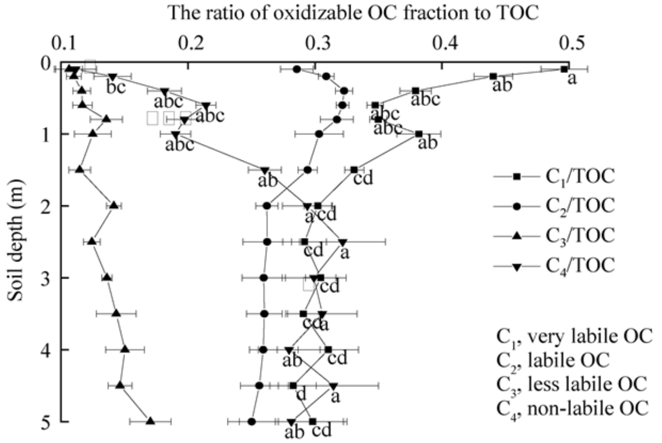

Fig. 1 The ratios of oxidizable organic carbon (OC) fractions to total organic carbon (TOC) along the soil profile. The ratio of oxidizable OC fractions to TOC in each soil layer were showed as the mean ratio among land-uses types except for two terraced croplands. Different letters along the soil profile indicated significant differences at $P<0.05$ level.

2.4 MDS analysis of the distribution of the oxidizable OC fractions and TOC

MDS analysis of TOC and C_1 contents showed that the natural and artificial grasslands were different from the other land-use types, the forested land was closed to shrubland I, terraced cropland I was closed to the sloped cropland, and orchard, check-dam cropland, terraced cropland II and shrubland II were similar (Stress=0.092, Fig. 2a; Stress=0.066, Fig. 2b). The MDS for C_2

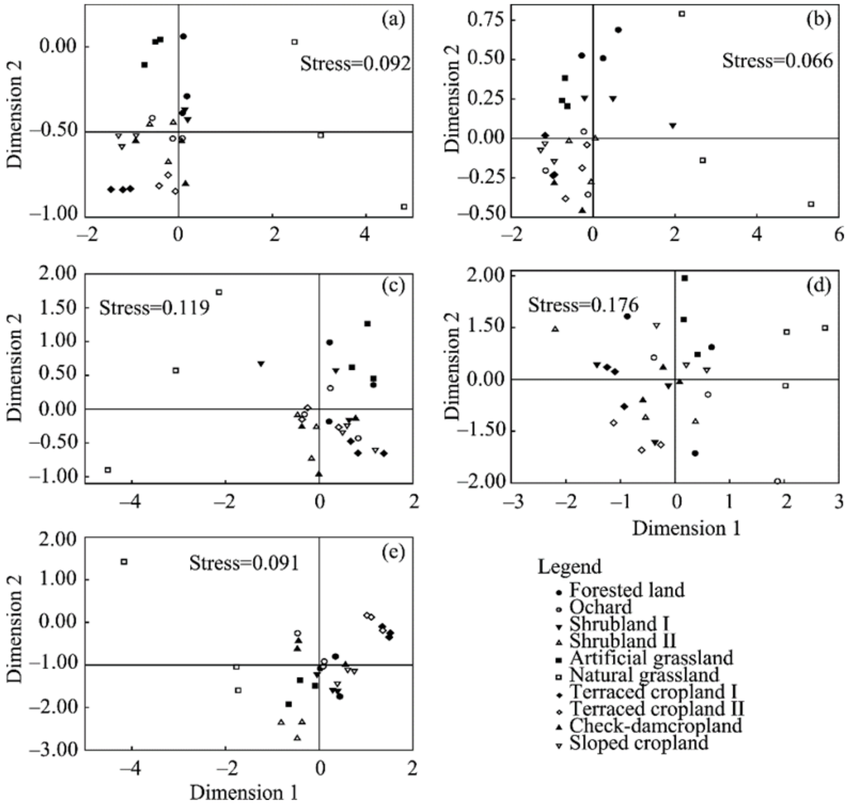

Fig. 2 Multidimensional scaling of (a) TOC; (b) C_1; (c) C_2; (d) C_3; (e) C_4. Dimension 1 represents the distribution of each factor along the soil profile, and dimension 2 represents the individual differences of the vegetation types. Interactions in the Euclidean-distance model stop when stress is less than 0.005.

content separated the natural grassland from the other land-uses, forested land was closed to shrubland I and artificial grassland, and the other land-use types were closed to each other (Stress=0.119, Fig. 2c). The MDS for C_3 separated terraced cropland II, natural grassland and artificial grassland, the orchard, forested land and sloped cropland were closed to each other, and the remaining land-uses were similar (Stress=0.176, Fig. 2d). The MDS for C_4 content separated the natural grassland, but two terraced cropland were closed to each other, artificial grassland was closed to shrubland II, and the remaining land-uses were similar (Stress=0.091, Fig. 2e).

3 Discussion

3.1 Distribution of oxidizable OC fractions along soil profiles

Labile fractions of OC changed along soil profile. The C_1 and C_2 contents in the 0–0.2 m soil layers were higher than in the other layers, which corroborated the findings of previous studies (Maia et al., 2007; Barreto et al., 2011) and indicated that the SOC was labile in the surface soil and could be easily lost through oxidization. The higher amounts of labile OC in topsoil compared to the other soil layers was mainly attributed to high inputs of residues and concentrations of fine roots (Leifeld and Kögel-Knabner, 2005; Zhou and Shangguan, 2007). In contrast, plant photosynthesis adds fewer residues to, but consumes more nutrients from the soil at increasing depth (Chen et al., 2007a; Barreto et al., 2011).

Distribution of stable fraction of OC changed in the deep soil profile in both terraced croplands, showing significantly lower C_4 content in the 1.0–5.0 m than the 0–1.0 m soil layers. This finding indicated that the terraced cropland had a significant effect on the vertical distribution of C_4. Reasons could be attributed to the lower TOC contents below 1.0 m compared to up 1.0 m soil layers (Zhang et al., 2013). The stable carbon is mainly formed during aggregation and through strong chemical bonding of the microbial products of decomposition to mineral soil matrix (Cotrofo et al., 2013, Tripathi et al., 2014). Lower TOC content, oxygen levels and temperatures below 1.0 m limited the decomposition of carbon source by soil microbes. Furthermore, the destruction of root system by human disturbance can reduce the replenishment of labile carbon in form of root fragments and exudates (Lorenz and Lal, 2005; Benbi et al., 2012).

3.2 Changes of the proportion of oxidizable OC fractions to TOC along the soil profile

We used the mean proportions of the fractions of oxidizable OC relative to TOC in each soil layer among land-uses, except for the two terraced croplands. The proportions of C_4 to TOC in the two terraced croplands were particularly small and were removed as outliers for decreasing the difference among groups. The proportions of the fractions of oxidizable OC to TOC followed the order $C_1/TOC>C_2/TOC>C_3/TOC$ and C_4/TOC ($P<0.05$) in the 0–1.5 m soil layers and the order C_1/TOC and $C_4/TOC>C_2/TOC>C_3/TOC$ ($P<0.05$) in the 2.0–5.0 m layers. Changes of the proportions of the oxidizable OC fractions relative to TOC above and below 1.5 m indicated that the composition and characteristics of the SOC varied with increasing soil depth. The SOC in the 0–1.5 m layers was mainly composed of labile carbon fractions (C_1 and C_2), but the stable carbon fraction (C_4) increased below 2.0 m. Previous studies also showed increasing turnover time of soil organic matter with soil depth (Trumbore and Zheng, 1996; Rumpel and Kögel-Knabner, 2011), indicating that deep soil contained high concentrations of stabilized carbon with long residence times. Given the stability and long turnover time of the carbon in deep soils, defined as deeper than 5.0 m by Harper and Tibbett (2013), more attention should be paid to deep soil, which may have a higher potential capacity to sequester carbon (Harrison et al., 2011).

3.3 Fractions of oxidizable OC in the various land-use types

Natural grassland and shrubland facilitate the oxidizability of SOC and improve soil quality in shallow soil layers. Previous studies in the same region demonstrated this, which showed that the highest contents of light fraction carbon (Liu et al., 2010) and microbial biomass carbon (Zhang et al., 2011) was found in natural grassland and shrubland. The present study also showed that the natural grassland had the highest C_1 and C_2 contents in the 0–0.4 m layers, followed by shrubland I in the 0–0.1m layer. C_1 and C_2 were labile fractions of oxidizable OC, implying that SOC could be more easily oxidized in the natural grassland and shrubland I than the other land-uses. Oxidation of SOC releases soil mineral nutrients and thus influences nutrient cycling for improving soil quality (Majumder et al., 2007; Mosquera et al., 2012). These higher C_1 and C_2 contents in the natural grassland were mainly attributed to the perennial growth of *A. sacrorum* and *S. bungeana* that produced large amounts of residues (Maia et al., 2007; Barreto et al., 2011; Guareschi et al., 2013). The extensive systems of fine roots in grassland also greatly contribute to higher C_1 and C_2 contents in shallow soil layers. Wei et al. (2009) reported that a grassland on the northern Loess Plateau of China had 33% and 34% more fine roots to a depth of 0.4 m than the forested land and shrubland, respectively. Furthermore, SOC, especially the labile fractions, could be preferentially removed by accelerated soil erosion because its density is lower than that of mineral fractions and because it is concentrated near the soil surface (Lai, 2005). Soil erosion was lower in the natural grassland and shrubland I than the sloped cropland (Zhu et al., 2010, 2014), which greatly contributed to the conservation of C_1 and C_2 contents in the surface soil.

The deep soil of natural grassland may have a high potential to sequester SOC and reduce CO_2 emission. These potentials were supported by our results, which showed that natural grassland had higher C_4 contents in the 1.0–4.5 m layers compared to the sloped cropland. C_4 is recalcitrant carbon with a higher chemical stability and molecular weight, and its turnover time is longer than that of the labile fraction of SOC (Chan et al., 2001; Guareschi et al., 2013; Rumpel and Kögel-Knabner, 2011). The deep soil of natural grassland is thus beneficial for the allocation and deposition of photosynthetic products. This phenomenon may be due to the higher root/shoot ratio of weeds and cumulative root fraction (Jackson et al., 1996) in deep soil of the natural grassland relative to the cropland. Fine-root residues and rhizodeposition are the main input sources of deep SOC (Shi et al., 2013). Kuzyakov and Domanski (2000) demonstrated that pasture plants can translocate 30%–50% of the total assimilated carbon belowground. Additionally, some dissolved OC transported with percolating water may be adsorbed onto mineral surfaces in deeper soil layers (Baldock and Skjemstad, 2000; Lorenz and Lal, 2005) and form recalcitrant SOC through complex pedological processes (Rumpel and Kögel-Knabner, 2011).

3.4 MDS of the carbon fractions and TOC

Similar MDS results for the TOC and C_1 contents showed that the natural and artificial grasslands differed from all other types of land-use types. Shrubland I was similar to forested land, terraced cropland I was similar to the sloped cropland, and orchard, terraced cropland II and shrubland II were similar to each other. These 10 types of land uses could thus be classified into five categories. Land-use types in the same category have similar effects on the vertical distributions of TOC and C_1. The similarity of the MDS for TOC and C_1 indicated that C_1 could be used as a sensitive indicator for changes in soil quality. Similar conclusions have been offered by Chan et al. (2001), Guareschi et al. (2013) and Majumder et al. (2007), who demonstrated that C_1 was a better indicator for the assessment of soil quality due to the relatively low cost and ease of estimation of these pools.

4 Conclusions

Soil depth significantly influences the distribution of the oxidizable OC fractions and its proportion to TOC. The contents of labile fractions of oxidizable OC were higher in the top soil layer than in deep soil layers. C_1/TOC significantly decreased in the 0–0.6 m and remained unchanged below 1.5 m, and C_4/TOC significantly increased to a depth of 2.5 m and remained unchanged below 2.5 m. The composition and characteristics of SOC greatly changed with soil depth, so the fate of deep SOC in response to land-use type should be considered. This study demonstrated that land-use type can significantly affect the fractions of oxidizable OC. The natural grassland had the highest C_1 and C_2 contents in the 0–0.4 m layers, followed by shrubland I in the 0–0.1 m soil layer, and natural grassland had the highest C_4 contents in the 1.0–4.5 m layers. Natural grassland and shrubland I may thus be the optimal choices for improving the quality of the SOC in shallow soil, and the deep soil of natural grassland has the potential to sequester SOC on the Loess Plateau.

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