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Short communication

Soil organic carbon on the fragmented Chinese Loess Plateau: Combining effects of vegetation types and topographic positions

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ABSTRACT

The influence of vegetation coverage and topography on soil organic carbon (SOC) stocks has been intensively studies. However, very few of the studies have recognized the potential combining effects of vegetation types and topographic positions onto SOC distribution, especially on the Chinese Loess Plateau where vegetation recovery has generated complex combination of fragmented topography and vegetation coverage. This study systematically sampled soil cores (259) from four vegetation types (woodland, grassland, cropland, and orchard) at three topographic positions (tableland, slope and valley bottom). Each soil core was divided into three layers: surface soil (0–20 cm), subsoil (20–60 cm) and deep soil (60–200 cm). Our results show that: (1) the SOC concentration declined over soil depths, regardless topographic positions or vegetation types. The absence of ancient cultivation layers at the valley bottoms further made the SOC stocks deep to 200 cm there much less than the tableland with thick loess soil layers (8.3 kg km^{-2} vs. 13.4 kg km^{-2}). (2) The SOC concentration of cropland varied evidently with topographic positions, with the greatest on the tableland (8.0 g kg^{-1}), and the least along the slope (5.3 g kg^{-1}). However, grassland was rather stable across the three topographic positions. (3) In addition, the SOC concentrations of the three vegetation types were comparable on the tableland (6.1 g kg^{-1}), while differed noticeably at the valley bottoms (5.0 g kg^{-1}). Overall, our findings in this study call for the account for each combination of topographic position and vegetation type, so as to properly assess regional SOC stocks for sustainable land use.

1. Introduction

Substantial research has dedicated to investigate the potential effects of vegetation types to soil carbon pools (SOC) (Ayoubi et al., 2011; Ayoubi et al., 2012; Don et al., 2011; Shahriari et al., 2011; Wang et al., 2016), and has primarily recognized the contributions from different above- and under-ground biomass types, amount and return rates (Leeuwen et al., 2017; Post and Kwon, 2000). In general, it is agreed that conversion from natural vegetation types (e.g., woodland, grassland) to cropland will lead to a decline of surface soil organic carbon (Ayoubi et al., 2012; Malhi et al., 2003; Wang et al., 2009), mainly because tillage practices introduce soil disturbance, breakdown and nutrient output (Ayoubi et al., 2012). Meanwhile, changing from cropland land back to grassland is likely to help sequester SOC (Zhang et al., 2014; Deng et al., 2014a), yet the sequestration rate is likely to approach a plateau after 10–20 years (Deng et al., 2014a; Deng et al., 2014b).

Nevertheless, very few of these studies have taken topographic positions into consideration when addressing the potential effects of different vegetation types (Fernández-Romero et al., 2014). In fact, topographic positions are fundamentally relevant for hilly regions where the spatial distribution of SOC is primarily defined by erosion events (Karchegani et al., 2012; Khormali et al., 2007; Khormali et al., 2009; Zhu et al., 2014). Unlike flatland, selective erosion and transport of fine/light particles from eroding sites (mostly slope shoulder), and deposition SOC-rich fractions at valley bottom, all affect spatial redistribution of SOC across landscapes (Kuhn and Armstrong, 2012; Hu et al., 2013; Soinne et al., 2016). Such spatial redistribution relocates SOC into different micro-climate conditions, which potentially determines the accumulation and decomposition processes of SOC (Ayoubi et al., 2012 Fern & ndez-Romero et al., 2014; Zhu et al., 2014). Meanwhile, different vegetation types on varying topographic positions also have distinctive soil surface coverage, which fundamentally influences SOC input, hydrological processes and hence the spatial redistribution of SOC along hillslopes (Ellerbrock et al., 2011; Fern & ndez-Romero et al., 2014; Seibert et al., 2007).

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Fig. 1. Photo of the study area.

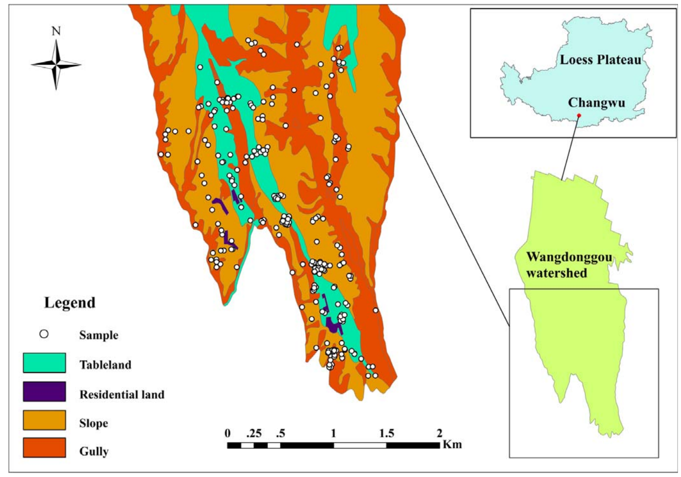

Fig. 2. Soil sampling sites and topographic positions of the study watershed.

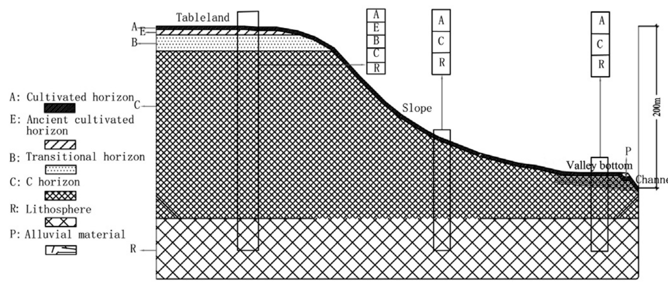

Fig. 3. Geological structure of tableland, slope and gully in the study watershed.

The Chinese Loess Plateau, a semiarid region covering a total area of 58×10^4 km^2, is characterized with thick (50 − 300 m) yet highly erodible soil (average soil loss rate 2860 t km^{-2} a^{-1}) (Wang et al., 2011; Zhu et al., 2014). Hundreds of years intensive cultivation and severe erosion has incised into the plateau, fragmented the vast flat area into tableland (remnant flat parts of the plateau) and slopes (or gullies), with depositions in valley bottoms (Fig. 1). In addition, severe erosion has exposed parent materials and even bedrocks on slope back, meanwhile depositing the eroded materials in valley bottoms, forming a patchwork in the watershed (Fig. 1). In order to curb soil erosion on the Loess Plateau, a national-level "Grain-for-Green" rehabilitation project was launched in 1980 s, which forcefully converted cropland on slopes of gradient > 25° back to forest or grassland (Deng et al., 2014b). Variations in topographic positions and changes in vegetation types have fragmented the Chinese Loess Plateau into a complex combination of tableland, slopes and valleys with cropland, grassland, orchard and woodland. However, it lacks systematic investigations to particularly address the coupling effects vegetation types and topographic positions on the fragmented Loess Plateau.

The objectives of this study are to investigate the difference in SOC in the surface soil (0–20 cm), subsoil (20–60 cm) and deep soil (60–200 cm) layers among four vegetation types at three topographic positions, so that to identify the interactive effects of vegetation types, topographic positions and soil depth on SOC pools on the Chinese Loess Plateau.

2. Materials and methods

2.1. Description of the study area

The study area is located in State Key Agro-Ecological Experimental Station in Wangdonggou watershed (35°13′ N–35°16′ N, 107°40′ E–107°42′ E), on the Loess Plateau, Shaanxi province, China (Fig. 2). According to the long-term data set collected since 1984, the study area has a continental monsoon climate with mean annual precipitation of 560 mm, varying from 296 to 954 mm in recent 30 years. Out of that, 60% occurs between July and September. The soils are derived from wind-deposited loess with abundant SOC and $CaCO_3$ during the Holocene (Huang et al., 2003), and belong to Loessi-Orthic Primosols (USDA Soil Taxonomy) and Cambisols (WRB) (Wang et al., 2015).

In this study, we mainly focused on three topographic positions: on tableland, along slope and at valley bottom (Fig. 2). To be specific, tableland is relatively flat (gradient < 5°) at the altitude of 1220 m with soil erosion rate < 100 t km^{-2} a^{-1} (Li and Su, 1991). Dated back to the ancient Loess Plateau, the tableland has a full set of soil horizons (Fig. 3 and Table 1): cultivated layer (Horizon A), ancient cultivated layer (Horizon E), transitional layer (Horizon B), and C horizon (Horizon C). Slopes mainly distribute at altitude of 1000–1220 m with gradients of 5–50°. It basically consists of Horizon A and C being exposed on slope backs at erosion rates of 100–20,000 t km^{-2} a^{-1} (Li and Su, 1991). The valley bottom is mostly at altitude of 1000 m with gradient < 10°. As it accumulates eroded materials from tableland and slopes, soils at valley bottoms are mostly mixture of sediment sitting on loess parent materials in the deep layer.

Based on local vegetation distribution patterns, four vegetation types were investigated in this study: cropland, grassland (*Artemisia gmelinii, Bothriochloa ischaemum, Medicago sativa* L.), apple orchard (*Malus pumila* mill) and woodland (*Robinia pseudoacacia* L.). To be specific, cropland is rainfed, and mainly cultivated with mono-winter wheat and corn (*Triticum aestivum.* L and *Zea mays* L.) having annual crop yield of 5000 kg ha^{-1} on average. Local management normally applies 600 kg N ha^{-1} and 375 kg P ha^{-1} chemical fertilizers every year, and removes crop residues for cooking or feeding cattle. Tillage practices are conducted twice a year to increase rainfall infiltration after the harvest (in July) and to prepare seed beds before the next sowing (in September). The apple orchard (*Malus pumila* Mill) was planted (by density of 2 m × 3 m) about 25–30 years ago, and tilled every year to control weeds. Fertilization management in apple orchard was similar to the cropland, and no irrigation was applied. Grassland and woodland have been redeveloped from cropland for 25–30 years, and received no fertilizer.

2.2. Soil sampling design

In mid-May 2012, soil samples were collected from the four vegetation types on the three topographic positions. Considering the demand for grains or fruits by local farmers who mostly live on the tableland meanwhile the impractical efforts to manage apple orchard at distant valley bottoms, no woodland was painted on tableland and no apple orchard was growing at valley bottoms. In total, 259 sampling

Table 1
General information on soil physical and chemical properties in the study area (informations source: Li and Su, 1991).

Topographic positions	Horizon of soil	Depth (cm)	SOM (%)	TN (%)	TP (%)	Olsen-P (ppm)	pH	Bulk density (g cm^{-3})	Clay (< 0.05 mm) (%)	Characteristics
Tableland	Cultivated layer	0–20	1.19	0.07	0.13	18.9	8.2	1.25	90	Grey-brown, granular structure, loose and porous, medium loam, newly formed, a little earthworm cast and wormhole.
	Ancient cultivated layer	20–60	0.83	0.05	0.10	12.6	8.1	1.33	91	Light yellow, loose, block structure, medium loam.
	Transitional layer	60–200	0.93	0.06	0.08	5.7	8.3	1.28	92	Yellow brown, loam, block structure, slightly compact, new formations were carbonate, pseudo-mycelia shape.
	C horizon	> 200	0.64	0.04	0.07	2.8	7.9	1.24	92	Loess, thick soil layer, strong soil and water conservation ability, strong lime reaction, loose and porous.
Slope	Cultivated layer	0–20	0.75	0.05	0.08	12.6	7.9	1.27	86	Young soil developed from loess mother material.
	C horizon	> 20	0.43	0.03	0.06	3.0	7.4	1.24	93	Loess, yellow-brown, strong lime reaction, comfortable texture, loose and porous.
Valley bottom	Cultivated layer	0–20	0.84	0.06	0.12	5.73	8.1	1.28	89	Located in low-lying land of gully of watershed, young soil developed from loess of slope deposit or diluvium.
	C horizon	*> 20*	*0.30*	*0.02*	*0.10*	*2.9*	*7.5*	*1.20*	*92*	*Loess, soil close to the cultivated horizon is a mixture of slope colluvial deposit, river sediment and loess.*

Note: SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; Olsen-P, available phosphorus.

sites were selected, each sampled with 3 quadrats as replicates. In particular for grassland, quadrats of 1 m × 1 m were used to determine herb coverage, height, species and aboveground litter. For woodland, quadrats of 10 m × 10 m were set up to determine aboveground litter, canopy height and density, diameter at breast height (DBH), and growth condition. Specific characteristics of vegetation are described in Table 2.

To be specific, soils were sampled deep to 200 cm using a soil auger with a diameter of 3 cm (3 replicates per plot). Surface litter was brushed aside before sampling. Soil bulk density of surface soil was determined on-site following the clod method using a steel ring with a total volume of 100 cm^3 (50.46 mm in diameter and 50 mm in height) (Da et al., 1997), and the information of bulk density in deep layers was adopted from the routine field investigation conducted by the Changwu State Key Agro-Ecological Experimental Station. For each of the 200 cm soil core, it was divided into 10 layers with an interval of 20 cm. Soil samples from each replicated layers were mixed thoroughly, air dried, and then crushed to pass through a 0.15 mm sieve. The SOC was measured following the K_2CrO_7–H_2SO_4 oxidation method (Sparks et al., 1996).

2.3. Data analysis

In order to better distinguish the differences of soil profiles at the three topographic positions, the 20 cm layers were then grouped into 0–20, 20–60 and 60–200 cm, so as to represent surface soil, subsoil and deep soil. The SOC stocks of each layer were then calculated using the following equations (Zhang et al., 2013):

$$\text{SOC stocks} = \sum_{i=1}^{n} \text{SOC}_i \times B_i \times H_i \tag{1}$$

where SOC stocks are the sum of SOC per unit land area to a depth of 2 m (g m^{-2}), SOC is the soil organic *C* concentration (g kg^{-1}), *B* is the bulk density (g cm^{-3}), *H* is the thickness of the soil layer sampled (cm), and the subscript *i* is the number of soil layer, respectively.

2.4. Statistical analysis

All statistical analyses were performed using SAS 6.12 for Windows. The data were subjected to three-way analysis of variance (ANOVA) with topographic positions, vegetation types, and soil depth as the main factors, followed by a least significant difference (LSD) test for post hoc comparisons at a 95% confidence interval.

3. Results and discussions

Across soil profiles, the SOC concentration declines with soil depths for all the vegetation types and topographic positions (Fig. 4). The differences of SOC between the surface 0–20 cm and the deep 60–200 cm were more pronounced at the valley bottoms than on the tableland (Fig. 4). While the SOC in surface 0–20 cm was slightly greater at the valley bottoms than other two topographic positions, the SOC in layers of 20–60 cm and 60–200 cm was rather low and stable for all the vegetation types at all the topograhpic positions. Such vertical distribution patterns suggest the potential overestimation in previous reports where only SOC concentraiton in topsoil was measuredand and extrapolated to estimate the SOC stocks on the Loess Plateau (Deng et al., 2014a; Zhu et al., 2014).

For different vegetation types, the SOC in surface soil of the grassland was stable around 8.7 g kg^{-1}, regardless the topograhpic positions (Fig. 4). This may suggest that grassland, relative to other three vegetation types, was more resilent to variations in topography, and therefore may potentially play an essential role in ecosystem restoration on the Chinese Loess Plateau. Among the other three vegetation types, cropland was most sensitive to different topographic

Table 2
Vegetation types in the Wangdonggou watershed.

Vegetation types	Topographic positions	Number of soil samples	Number of years	Mean canopy height (m)	Mean plant height (m)	Mean DBH (cm)	Canopy cover (%)	Litter production (Mg ha^{-1})	Dominant plant species
Cropland	Tableland	21							*Triticum aestivum.*L and *Zea mays* L.
	Slope	4							
	Valley bottom	15							
Grassland	Tableland	9	25–30		0.2		48.5	5.8	*Artemisia gmelinii, Bothriochloa ischaemum, Medicago sativa* L.
	Slope	48							
	Valley bottom	33							
Orchard	Tableland	27	25–30	2.8	2.3	22.7	59.3	0.2	*Malus pumila* Mill.
	Slope	21							
Woodland	Slope	56	25–30	4.1	3.2	12.1	45.2	13	*Robinia pseudoacacia* L.
	Valley bottom	25							

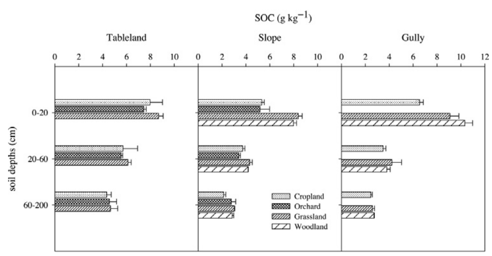

Fig. 4. SOC content (g kg^{-1}) at different topographic positions and land uses.

positions (Fig. 4), ranging from 8.0 g kg^{-1} on the tableland, down to 5.3 g kg^{-1} along the slope, and back to 6.5 g kg^{-1} at the valley bottoms (Fig. 4). On the one hand, this may be resulted from the spatial distribution of SOC over erosion and deposition processes, namely depleting SOC-rich soil fractions from eroding sites on the tableland and along the slopes, and depositing them at the valley bottoms (Hu et al., 2013; Scowcroft et al., 2000; Seibert et al., 2007). On the other hand, the enrichment of SOC at the valley bottoms potentially promoted crop yield, and thus more abundant crop residues and root growth, which may eventually contribute to SOC accumulation there (Zhu et al., 2014).

Specifically on the tableland, the SOC was comparable for all the three vegetation types (cropland, orahcard, grassland) and all the individual soil layers. However, the SOC at the valley bottoms was much more dependent on the vegetation types, with woodland of 10.3 g kg^{-1} but cropland of 6.5 g kg^{-1} in the topsoil (Fig. 4). This is mostly because the more abundantly available soil water at the valley bottoms can provide more favourable conditions for the water-demanding woodland (Zhang et al., 2015), while the soil water distribution and sunlight were equally available for all the vegetation types on the Tableland.

For the SOC stocks, the distributions were comparable among the four vegetation types, yet rather different over the topograhic positions (Fig. 5). The tableland areas evidently had much greater SOC stocks (around 13.4 kg km^{-2}) than at the other two topographic positions (about 8.0 kg km^{-2}). This is partially because of the more fertile soil on the tableland, and is also due to the absence of deep soil along the eroding slopes and depositional areas at the valley bottoms (Table 1).

4. Conclusions

This study systematically investigated the distributions of SOC deep to 200 cm of four vegetation types under three topographic positions in the Chinese Loess Plateau. Our results show that the SOC differed across topographic positions, with the greatest concentration on flat tableland and the lowest along the slopes. Such spatial variations were not uniform but dependent on vegetation types, with cropland being most sensitive while grassland being the most resilient variations in topographic positions. In addition, the SOC stocks deep to 200 cm also point

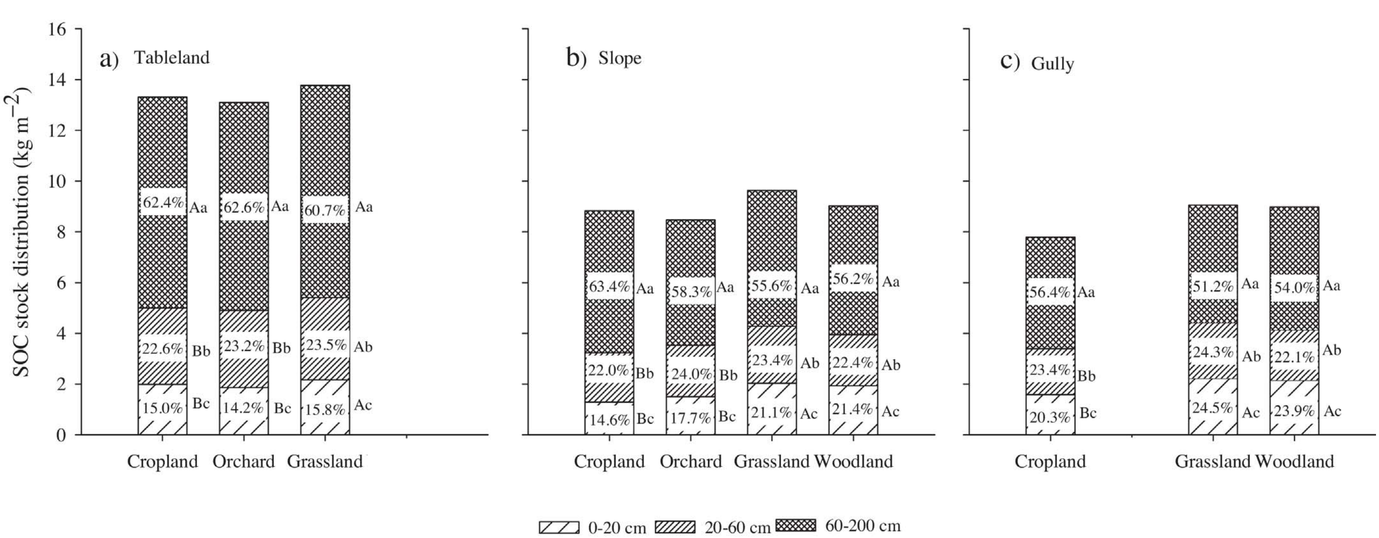

Fig. 5. Vertical distribution of SOC stocks (kg m^{-2}) and percentage (%) at different topographic positions and land uses. Different capital letters of the same layer are significantly different at $P < 0.05$ under different land uses. Different lowercase letters of the same land use are significantly different at $P < 0.05$ under different layers.

to the potential bias caused by differently structured soil profiles. Applying SOC concentration obtained from an arbitrary soil depth to estimate SOC stocks of the entire profile is very likely to under-estimate the SOC stocks on the tableland where the loess soil layers were abundantly thick, yet to over-estimate the SOC stocks at the valley bottoms where the ancient cultivation layer and transitional layers were missing. Therefore, it needs to account for each combination of topographic position and vegetation type, rather then assuming average values for the same vegetation or topography, when assessing the regional SOC stocks for sustainable land use.

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