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Soil organic carbon fractions and sequestration across a 150-yr secondary forest chronosequence on the Loess Plateau, China

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ABSTRACT

Restoration of natural vegetation is recommended as an effective approach to restore soil function and rebuild degraded ecosystems. Information is lacking about the long-term results of secondary forest succession on the Loess Plateau with respect to soil organic carbon (SOC) fractions and sequestration in the root-zone soil profile. We investigated the differences in SOC fractions down to 100 cm depths along a 150-yr chronosequence, including cropland (control) and five successional stages (pioneer weeds, herbage, shrub, early forest, and climax forest). Total, labile, and non-labile SOC concentrations increased rapidly at early successional stages (before shrub, <50-yr) and then gradually leveled off. Total SOC stock was highest at the climax forest stage (64.3 Mg ha^{-1}) and lowest in cropland (39.9 Mg ha^{-1}). Nearly half (~44.8%) of total SOC stock was stored in surface soils (0–20 cm) and the majority (76.4%) existed in the non-labile fraction. The ratio of labile to non-labile fraction decreased with depth but remained stable across successional stages. The mean SOC sequestration potential and rate relative to cropland were 20.5 Mg ha^{-1} and 0.73 Mg ha^{-1} yr^{-1}, respectively. Although the SOC sequestration potential decreased with depth (64.7% for 0–20 cm *vs.* 35.3% for 20–100 cm), it decreased by 3.1 Mg ha^{-1} in the surface and increased by 3.4 Mg ha^{-1} in the subsurface from herbage to climax forest stage. This study indicated that long-term secondary forest succession played a positive role in SOC sequestration on the Loess Plateau, especially in the subsurface soil layers.

1. Introduction

Soil organic carbon (SOC) is the largest C stock in the terrestrial ecosystem (Batjes, 1996). The dynamics of SOC stocks is closely related to the global C cycle through soil sequestration and emission (Lal, 2004). Vegetation restoration is often adapted to increase SOC storage and sequestration for mitigating CO_2 emissions and restoring ecosystem functions (Guo and Gifford, 2002; Lal, 2004). This strategy is of particular importance in arid and semi-arid regions where fragile ecosystems suffer severe soil degradation and erosions.

Land-use changes resulting from natural vegetation restoration substantially affect SOC stocks and sequestration capacity (Degryze et al., 2004; Post and Kwon, 2000). Guo and Gifford (2002) concluded that the SOC stocks increased by 53% due to cropland conversion to secondary forest, whereas a 42% decrease occurred during native forest conversion to cropland. Along with vegetation restoration, changes in the plant species composition can alter litter input, root architecture (Schedlbauer and Kavanagh, 2008), and soil aggregation (An et al., 2010). These mechanisms will further control the storage and stabilization of SOC as related to depth (Blanco-Canqui and Lal, 2004). Extensive studies have focused on the spatial variability of SOC stocks and sequestration potential in the upper 40-cm profile, which has a higher accumulation of SOC and more active exchange with the atmospheric C. Recently, the subsurface layers have been shown to play a vital role in SOC storage and sequestration because of their higher SOC stocks and recalcitrance (Jobbágy and Jackson, 2000; Rumpel and Kögel-Knabner, 2011). Knowledge of SOC dynamics in deeper soil profile is essential to better understand how vegetation restoration affects SOC storage and sequestration.

Fractionation of functional SOC pools is crucial to understanding the responses of SOC quality to land use changes (Poeplau and Don, 2013). Total organic C (TOC) may be limited or absent for SOC quality changes under soil management practices. The fractions more sensitive or recalcitrant to land managements have received increasing attention, such as labile organic C (LOC) and non-labile organic C (NLOC) based on their degree of oxidation by $KMnO_4$ (Blair et al., 1995; Debasish-Saha et al., 2014; Orgill et al., 2014). The LOC with higher turnover rate is considered an early indicator of SOC changes (von Lützow et al., 2007), while the NLOC with lower turnover rate is related to SOC sequestration capacity (Sierra et al., 2013). Quantifying the changes in SOC fractions can provide an early and sensitive assessment of SOC stocks and

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elucidate SOC sequestration as induced by vegetation succession (Haynes, 2005; Islam and Weil, 2000; Orgill et al., 2014).

In northwestern China, the Loess Plateau experiences land degradation as a consequence of frequent human activities and severe soil erosion. Associated environmental problems include soil organic matter decrease and downstream sedimentation. In order to control the water and soil loss and restore the regional agro-ecosystem environment, the Chinese government initiated the 'Grain-for-Green Project' by converting cultivated land with slope exceeding 25° to forestland and/or grassland since 1999. This project has significantly promoted SOC accumulation in the soil profile and enhanced SOC storage over a decade on the Loess Plateau (Chen et al., 2007; Zhang et al., 2010). However, the time of implementing the 'Grain-for-Green Project' is significantly shorter than the entire successional process of natural vegetation. Research on SOC dynamics in a long-term vegetation succession chronosequence is necessary to obtaining base-line data of SOC storage and estimating SOC sequestration potential in the future. Despite numerous reports on SOC dynamics during vegetation restoration on the Loess Plateau (Deng et al., 2013; Jia et al., 2012), information is lacking on SOC fractions and sequestration potential in deeper soil profile (~100 cm) under long-term secondary forest succession.

The objectives of the present study were to investigate the dynamics of SOC fractions in a 100-cm soil profile and evaluate SOC sequestration potential in a 150-yr secondary forest chronosequence on the Loess Plateau. The results will provide reference data for restoring natural vegetation in the semi-arid plateau region.

2. Materials and methods

2.1. Site description

This study was conducted on the Lianjiabian forest farm, Heshui county, Gansu province, China (108°10′–109°08′E, 35°03′–36°37′N). The study area is part of the northern Ziwuling forest region which covers a total area of ~23,000 km^2 and belongs to the hilly and gully zone of the Loess Plateau (Zou et al., 2002). The altitude is 1211–1453 m above sea level and the relative height difference within the site is approximately 200 m. The study area is located in temperate zone. The climate is semi-arid monsoon with a mean annual rainfall of 587 mm and a mean annual temperature of 7.4 °C. The sun-faced slopes present no vertical climatic variations. This area is covered by loess soils within the depth range of 50 to 130 m. The soil develops from primitive or secondary loess parent materials below which there is 80–100 m thick laterite consisting of calcareous cinnamon soil (Cheng et al., 2012; Deng et al., 2013). Plant roots are generally distributed in the top 10 m of soil (Zou et al., 2002). The topsoil pH ranges from 8.0 to 8.3.

In the study area, there are deciduous broadleaf forests characterized by the climax vegetation of *Quercus liaotungensis* Koidz (Zou et al., 2002). From 1842 to 1866, the present vegetation started to recover naturally on abandoned cropland because of a national conflict. From 1940s to 1960s, some lands were reclaimed for arable cultivation and subsequently abandoned during wars and natural disasters. In the 2000s, vast croplands were gradually abandoned over a decade due to the 'Grain-for-Green Project'. Spatially, a series of successional stages exist with different abandoned ages. According to the spatial existence of successional stages, a complete time series of positive vegetation succession is formed, with the climax forest (*Q. liaotungensis*) recovered over ~150-yr (Zou et al., 2002). This secondary succession series started from abandoned cropland and progressed in the following order: pioneer weeds (pioneer plants that start the natural restoration process after crop harvest), herbage, shrub, early forest, and climax forest stages (Wang et al., 2010; Zou et al., 2002).

2.2. Experimental design and soil sampling

Temporal changes in SOC fractions were investigated using space-for-time substitution, a method that is commonly used to study the changes in similar soils under consistent climatic conditions over time (Sparling et al., 2004). Five successional stages were selected to construct a ~150-yr series of secondary vegetation succession, including pioneer weeds (S1), herbage (S2), shrub (S3), early forest (S4), and climax forest (S5) stages. A cropland site (S0) one month after harvest was used as the control. Two communities were selected at the S2, S3, and S4 stages, while one community was selected for each of the other stages (Fig. 1). Three replicated plots (10 m × 10 m for S4 and S5, 5 m × 5 m for S3, and 1 m × 1 m for S2) were randomly chosen in each community. Vegetation survey and soil sampling were undertaken in May 2006. Basic information of soil, topography and vegetation species was shown in Table 1.

A 100-cm soil profile was dug in each plot after the leaf litter and humus layer was removed. Mineral soil samples were taken at 0–5, 5–10, 10–20, 20–40, 40–70, and 70–100 cm depth intervals. Composite samples were mixed by depth for individual successional stages. After roots and other plant debris were removed, all samples were air-dried and then passed through 0.149- and 0.5-mm meshes for TOC and LOC analysis, respectively. Additionally, three duplicate soil cores per plot were taken from the mineral soil surface using stainless cylinders (5 cm inner diameter and 5 cm height) for bulk density (BD) analysis.

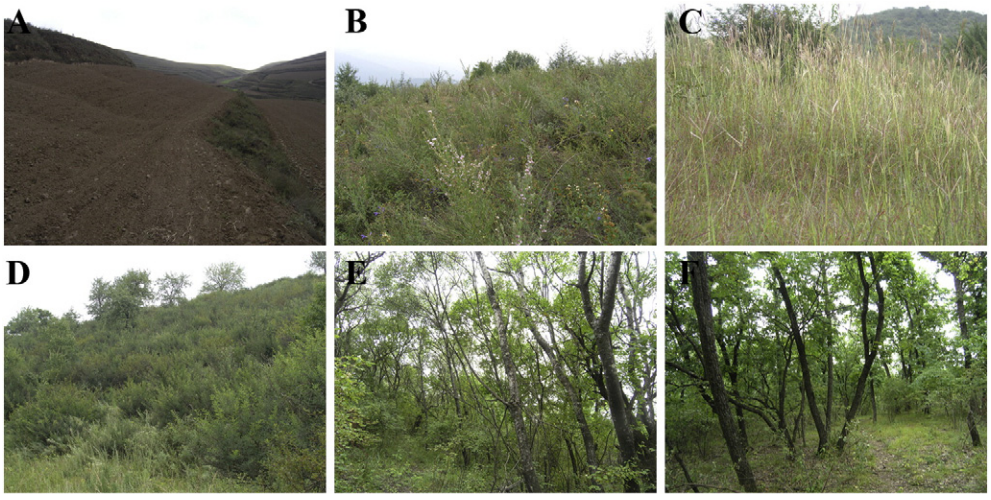

Fig. 1. Photos of different successional stages in the study site. (A) cropland control; (B) pioneer weeds; (C) herbage; (D) shrub; (E) early forest; and (F) climax forest.

Table 1
Summary of features of soil, topography and vegetation in different successional stages in the study site.

Site	S0	S1	S2		S3		S4		S5
Successional stage	Cropland	Pioneer weeds	Herbage		Shrub		Early forest		Climax forest
Coordinate	N 36°4′26.9″ E 108°28′5.4″	N 36°05′19.2″ E 108°31′36.4″	N 36°04′52.3″ E 108°31′50.1″	N 36°04′53.4″ E 108°31′49.1″	N 36°05′03.2″ E 08°31′52.6″	N 36°05′28.2″ E 108°31′40.9″	N 36°02′55.3″ E 08°31′45.1″	N 36°02′58.4″ E 08°31′36.5″	N 36°03′00.9″ E 108°31′33.4″
Elevation (m)	1482	1410	1347	1306	1329	1414	1447	1420	1431
Aspect (°)	NW80	NW67	SW75	SW75	SW68	NW53	NW40	NW15	NW35
Slope (°)	14	14	13	15	27	13	13	10	12
Coverage (%)	0	70	91	95	80	85	90	93	95
Age of stages (yr)	0	6	16	24	45	30	100	100	150
Dominant plant species		*Lespedeza bicolorr*	*Artemmisia sacronum*	*Bothriochloa ioaischemum*	*Sophora vicitifolia, Stipa bungeana*	*Hippophae rhamnoides, Stipa bungeana*	*Populus davidiana, Spiraea pubescens, Carex lanceolata*	*Betula platyphylla, Viburnum mongolicum, Carex lanceolata*	*Quercus liaotungensis, Rosa hugonis, Carex lanceolata*
Clay (%, <0.002 mm)	6.2	8.7	14.0	13.2	12.9	13.5	14.3	14.7	15.6
Silt (%, 0.002–0.05 mm)	65.8	69.1	70.0	71.5	72.2	73.0	73.6	73.1	72.7
Sand (%, >0.05 mm)	28.1	22.2	16.0	15.3	14.9	13.5	12.0	12.2	11.7
Total N (g kg^{-1})	0.58	0.67	0.77	0.75	0.82	0.85	0.90	0.89	0.93
Available P (mg kg^{-1})	5.21	4.76	3.78	3.64	3.59	3.72	3.44	3.93	4.02
$CaCO_3$ (%)	12.5	12.1	11.8	11.6	11.3	11.4	10.4	10.9	10.7

The major soil physical and chemical properties of each successional stage are presented in Table 1.

2.3. Soil analysis and data calculation

TOC was determined by the dichromate wet oxidation method (Nelson and Sommers, 1982), LOC was determined following the method of Blair et al. (1995) and Vieira et al. (2007): Air-dried soil samples containing ~15 mg C were weighed into 100-ml centrifuge tubes and 25 ml of 333 mM $KMnO_4$ was added into each vial. The centrifuge tubes were shaken for 1 h and then centrifuged for 5 min at 2000 rpm. The supernatants were diluted 1:250 with deionized water. The absorbance values of diluted samples and the standards at 565 nm were measured using a UV-visible spectrophotometer (Model UV-1240, Shimadzu Corp., Kyoto, Japan). The change in $KMnO_4$ concentration was used to estimate the amount of SOC oxidized, *e.g.*, LOC. The concentration of NLOC (SOC fraction not oxidized by 333 mM $KMnO_4$) was calculated from the difference between TOC and LOC concentrations. Soil cores were oven-dried at 105 °C for 48 h and BD was calculated through dividing the weight of dried soil by the volume of core (Veihmeyer and Hendrickson, 1948).

SOC (TOC, LOC, and NLOC) concentrations for a given soil depth were calculated as the weighted mean of the individual depth. The corresponding SOC stocks (C_T, C_L, and C_{NL}) were calculated as the sum of the individual depth using the following equation:

$$C_s = C_c \times BD \times D \times (1 - F_{2mm}) \times 10^{-1} \quad (1)$$

where C_s is SOC stock (Mg ha^{-1}); C_c is SOC concentration (g kg^{-1}); BD is bulk density (g cm^{-1}); D is soil layer thickness (cm); and F_{2mm} is the proportion of >2 mm coarse fraction. In the study area, coarse particles rarely occur in the loessial soil (Liu et al., 2011). Thus, F_{2mm} was considered negligible. The ratio of C_L to C_{NL} (C_L/C_{NL}) was calculated.

SOC sequestration potential (ΔC_s, Mg ha^{-1}) was calculated for each successional stage by setting the C_s of S0 as the baseline. SOC sequestration rate (R_s, Mg ha^{-1} yr^{-1}) was estimated depending on the changes in ΔC_s with successional stage.

2.4. Statistical analysis

Statistical analysis was performed using SPSS 17.0 (SPSS Inc., Chicago, IL, USA). Two-way ANOVA was performed to examine the differences in SOC concentrations with successional stage and soil depth as two fixed factors. One-way ANOVA was used to examine the effect of successional stage on soil BD. Multiple comparisons of the means were performed using the least significant difference test. $P < 0.05$ was considered statistically significant.

3. Results

3.1. SOC concentrations

For different successional stages, there were significant differences in LOC concentration at 0–70 cm depths and NLOC concentration at 0–40 cm depths (Table 2). Across the 100-cm soil profile, the averages of LOC and NLOC concentrations accounted for 11.2–35.3% and 64.7–88.8% of TOC concentration, respectively. These SOC concentrations gradually increased with successional stage and showed significant differences before S3 (<50 yr). The SOC concentrations tended to level off at late successional stages, although LOC concentration significantly differed between S2 and S5. There were similar changes in TOC concentration as compared with NLOC concentration. S5 had the highest LOC (8.9 g kg^{-1}) and NLOC (17.8 g kg^{-1}) concentrations at 0–5 cm depth among all the successional stages.

At each successional stage, SOC concentrations significantly differed among soil depths and tended to decrease with depth (Table 2). The highest concentrations occurred at 0–5 cm depth,

Table 2
Distribution of soil organic carbon (total, TOC; labile, LOC; non-labile, NLOC) fractions in the 100-cm soil profile of different successional stages.

Soil depth (cm)	S0	S1	S2	S3	S4	S5
TOC concentration (g kg^{-1})						
0–5	10.7 ± 1.2 aB	11.8 ± 1.0 aB	23.7 ± 2.3 aA	24.3 ± 1.3 aA	25.5 ± 1.2 aA	26.8 ± 1.1 aA
5–10	10.2 ± 0.9 aB	10.3 ± 0.5 aB	14.4 ± 0.7 bA	14.9 ± 0.9 bA	16.0 ± 0.8 bA	15.3 ± 1.2 bA
10–20	4.5 ± 0.8 bC	5.4 ± 1.1 bC	8.2 ± 0.3 cB	8.2 ± 0.5 cB	9.7 ± 0.7 cA	9.5 ± 0.8 cA
20–40	2.5 ± 0.2 bC	3.1 ± 0.1 bcC	4.1 ± 0.2 dB	4.3 ± 0.4 dAB	4.5 ± 0.5 dA	5.0 ± 0.8 dA
40–70	2.6 ± 0.3 b	2.7 ± 0.5 c	2.8 ± 0.1 e	2.9 ± 0.1 e	3.3 ± 0.2 e	3.3 ± 0.4 e
70–100	2.5 ± 0.3 b	2.6 ± 0.2 c	2.8 ± 0.1 e	2.9 ± 0.1 e	2.9 ± 0.1 e	2.9 ± 0.1 e
LOC concentration (g kg^{-1})						
0–5	3.8 ± 0.1 aC	4.0 ± 0.1 aC	7.9 ± 0.2 aB	8.0 ± 0.5 aB	8.3 ± 0.1 aAB	8.9 ± 0.6 aA
5–10	3.3 ± 0.1 bB	3.3 ± 0.1 bB	4.7 ± 0.5 bA	4.8 ± 0.3 bA	5.0 ± 0.2 bA	5.1 ± 0.1 bA
10–20	1.4 ± 0.0 cC	1.7 ± 0.1 cC	2.5 ± 0.5 cB	2.5 ± 0.1 cB	2.9 ± 0.1 cAB	3.0 ± 0.1 cA
20–40	0.6 ± 0.1 dD	0.7 ± 0.0 dC	0.9 ± 0.1 dB	1.0 ± 0.1 dAB	1.0 ± 0.1 dAB	1.1 ± 0.1 dA
40–70	0.4 ± 0.0 dC	0.4 ± 0.0 dC	0.5 ± 0.0 eB	0.5 ± 0.0 eAB	0.5 ± 0.0 eAB	0.5 ± 0.0 eA
70–100	0.3 ± 0.0 d	0.3 ± 0.0 d	0.3 ± 0.0 e	0.3 ± 0.0 e	0.3 ± 0.1 e	0.3 ± 0.1 f
NLOC concentration (g kg^{-1})						
0–5	6.9 ± 1.1 aB	7.8 ± 1.1 aB	15.8 ± 2.2 aA	16.3 ± 1.3 aA	17.2 ± 1.1 aA	17.8 ± 1.2 aA
5–10	6.9 ± 0.9 aB	7.0 ± 0.6 aB	9.8 ± 0.5 bA	10.1 ± 1.0 bA	11.0 ± 0.9 bA	10.2 ± 1.2 bA
10–20	3.1 ± 0.8 bC	3.7 ± 1.0 bC	5.7 ± 0.2 cB	5.7 ± 0.5 cB	6.8 ± 0.7 cA	6.5 ± 0.8 cA
20–40	1.9 ± 0.2 bC	2.4 ± 0.1 bC	3.2 ± 0.2 cdB	3.3 ± 0.3 dAB	3.4 ± 0.5 dA	3.9 ± 0.8 dA
40–70	2.2 ± 0.1 b	2.3 ± 0.5 b	2.3 ± 0.1 d	2.4 ± 0.1 d	2.8 ± 0.2 d	2.8 ± 0.4 e
70–100	2.3 ± 0.1 b	2.3 ± 0.2 b	2.5 ± 0.1 d	2.6 ± 0.1 d	2.6 ± 0.1 d	2.6 ± 0.1 e

Data are presented as mean ± standard error ($n = 3$).
For the same successional stage and SOC fraction, different lower letters indicate significant differences among soil depths at $P < 0.05$. For the same soil depth and SOC fraction, different capital letters indicate significant differences among successional stages at $P < 0.05$.

while the greatest decreases appeared at 10–20 cm depth (Table 2). However, vegetation succession tended to significantly affect SOC concentrations at deeper depths. Specifically, TOC and NLOC concentrations varied from 0–10 cm depths of S0 to 0–40 cm depths of S5, while LOC concentration changed from 0–20 cm depths of S0 and S1 to 0–70 cm depths of S5. Compared with TOC and NLOC concentrations, LOC concentration showed higher sensitivity to both successional stage and soil depth.

3.2. Bulk density

Vegetation succession significantly influenced soil BD at 0–20 cm depths, other than at deeper depths (Fig. 2). Temporally, BD gradually decreased with successional stage and the lowest value occurred at 0–5 cm depth of S4 (0.75 g cm^{-3}). At each successional stage, BD generally increased from upper to lower depths. The BD values at 20–100 cm depths were ~1.25 g cm^{-3} across successional stages.

3.3. SOC stocks

At 0–40 depths, C_T significantly changed with successional stage ($P > 0.05$). It significantly increased before the S3 stage and then changed slightly thereafter (Fig. 3). The S5 stage (64.3 Mg ha^{-1}) had the highest C_T for the whole soil profile, followed by S2 (64.0 Mg ha^{-1}), S3 (62.5 Mg ha^{-1}), S4 (62.4 Mg ha^{-1}), and S1 (48.8 Mg ha^{-1}) stages; S0 (39.9 Mg ha^{-1}) came the last. Surface (0–20 cm) soil C_T contributed to 37.0%, 41.1%, 50.6%, 49.2%, 45.5%, and 45.5% of the whole-profile C_T for S0, S1, S2, S3, S4, and S5, respectively. Subsurface (20–100 cm) soil C_T gradually increased along with vegetation succession, ranging from 25.1 to 35.0 Mg ha^{-1}.

For the whole soil profile, C_L and C_{NL} accounted for 22.2–24.5% and 75.7–77.8% of C_T, respectively. The absolute increase of C_{NL} was greater than that of C_L along with vegetation succession. The C_L/C_{NL} ratio remained stable across successional stages but substantially decreased from 0.50 to 0.13 with depth (Table 3). At each successional stage, the C_L/C_{NL} values were similar at 0–20 cm depths, 3-fold greater than those at lower depths.

3.4. SOC sequestration potential

The whole-profile ΔC_s relative to S0 was 8.8, 24.1, 22.6, 22.5, and 24.4 Mg ha^{-1} for S1, S2, S3, S4, and S5, respectively (Table 4). There was a substantial improvement of ΔC_s in the soil profile at early successional stages (before S3). The mean ΔC_s across successional stages was

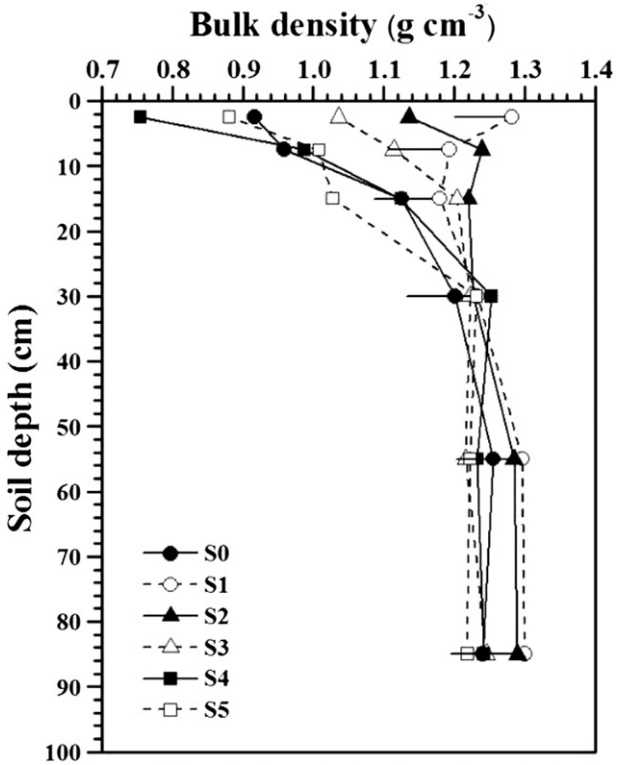

Fig. 2. Distribution of bulk density in the 100-cm soil profile of different successional stages. S0, cropland control; S1, pioneer weeds; S2, herbage; S3, shrub; S4, early forest; and S5, climax forest. Error bars represent the least significant difference value at $P < 0.05$.

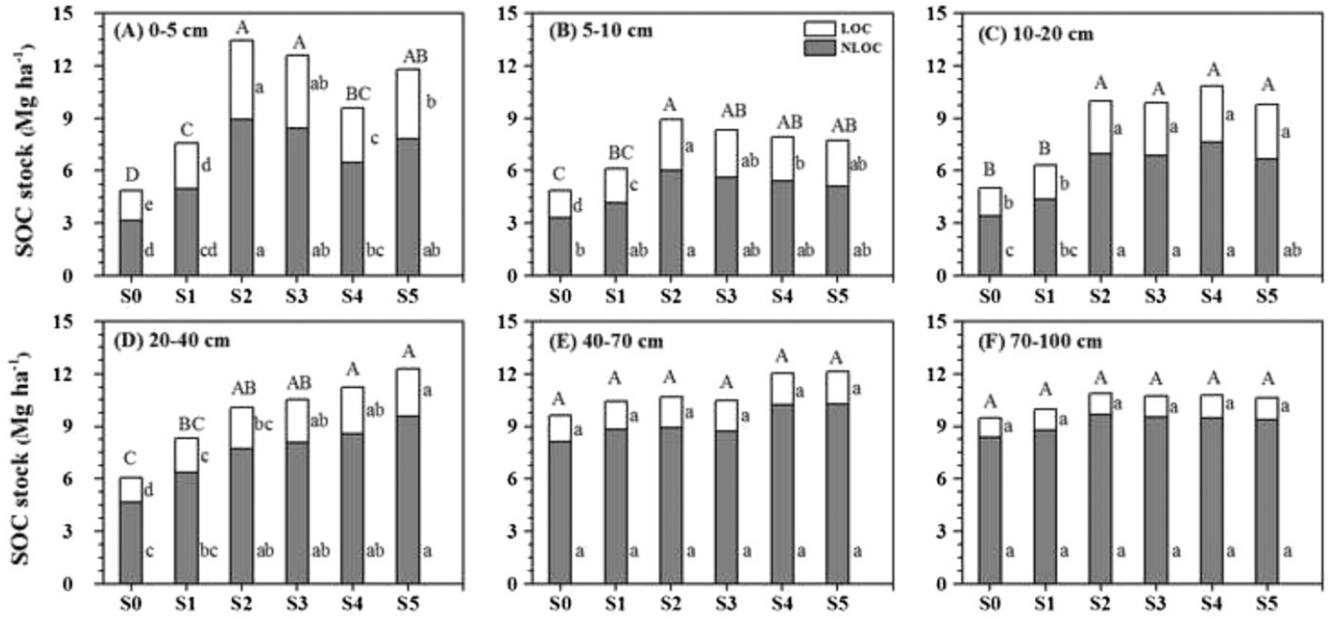

Fig. 3. Distribution of soil organic carbon (SOC: labile, LOC; non-labile, NLOC) stocks in the 100-cm soil profile of different successional stages. S0, cropland control; S1, pioneer weeds; S2, herbage; S3, shrub; S4, early forest; and S5, climax forest. For the same soil depth, different lower letters (LOC or NLOC) and upper letters (total SOC) indicate significant differences among successional stages at $P < 0.05$.

~64.7% and 35.3% in the surface 0–20 cm and subsurface 20–100 cm layers, respectively. Despite its decreasing trend with depth, the ΔC_s gradually increased with vegetation succession at 20–70 cm depths. From S2 to S5, surface (0–20 cm) soil ΔC_s decreased by 3.1 Mg ha^{-1}, while subsurface (20–100 cm) soil ΔC_s increased by 3.4 Mg ha^{-1}.

Along the 150-yr chronosequence, the mean R_s for the whole soil profile was 0.73 Mg ha^{-1} yr^{-1} (Table 4). At individual successional stages, the whole-profile R_s was 1.47, 1.20, 0.60, 0.22, and 0.16 Mg ha^{-1} yr^{-1} for S1, S2, S3, S4, and S5, respectively. Clearly, higher R_s occurred in grasslands such as S1 and S2.

4. Discussion

This study showed that long-term vegetation succession on the Loess Plateau positively increased TOC, LOC, and NLOC concentrations in the 100-cm soil profile. These SOC concentrations substantially increased at early successional stages (before S3, <50 yr), then tended to level off (Table 2, Fig. 2). This observation is consistent with previous findings (Deng et al., 2013; Schedlbauer and Kavanagh, 2008). Vegetation biomass resulting from aboveground leaf litter and belowground roots is the main source of organic matter input into the soil, which can change with vegetation type (Laganiere et al., 2010). In the study area, the higher root mass density and turnover of surface grassland soils may explain their higher SOC accumulation within a short restoration time, as compared to shrub and forest soils (Rasse et al., 2005). In the subsurface soil layers, the changes in SOC concentrations can be attributed to different root architectures and exudates among successional stages and leaching of dissolved organic matter (Rumpel and Kögel-Knabner, 2011). The lower SOC concentrations of S0 under conventional tillage may be due to C loss resulting from soil erosion, higher organic matter decomposition associated with aggregate disruption, and/or C input reduction caused by continuous removal of crop residues (Blanco-Canqui and Lal, 2004; Debasish-Saha et al., 2014).

Vegetation succession had no significant effects on soil BD below 20 cm depth (Fig. 2), indicating that SOC stocks in deeper soil layer were mainly determined by SOC concentration in the study area. Across successional stages, surface (0–20 cm) and subsurface (20–100 cm) soil C_T contributed to ~44.8% and 55.2% of whole-profile C_T, respectively (Fig. 3). Similarly, a previous study reported that the amount of SOC stored at 0–20 cm depth accounted for 33%, 42%, and 50% of whole-profile SOC (0–100 cm) for shrub, grassland, and forest, respectively (Jobbágy and Jackson, 2000). However, subsurface C_T gradually increased with successional stage, varying from 25.1 to 35.0 Mg ha^{-1} (Fig. 3). Root biomass profiles generally descend in the order of grasses, trees, and shrubs (Jackson et al., 1996). The decreasing trend of C_T with successional stage may be related to the root biomass increase in the subsurface soil layers, which potentially governs the vertical distribution of SOC (Jobbágy and Jackson, 2000).

The LOC and NLOC fractions separated by their resistance to $KMnO_4$ oxidation showed increasing trends with successional stage, the same as TOC (Fig. 2, Table 2). The C_L and C_{NL} increased simultaneously at each depth interval (Fig. 3, Table 3), while LOC displayed higher sensitivity than NLOC and TOC to both successional stage and soil depth (Table 2). The increases in LOC and NLOC fractions may be related to organic C input from plant litter and roots, respectively (Sierra et al., 2013). The contents of lignin and other recalcitrant compounds (*e.g.*, tannins) (Kraus

Table 3
Distribution of the ratio of C_L (labile organic carbon stock) to C_{NL} (non-labile organic carbon stock) (C_L/C_{NL}) in the 100-cm soil profile of different successional stages.

Soil depth (cm)	S0	S1	S2	S3	S4	S5
0 − 5	0.55 ± 0.11 a	0.52 ± 0.09 a	0.50 ± 0.10 a	0.49 ± 0.04 a	0.48 ± 0.03 a	0.50 ± 0.05 a
5 − 10	0.47 ± 0.07 a	0.48 ± 0.05 a	0.48 ± 0.04 a	0.47 ± 0.06 a	0.45 ± 0.05 a	0.50 ± 0.07 a
10 − 20	0.46 ± 0.11 a	0.45 ± 0.11 a	0.43 ± 0.04 a	0.44 ± 0.03 a	0.42 ± 0.04 a	0.47 ± 0.06 a
20 − 40	0.30 ± 0.04 b	0.30 ± 0.03 b	0.30 ± 0.02 b	0.31 ± 0.01 b	0.31 ± 0.04 b	0.29 ± 0.06 b
40 − 70	0.18 ± 0.01 bc	0.18 ± 0.04 bc	0.20 ± 0.02 bc	0.20 ± 0.02 bc	0.18 ± 0.02 bc	0.18 ± 0.02 bc
70 − 100	0.13 ± 0.01 c	0.14 ± 0.02 c	0.13 ± 0.01 c	0.13 ± 0.01 c	0.13 ± 0.02 c	0.14 ± 0.03 c

Data are presented as mean ± standard error.
For the same successional stage, different lower letters indicate significant differences among soil depths at $P < 0.05$.

Table 4
Soil organic carbon sequestration potential (ΔC_s, Mg ha^{-1}) and rate (R_s, Mg ha^{-1} yr^{-1}) in the 100-cm soil profile of different successional stages.

Soil depth (cm)	S1		S2		S3		S4		S5	
	ΔC_s	R_s	ΔC_s	R_s	ΔC_s	R_s	ΔC_s	R_s	ΔC_s	R_s
0 − 5	2.7	0.45	8.6	0.43	7.7	0.20	4.7	0.05	6.9	0.05
5 − 10	1.3	0.21	4.1	0.20	3.4	0.09	3.0	0.03	2.8	0.02
10 − 20	1.3	0.22	5.0	0.25	4.9	0.13	5.8	0.06	4.8	0.03
20 − 40	2.3	0.38	4.0	0.20	4.5	0.12	5.1	0.05	6.2	0.04
40 − 70	0.8	0.14	1.1	0.05	0.9	0.02	2.4	0.02	2.5	0.02
70 − 100	0.5	0.08	1.4	0.07	1.3	0.03	1.3	0.01	1.1	0.01
0 − 20	5.3	0.88	17.6	0.88	16.0	0.43	13.6	0.14	14.5	0.10
20 − 100	3.6	0.59	6.5	0.32	6.6	0.18	8.9	0.09	9.9	0.07
0 − 100	8.8	1.47	24.1	1.20	22.6	0.60	22.5	0.22	24.4	0.16

et al., 2003) are generally higher in plant roots than in leaf litter, which contribute to the chemical recalcitrance of SOC (Sierra et al., 2013). In the soil profile, plant litter and root biomass generally increase with successional stage, thereby increasing SOC input and subsequently promoting LOC and NLOC accumulation.

The mean R_s for the whole soil profile was estimated to be 1.34 Mg ha^{-1} yr^{-1} over a 20-yr period. This value is comparable to the SOC accumulation rate reported by Silver et al. (2000), *i.e.*, 1.30 Mg ha^{-1} yr^{-1} during the first 20 yr of tropical reforestation. Although surface (0–20 cm) soil ΔC_s was higher, subsurface (20–100 cm) soil ΔC_s gradually increased from S2 to S5 (Table 4). Vegetation restoration probably has contributed to the formation of stable soil aggregates (An et al., 2010; Li and Shao, 2006), thus facilitating physical protection of SOC within aggregates (Blanco-Canqui and Lal, 2004). Moreover, SOC in the deeper profile is protected from the accelerated decomposition by the lower oxygen diffusion rate (Fontaine et al., 2007). Collectively, these results suggested that the SOC stock in deeper soil layer (below 20 cm depth) of long-term vegetation restoration (>50 yr) played a positive role in SOC sequestration on the Loess Plateau.

5. Conclusions

Total, labile, and non-labile SOC concentrations decreased with depth in a 100-cm soil profile on the Loess Plateau. These SOC concentrations gradually increased with successional stage along a 150-yr secondary forest chronosequence, especially before the shrub stage. Long-term vegetation succession increased the labile and non-labile SOC stocks at different depths, with the majority stored in surface soils (0–20 cm). Although SOC sequestration potential was higher in the surface soil layer, it increased from herbage to climax forest stage in the subsurface soil layers. This study emphasizes the importance of SOC sequestration in the root-zone soil profile under vegetation restoration. The results indicate that long-term restoration of natural vegetation plays a positive role in SOC sequestration and soil C sink in the study region. The information provided will benefit the evaluation of SOC storage in relation to vegetation restoration at regional or national scales.

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