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Changes of soil carbon in five land use stages following 10 years of vegetation succession on the Loess Plateau, China

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ABSTRACT

Changes in land use caused by natural vegetation succession can enhance the soil organic carbon (SOC) and carbon (C) stock of terrestrial ecosystems, as reported in many studies throughout the world. However, the dynamics of SOC and soil C stocks and their changes in each succession stage are not clearly following restoration age. Additionally, whether litter and fine roots have positive effects on SOC and soil C sequestration is unclear. We simultaneously studied litter and fine root production and SOC and C stocks along a natural vegetation succession – abandoned farmland, grassland, shrubland, pioneer woodland to natural climax forest – in 2005 and 2015 on the Loess Plateau of China. This allowed a better understanding of the variations of SOC and soil C stock in different land use stages in relation to soil layers and effects of litter and fine roots following vegetation restoration. The land use stages and soil layers significantly affected the rates of SOC and soil C sequestration change. The SOC and soil C stocks in the 0–60 cm soil profile rapidly increased over the course of the long-term natural vegetation succession. During 2005 to 2015, the topsoils (0–20 and 20–40 cm) had higher rates of SOC change (from 0.06 to 0.55 and from 0.23 to 0.51 $g\ kg^{-1}\ yr^{-1}$, respectively) and soil C sequestration rates (from 0.37 to 1.09 and from 0.40 to 1.16 $Mg\ ha^{-1}\ yr^{-1}$, respectively) than subsoils (40–60 cm, from 0.04 to 0.36 and from 0.05 to 1.16 $Mg\ ha^{-1}\ yr^{-1}$). The litter and fine root production increased with age of the natural vegetation succession, and had significant positive effects on changes in SOC and soil C sequestration. Therefore, long-term natural vegetation restoration improved the SOC accumulation, and increased litter and fine root inputs were probably the main factors contributing to soil C sequestration.

1. Introduction

Soil organic carbon (SOC) as a key component of the global carbon (C) cycle and its potential as a sink for atmosphere carbon dioxide (CO_2) on a global scale has been widely discussed in the scientific literature (DeGryze et al. 2004; IPCC, 2007; Stockmann et al. 2013; Deng and Shangguan 2017). It has long been recognized that land use/cover change and management can alter the amount of organic C stored in the soil (Van der Werf et al. 2009; Laganière et al. 2010; Deng et al. 2017; Kalinina et al., 2015a, b) and this in turn affects both soil fertility and atmospheric CO_2 concentration (Powers et al. 2011; Deng et al. 2017). Many studies around the world have reported that the SOC content declines by 20%–43% after natural forest or perennial grassland is converted to agricultural land (Guo and Gifford 2002; Don et al. 2011). In contrast, vegetation restoration through conversion of farmland into grassland or forest has been shown to increase SOC by increasing C derived from new vegetation (Laganière et al. 2010; Deng et al. 2016). Therefore, vegetation restoration (e.g. afforestation, natural restoration and grass planting) have been proposed as effective methods for reducing atmospheric CO_2 due to C sequestration in soils (UNFCCC, 2009; IPCC, 2007; Deng et al. 2017).

Many recent studies have examined the dynamics of SOC and soil C stocks following vegetation restoration (Laganière et al. 2010; Aryal et al. 2014; Wang et al. 2016; Karelin et al. 2017), but have obtained varied results. For example, Sean et al. (2012) illustrated that changes in SOC with afforestation were positively correlated with plantation age and Nave et al. (2012) demonstrated that afforestation had significant positive effects on SOC sequestration in the USA, although these effects require decades to manifest and primarily occur in the uppermost (and perhaps most vulnerable) portion of the mineral soil profile. However, Smal and Olszewska (2008) documented that soil C stock significantly decreased in Scots pine (*Pinus silvestris* L.) forests in sandy post-arable

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soils. In addition, many studies reported that soil C stock initially declined and then increased following farmland conversion into forestland (Kalinina et al. 2009, 2013). The soil C dynamic pattern remains unclear because different land-use conversion types and soil depths have been combined, with large differences in depths and land-use conversion types in temporal C stock changes (Deng et al. 2016). Thus, our understanding of soil C dynamics for different soil depths and land-use conversion types remains incomplete.

The Loess Plateau in China is well known for the most severe soil erosion in the world (Fu 1989). Vegetation degradation and exponential population growth have caused massive amounts of soil and water to be lost (Liu et al. 2007). To control soil erosion and restore ecosystems, China has launched the "Grain for Green" Program, aimed at restoring degraded farmland to forest and grassland (Deng et al. 2017). In the study area, farmland had already been abandoned, and processes of natural and artificial restoration were underway (Deng et al. 2013, 2016; Cheng et al. 2015). Previous studies reported that natural vegetation restoration can recover the properties of degraded soil and maintain soil fertility (Feldpausch et al. 2004). For this reason, understanding natural vegetation restoration processes on the Loess Plateau is becoming increasingly important. Deng et al. (2013) studied SOC and soil C stock dynamics along with the natural vegetation succession from abandoned farmland to natural climax forest in the Ziwuling Forest Region of the Loess Plateau, and found that SOC and soil C stocks in the 0–60 cm soil profile rapidly increased in long-term (~150 years) natural vegetation succession. However, dynamics of SOC and soil C stock and their change rates in every land use stage were not clear following restoration age. In addition, although we know that land use and vegetation development stages affects SOC and C stock, the difference in the dynamics of SOC and C stocks in each of these stages are not clear. It also remains unclear whether changes in input from litter and fine roots have a positive effect on SOC and soil C sequestration.

Therefore, this study used two times of a field survey on five land use stages: abandoned farmland (AF), grassland (GL), shrubland (SL), pioneer woodland (WL) and natural climax forest (NF) in 2005 and 2015 in the Ziwuling Forest Region of the Loess Plateau. The objectives were to: (i) explore the variations of SOC and soil C stock for different land use stages and soil layers; (ii) quantify the contributions of relevant factors (land use stage, soil layer and age) to variations in SOC and soil C stock; and (iii) examine the effects of litter and fine roots on SOC and soil C sequestration.

2. Materials and methods

2.1. Study area

The study was conducted at Lianjiabian Forest Farm in Heshui County of Gansu Province (33°50′–36°50 N′, 107°30′–109°40′E and 1100–1756 m a.s.l.), in the Ziwuling Mountain region in the central south of the Loess Plateau (Fig. 1). The Ziwuling Mountain region covers an area of 23,000 km^2, with a warm-temperate and sub-humid continental monsoon climate. The annual mean temperature is 10 °C and the mean annual rainfall is 587 mm (1960–2010). The soil humid is about 12%–14%. The study area has landforms typical of loess hilly topography with altitude range of 1300–1700 m. Loessial soil (*Calcic Cambisols*) is the main soil type, developed from primary or secondary loess parent materials, which are evenly distributed 50–130 m deep and present on top of a red earth consisting of calcareous cinnamon soil. The area has a warm temperate deciduous broad-leaved forest biome. The natural vegetation is deciduous broadleaf forest of which the climax vegetation is *Quercus liaotungensis* Koidz forest. In the region, *Populus davidiana* Dode communities dominate pioneer forests, *Hippophae rhamnoides* (Linn.) is the main shrub species, and *Bothriochloa ischaemun* (Linn.) Keng and *Lespedeza davurica* (Laxm.) Schindl. are the main herbaceous species. Previous research in the study area showed that secondary forests naturally regenerated on AF from GL, SL and WL to NF (*Q. liaotungensis*) over the past 150–160 years (Deng et al. 2013; Wang et al. 2016). AF has usually been abandoned for about 5 years in the study area.

2.2. Experiment design and sampling

The first field survey was undertaken between 15 July and 15 August 2005, and the second survey between 15 July and 15 August 2015 using the same sampling sites as 2005. The sampling areas of the communities involved were determined according to their sizes. There were five 20 m × 20 m plots chosen in WL and NF communities, five 5 m × 5 m plots in SL communities, and five 2 m × 2 m plots in the herbaceous communities (i.e. AF and GL). The plots were not > 5 km apart and their largest relative elevation difference was < 120 m. Most plots had a slope gradient below 20° and faced north. All surveyed soils developed from the same parent materials and had vegetation for differing numbers of years. To minimize the effects of site conditions on experimental results, all selected sites had a similar slope aspect, slope gradient, elevation, soil type and land use history. The basic information of the sites is shown in Table 1.

Soil samples were taken at five points lying at the four corners and center of the soil sampling sites described above. Soil drilling samplers were used to sample soil in three soil layers: 0–20, 20–40 and 40–60 cm. In each plot, ground litter and fine roots were removed and then soils were sampled at the five points and mixed according to soil layers to form one soil sample. All soil samples were air-dried and sieved through a 2 mm screen, and prepared for SOC analysis. Bulk density (BD) of the soil at sampling sites was measured in the different soil layers using a soil bulk sampler of 5 cm diameter and 5 cm high stainless-steel cutting ring (three replicates) at points adjacent to the soil sampling quadrats by measuring the original volume of each soil core and the dry mass after oven-drying at 105 °C. In addition, before sampling soil, five 1 m × 1 m quadrats were set in the five soil sampling points of SL, WL and NF sites, and five 0.5 m × 0.5 m quadrats set in the five soil sampling points of AF and GL sites. We collected all ground litter in quadrats to measure litter biomass in the five land use stages.

To measure fine root biomass, root sampling was performed with three replicates in three soil layers of 0–20, 20–40 and 40–60 cm in each quadrat using a 9 cm diameter root auger. The majority of the roots found in the soil samples thus obtained were then isolated using a 2 mm sieve. The remaining fine roots taken from the soil samples were isolated by spreading the samples in shallow trays, overfilling the trays with water and allowing the outflow from the trays to pass through a 0.5 mm sieve. No attempts were made to distinguish between living and dead roots. All roots thus isolated were oven-dried at 65 °C and weighed to within 0.01 g.

2.3. Laboratory assays

Soil BD was calculated depending on the inner diameter of the core sampler, sampling depth and oven-dried weight of the composite soil samples (Deng et al. 2013; Fig. 2). SOC was assayed using dichromate oxidation (Kalembasa and Jenkinson 1973).

2.4. Soil C stock calculation

In our sample soils, there was no coarse fraction (i.e. > 2 mm) and so we did not need to insert "1 – coarse fragment (%)" in formulae. The following equation was used to calculate SOC stock (Guo and Gifford 2002):

$$Cs = \frac{BD \times SOC \times D}{10} \quad (1)$$

in which, Cs is SOC stock in Mg ha^{-1}, BD is in g cm^{-3}, SOC is in g kg^{-1} and D is soil thickness in cm.

Changes in SOC and C sequestrations were estimated based on

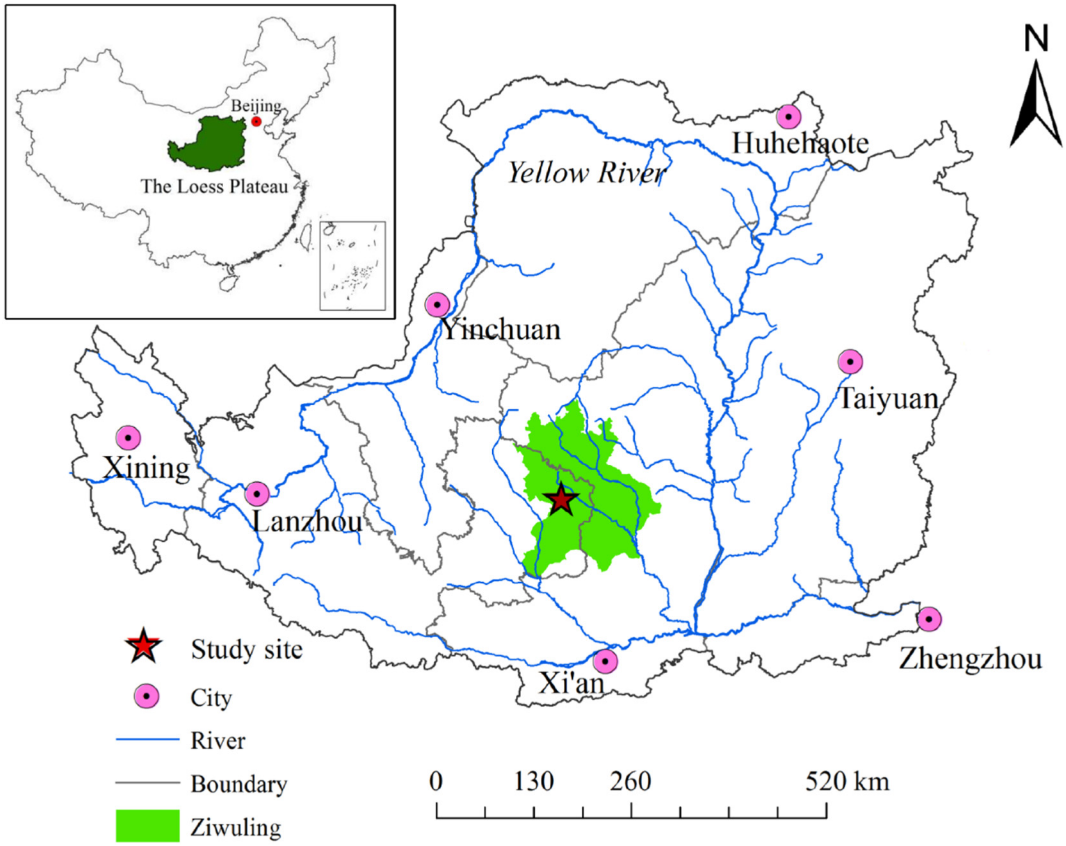

Fig. 1. Location of the Lianjiabian Forest Farm. The shaded area in the upper left corner of the map is the Loess Plateau of China, and the shaded area in the main map is the Ziwuling Mountains on the Loess Plateau.

Table 1
Geographical and vegetation characteristics in five land use types in the Ziwuling Forest Region of the Loess Plateau, China.

Land use stages	Latitude (N)	Longitude (E)	Altitute (m)	Aspect (°)	Slope (°)	Coverage (%)	Soil moisture[a] (%)	Main plant species
AF	36°05′05.4″	108°31′57.4″	1357	NE70	15–20	65–70	6–12	*Lespedeza bicolorr*
GL	36°05′19.6″	108°31′36.5″	1416	NE65	15–20	80–85	6–14	*B. ischaemum*
SL	36°05′06,3″	108°31′54.8″	1343	NE65	15–25	85–90	9–11	*H. rhamnoides*
WL	36°02′54.6″	108°31′44.6″	1445	NE45	15–20	85–90	10–12	*P. davidiana,*
NF	36°03′15.6″	108°32′29.7″	1427	NW35	15–25	90–95	10–12	*Q. liaotungensis*

Note: AF, Abandoned farmland; GL, Grassland; SL, Shrub land; WL, Woodland; NF, Natural climax forest.
Soil moisture was measured gravimetrically and expressed as a percentage of soil water to dry soil weight.
[a] Indicates 0–60 cm soil moisture.

changes in C stocks at different times following farmland conversion. We set the C stocks in 2005 as the baseline for calculating changes in SOC and C sequestration after 10 years from 2005 to 2015. We used the following formulae to calculate the changes in SOC and C sequestration:

Changes in SOC (g kg^{-1}):

$$\Delta SOC = SOC_{2015} - SOC_{2005} \quad (2)$$

or C sequestration (Mg ha^{-1}):

$$\Delta C_s = C_{2015} - C_{2005} \quad (3)$$

in which, SOC_{2005} and SOC_{2015} represent SOC in 2005 and 2015 (g kg^{-1}), respectively; and C_{2005} represents soil C stock in 2005 (Mg ha^{-1}) and C_{2015} represents soil C stock in 2015 (Mg ha^{-1}).

We used the mean rate of change in SOC and C stock to indicate the rate of SOC change and C sequestration rate after the 10 years of 2005–2015. The calculated equations are as follows:

$$\text{Rate of SOC change (g kg}^{-1}\text{ yr}^{-1}) = \text{SOC}_{2015} - \text{SOC}_{2005}/\Delta\text{Age} \quad (4)$$

$$\text{C sequestration rate (Mg ha}^{-1}\text{ yr}^{-1}) = \text{C}_{2015} - \text{C}_{2005}/\Delta\text{Age} \quad (5)$$

in which, $SOC_{2015} - SOC_{2005}$ is the change in SOC during 2005–2015 (g kg^{-1}), $C_{2015} - C_{2005}$ is C sequestration during 2005–2015 (Mg ha^{-1}) and ΔAge = 10 years.

2.5. Statistical analysis

ANOVA was conducted to evaluate whether the SOC, soil C stock, the rates of SOC change and soil C sequestration rate, as well as fine roots and litter significantly differed in different soil layers and land use stages. There were *t*-tests conducted to evaluate whether restoration age significantly increased SOC and soil C stocks in different soil layers. Differences were evaluated at $P < 0.05$ level. When the test for homogeneity of variance was passed and significance was observed at $P < 0.05$, a least significant difference (LSD) test was used for multiple comparisons. Regression analysis was used to determine the relationship between changes in SOC, soil C sequestration and the changes in litter and fine roots. In addition, a general linear model (GLM) model

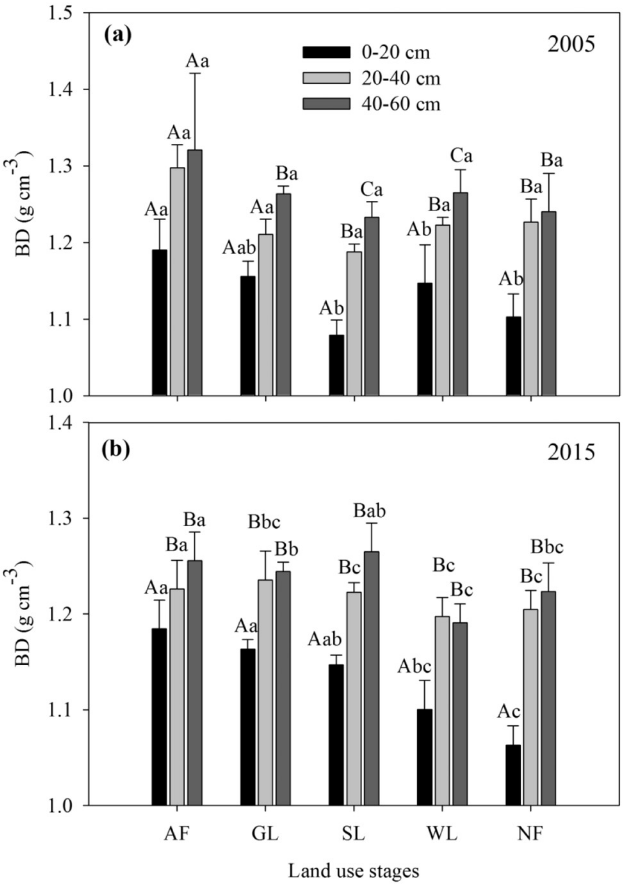

Fig. 2. Soil bulk density (BD) for five land use types accompanying vegetation restoration during 2005–2015. Note: Different uppercase and lowercase letters indicate significant differences among soil layers and among land use stages, respectively ($P < 0.05$); The values are mean + SE (error bar), n = 5. AF, Abandoned farmland; GL, Grassland; SL, Shrub land; WL, Woodland; NF, Natural climax forest.

was used to quantify the contributions of relevant factors (land use stage, soil layer and age) to the variations in SOC and soil C stock. All statistical analyses were performed using the software program SPSS, ver. 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Variation of SOC in five land use stages

Land use stages, soil layers and restoration age significantly affected SOC ($P < 0.05$). In 2005, from AF to NF, the SOC in 0–20, 20–40 and 40–60 cm layers increased: from 13.54 to 22.86, from 6.41 to 18.54 and from 5.10 to 12.5 g kg^{-1}, respectively (all $P < 0.05$; Table 2). In 2015, SOC had similar variation patterns to those in 2005 (Table 2). The SOC values changed from 14.68 to 28.34, from 9.80 to 24.16 and from 5.57 to 16.12 g kg^{-1} in the 0–20, 20–40 and 40–60 cm soil layers, respectively (all $P < 0.05$; Table 2). Generally, SOC in 0–60 cm layers of the five land use stages increased during 2005–2015. Among them, SOC of 0–20, 20–40 and 40–60 cm layers in both AF and NF significantly increased (Table 2, $P < 0.05$).

3.2. Variation of soil C stock in five land use stages

Land use stages, soil layers and restoration age had significant effects on soil C stocks ($P < 0.05$). In 2005, soil C stock in the 0–20, 20–40 and 40–60 cm layers all increased from AF to NF (all $P < 0.05$; Table 3): from 32.20 to 50.44, from 15.18 to 45.46 and from 12.81 to 32.48 Mg ha^{-1}, respectively. In 2015, soil C stocks in the corresponding three soil layers had similar variation patterns with those in 2005 (Table 3): increasing from 35.99 to 61.39, from 25.38 to 57.02 and from 14.71 to 32.99 Mg ha^{-1} from AF to NF (Table 3; all $P < 0.05$). In addition, the whole soil C stocks in 0–60 cm soil layers of the five land use stages all increased after 10 years of restoration (Table 3). Among them, soil C stocks of 0–20, 20–40 and 40–60 cm soil layers in AF significantly increased after restoration during 2005–2015 (Table 3, $P < 0.05$).

Table 2
Soil organic carbon (SOC) of different soil layers in five land use types accompanying vegetation restoration during 2005–2015. AF, Abandoned farmland; GL, Grassland; SL, Shrub land; WL, Woodland; NF, Natural climax forest.

Land use stages	Soil layers (cm)	Year		F	P
		2005 (g kg^{-1})	2015 (g kg^{-1})		
AF	0–20	13.54 ± 09Ad	14.68 ± 0.48Ad	5.44	0.049*
	20–40	6.41 ± 0.08 Bd	9.80 ± 0.43 Bd	60.22	0.000**
	40–60	5.10 ± 0.03Cc	5.57 ± 0.12Cc	13.83	0.006**
GL	0–20	17.58 ± 0.53Ac	18.17 ± 1.17Ac	0.21	0.661
	20–40	8.42 ± 0.09Bc	10.75 ± 0.35Bcd	42.46	0.000**
	40–60	5.21 ± 0.31Cb	6.73 ± 0.67Cc	4.27	0.073
SL	0–20	19.86 ± 0.77Ab	22.95 ± 0.90Ac	6.01	0.041*
	20–40	11.31 ± 0.37Bb	14.65 ± 1.59Bc	0.68	0.435
	40–60	6.21 ± 0.48Cbc	8.44 ± 0.96Bb	16.85	0.003**
WL	0–20	22.12 ± 0.05Aa	25.36 ± 1.27Ab	13.17	0.013*
	20–40	18.07 ± 0.6Aa	21.06 ± 0.74Bb	4.94	0.057
	40–60	12.45 ± 0.65Ba	15.12 ± 0.69Ca	0.49	0.503
NF	0–20	22.86 ± 0.15Aa	28.34 ± 1.36Aa	34.04	0.000**
	20–40	18.54 ± 0.36Ba	24.16 ± 0.23Ba	149.00	0.000**
	40–60	12.50 ± 0.71Ca	16.12 ± 0.23Ca	8.56	0.016*

Note: Different uppercase and lowercase letters indicate significant differences among soil layers and among land use stages, respectively ($P < 0.05$); * and ** indicate significant differences between 2005 and 2015 ($P < 0.05$ and $P < 0.01$, respectively). The values are mean ± standard error (SE), $n = 5$.

Table 3
Soil C stocks of different soil layers in five land use types accompanying vegetation restoration during 2005–2015. AF, Abandoned farmland; GL, Grassland; SL, Shrub land; WL, Woodland; NF, Natural climax forest.

Land use stages	Soil layers (cm)	Year		F	P
		2005 (Mg ha^{-1})	2015 (Mg ha^{-1})		
AF	0–20	32.20 ± 0.72Ac	35.99 ± 1.29Ad	6.51	0.034*
	20–40	15.18 ± 0.4 Bd	25.38 ± 0.84Bc	118.14	0.000**
	40–60	12.81 ± 0.26Cc	14.71 ± 0.3Cc	22.83	0.001**
GL	0–20	40.67 ± 1.66Abc	42.31 ± 2.89Ac	0.24	0.635
	20–40	20.39 ± 0.52Bc	26.62 ± 1.36Bbc	18.26	0.003**
	40–60	12.94 ± 0.72Cc	17.00 ± 1.63Cc	5.17	0.053
SL	0–20	43.07 ± 1.88Ab	45.53 ± 1.97Ac	0.81	0.395
	20–40	26.88 ± 0.85Bb	30.85 ± 3.74Bb	1.07	0.331
	40–60	15.34 ± 1.28Cb	26.98 ± 2.73Bb	14.85	0.005**
WL	0–20	49.04 ± 2.21Aa	55.81 ± 3.77Ab	1.18	0.307
	20–40	44.27 ± 1.48Aa	50.36 ± 1.81Ab	3.05	0.109
	40–60	31.28 ± 1.63Ba	35.32 ± 1.85Bab	0.00	0.987
NF	0–20	50.44 ± 1.48Aa	61.39 ± 2.13Aa	17.85	0.003**
	20–40	45.46 ± 1.16Ba	57.07 ± 0.81Ba	66.96	0.000**
	40–60	32.48 ± 1.09Ca	32.99 ± 0.77Ca	0.14	0.714

Note: Different uppercase and lowercase letters indicate significant differences among soil layers and among land use stages, respectively; * and ** indicate significant differences between 2005 and 2015 ($P < 0.05$ and $P < 0.01$, respectively). The values are mean ± SE, n = 5.

3.3. Rates of SOC change and soil C sequestration in five land use stages

Land use stages and soil layers had significant effects on the rate of

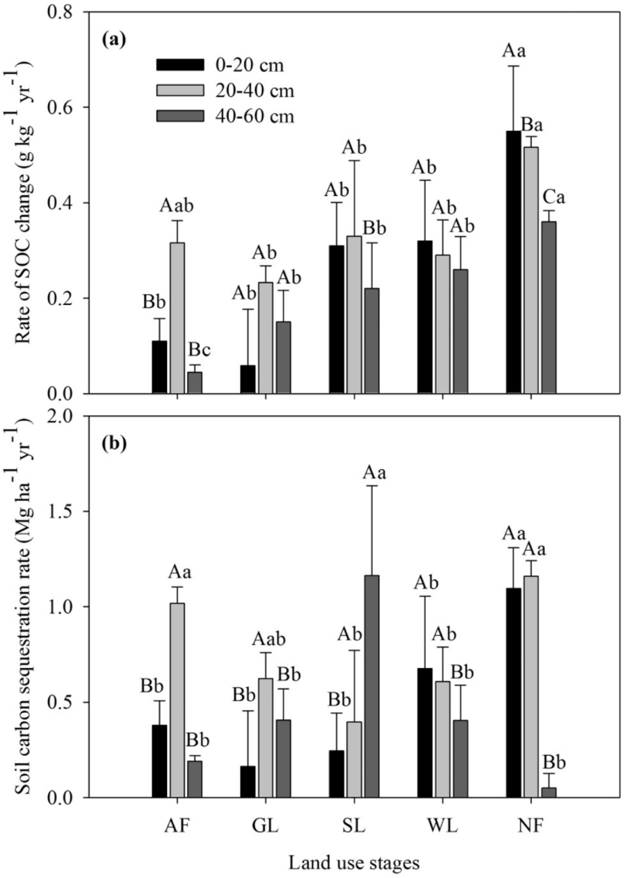

Fig. 3. Rates of SOC change (a) and soil C sequestration (b) in five land use types accompanying vegetation restoration during 2005–2015. Note: Different uppercase and lowercase letters indicate significant differences among soil layers and among land use stages, respectively ($P < 0.05$); The values are mean + SE (error bar), $n = 5$. AF, Abandoned farmland; GL, Grassland; SL, Shrub land; WL, Woodland; NF, Natural climax forest.

SOC change (Fig. 3a). The rates of SOC change in the 0–20 and 40–60 cm soil layers significantly increased from 0.11 to 0.55 and from 0.04 to 0.36 g kg^{-1} yr^{-1}, respectively (Fig. 3a). The rates of SOC change in the 20–40 cm soil layer initially declined from AF to GL (0.31 and 0.23 g kg^{-1} yr^{-1}, respectively) and then increased to NF (0.51 g kg^{-1} yr^{-1}) (Fig. 3a). In the early land use stages (AF and GL), the rates of SOC change were the highest in the 20–40 cm soil layer, and in the later land use stages (SL, WL and NF) were higher in the 0–20 and 20–40 cm layers (Fig. 3a). The land use stages and soil layers had significant effects on soil C sequestration rate (Fig. 3b). Generally, soil C sequestration rates in the 0–20 cm soil layer increased from AF to NF (0.37 to 1.09 Mg ha^{-1} yr^{-1}, respectively) (Fig. 3b); and in the 20–40 cm soil layer, initially declined in AF (1.01 Mg ha^{-1} yr^{-1}) to SL (0.39 Mg ha^{-1} yr^{-1}) and then increased to NF (1.19 Mg ha^{-1} yr^{-1}) (Fig. 3b). The rates in the 40–60 cm layer showed fluctuating changes from AF to NF (Fig. 3b).

3.4. Variation in litter and fine roots in five land use stages

Litter increased from AF to NF in both 2005 and 2015 (Fig. 4, $P < 0.05$). Moreover, litter increased during 2005–2015 in all land use stages (Fig. 4). However, litter did not significantly increase for all five land use stages from AF to NF. Only litter for AF and WL significantly increased during 2005–2015 (Fig. 4).

Land use stages and soil layers in both 2005 and 2015 significantly affected fine root biomass ($P < 0.05$). Fine root biomass in every soil layer significantly increased from AF to NF in both years ($P < 0.05$)

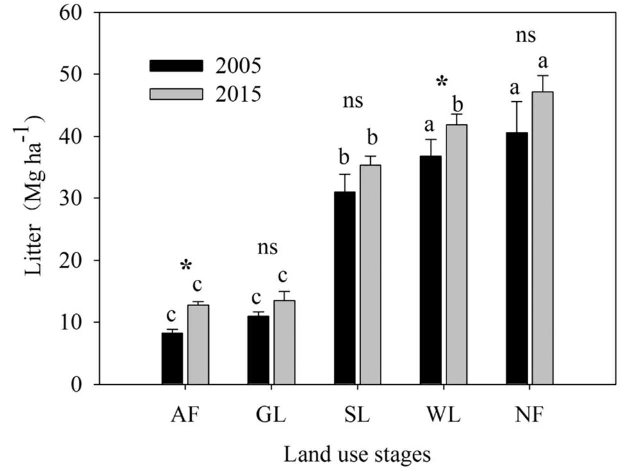

Fig. 4. Litters in five land use types accompanying vegetation restoration during 2005–2015. Note: Different lowercase letters indicate significant difference among land use stages in each year ($P < 0.05$); * indicates significant difference between the two years ($P < 0.05$), ns indicates non-significant ($P > 0.05$). The values are mean + SE (error bar), n = 5. AF, Abandoned farmland; GL, Grassland; SL, Shrub land; WL, Woodland; NF, Natural climax forest.

Table 4
Fine roots of different soil layers in five land use types accompanying vegetation restoration during 2005–2015. AF, Abandoned farmland; GL, Grassland; SL, Shrub land; WL, Woodland; NF, Natural climax forest.

Land use stages	Soil layers (cm)	Year	
		2005 (Mg ha^{-1})	2015 (Mg ha^{-1})
AF	0–20	8.65 ± 2.02Ac	13.42 ± 0.83Ac
	20–40	2.64 ± 0.36Bb	4.03 ± 0.45Bb
	40–60	1.41 ± 0.31Bb	1.87 ± 0.2Cb
GL	0–20	19.5 ± 3.09Ab	23.61 ± 2.08Ab
	20–40	3.04 ± 0.86Bb	4.87 ± 0.60Bb
	40–60	1.56 ± 0.11Bb	2.1 ± 0.08Bb
SL	0–20	21.26 ± 0.76Ab	25.9 ± 1.29Ab
	20–40	4.11 ± 0.63Bb	9.1 ± 0.60Ba
	40–60	1.69 ± 0.05Cb	2.7 ± 0.13Cb
WL	0–20	45.66 ± 3.99Aa	51.33 ± 2.43Aa
	20–40	10.73 ± 1.98Ba	15.24 ± 1.98Ba
	40–60	5.61 ± 0.46Ba	8.15 ± 0.56Ca
NF	0–20	48.5 ± 1.19Aa	53.18 ± 4.58Aa
	20–40	13.47 ± 1.52Ba	21.61 ± 2.22Ba
	40–60	7.91 ± 0.42Ca	8.72 ± 1.36Ba

Note: Different uppercase and lowercase letters indicate significant differences among soil layers and among land use stages, respectively ($P < 0.05$); The values are mean ± SE, n = 5.

(Table 4) and increased in the restoration during 2005–2015 (Table 4, $P > 0.05$).

3.5. Relationship between changes in SOC and soil C sequestration and changes in litter and fine roots

Litter and fine roots had significant positive effects on changes in SOC and soil C sequestration (Fig. 5). Both SOC and soil C sequestration significantly increased with increase in litter ($P < 0.01$ and $P < 0.05$, respectively) and fine roots (both $P < 0.01$) (Fig. 5a and b).

4. Discussion

Land use change can cause a change in soil C (Guo and Gifford 2002; DeGryze et al. 2004; Don et al. 2011; Wang et al. 2016; Deng and

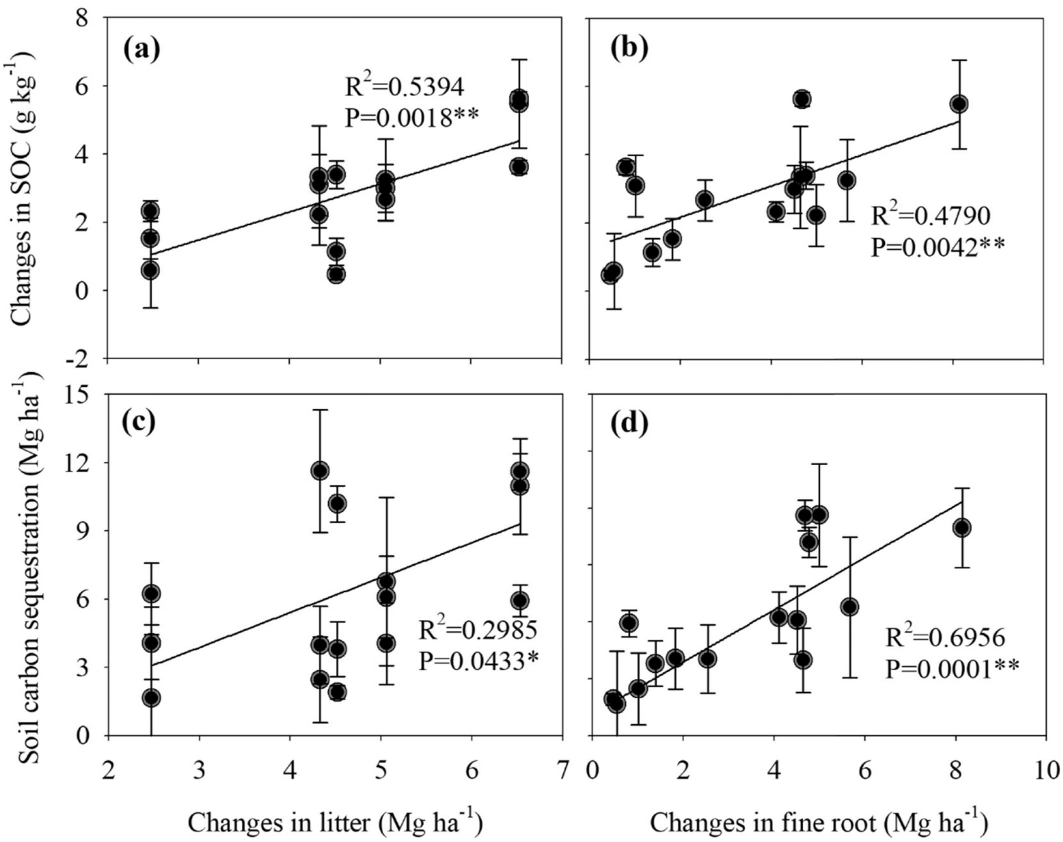

Fig. 5. Relationships between the changes in SOC and soil C sequestration and changes in litter and fine roots. Note: The data are mean values of each soil layer in the five land use stages. * and ** indicate significant ($P < 0.05$ and $P < 0.01$, respectively). The values are mean ± SE (error bar).

Table 5
Quantification of the contributions of land use stage, soil layers, age and their interactions to SOC and soil C stock using the GLM in five land use types after 10 years of vegetation restoration during 2005–2015. Note: * indicates a significant effect ($P < 0.05$).

	Land use stages (%)	Soil layers (%)	Age (%)	Interactions (%)	Residual (%)
SOC	40.8*	47.5*	2.0*	5.5	4.2
Soil carbon stock	42.7*	42.6*	2.3*	6.3	6.1

Shangguan 2017). Changes in land use caused by vegetation restoration probably enhance the C sequestration capacity of terrestrial ecosystems on the Loess Plateau (Deng et al. 2016), and soil C shows significant positive correlations in the process of vegetation restoration (Deng et al. 2016; Wang et al. 2016). In our study, the SOC in 0–20, 20–40 and 40–60 cm layers all increased from AF to NF in both 2005 and 2015 (Table 2), and the GLM analysis showed that land use stages had an important impact on SOC (Table 5), indicating that long-term natural vegetation restoration had improved SOC accumulation. These results agree with those of Wang et al. (2016), who studied changes in the SOC of 0–100 cm soil profiles during long-term natural vegetation restoration on abandoned farmland. Many studies have reported that SOC can be increased by raising organic matter input (Smith 2008), preventing soil erosion (Zhou et al. 2012) and decreasing both weathering and microbial decomposition following vegetation restoration (Lal 2005; Smith 2008). In addition, the GLM analysis showed that soil layers had an important impact on SOC (Table 5). In our study, the topsoils had higher SOC than subsoils for the five land use stages (Table 2). Similar to our findings, changes in SOC in different soil layers were previously demonstrated in terms of various soil properties (Deng et al. 2013; Wang et al. 2014). Nelson et al. (2008) reported that increased aboveground and belowground C inputs resulting from vegetation biomass are probably the main factors contributing to soil C sequestration. We also found that litter and fine root biomass in every soil layer significantly increased from AF to NF (Fig. 4 and Table 4).

Generally, soil depth is stable, meaning that soil C stock is determined by SOC and soil BD (Deng et al. 2013). With vegetation restoration, soil BD no longer significantly varied (Fig. 2) leaving SOC as the key factor affecting soil C stock in the process of restoration. The soil C stock presented similar trends to those of SOC across the vegetation restoration stages (Tables 2 and 3) – we previously found that soil C stock in 0–60 cm soil layers increased with long-term vegetation restoration (Deng et al. 2013; Wang et al. 2016). In the present study, the GLM analysis also showed that land use stages and soil layers had a significant impact on soil C stock ($P < 0.05$, Table 5), indicating that vegetation restoration could affect the distribution of soil C stocks in the soil profile. The 2 years of measurements both showed that soil C stocks were higher in topsoil than in subsoils in the five land use stages from AF to NF (Table 3). Nelson et al. (2008) also reported that litter and fine root biomass input into soils resulted in sequestration of soil C. Our results also showed that litter and fine roots were highly consistent with soil C stock in every soil layer following vegetation restoration from AF to NF (Tables 3 and 4, and Fig. 4).

Recently it was reported that land use and depth of sampling were important factors in changes in SOC and soil C stocks (Strahm et al. 2009; VandenBygaart et al. 2010). We also found that land use stages and soil layers significant affected the rates of SOC change and soil C sequestration, with a range of results (Fig. 3). For example, the rates of SOC change in the 0–20 and 40–60 cm soil layers significantly increased from AF to NF; and in the 20–40 cm layer initially declined from AF to GL (0.31 and 0.23 g kg^{-1} yr^{-1}, respectively) and then increased to NF (0.51 g kg^{-1} yr^{-1}) (Fig. 3a). Additionally, soil C sequestration rates in the 0–20 cm layer increased from AF to NF (0.37 and 1.09 Mg ha^{-1} yr^{-1}, respectively); in the 20–40 cm layer initially declined in AF to SL (1.01 and 0.39 Mg ha^{-1} yr^{-1}, respectively) and then increased to NF (1.19 Mg ha^{-1} yr^{-1}); and in the 40–60 cm layer showed fluctuating changes from AF to NF (Fig. 3b). In addition, our results showed that restoration age was an important factor affecting SOC and C stock dynamics, consistent with many studies following vegetation restoration (Guo and Gifford 2002; Laganière et al. 2010; Karhu et al. 2011; Deng and Shangguan 2017). For example, Deng and Shangguan (2017) reported that restoration age was the main factor affecting soil C sequestration rate after farmland conversions in China; Shi et al. (2013) found globally that stand age played an important role in C sequestration after farmland conversion into forest.

Production and input of litter and fine roots are key processes linking soil C inputs in the terrestrial ecosystem (Klotzbücher et al. 2011; Zhang et al., 2013). Most of the terrestrial net primary production enters the soil as dead organic matter (Swan et al. 2009). Leaf litter and fine roots are considered "fast C pools" (Meier and Leuschner 2010), which have major control over CO_2 fluxes from soils (Klotzbücher et al. 2011). Generally, litter and fine root production increases with stand age during vegetation succession (Yan et al. 2009; Zhang et al., 2013) – we also found similar results (Table 4, Fig. 4). Because litter and fine roots are the main input of C to soil (Ostertag et al. 2008), so they had a significant positive effect on SOC and soil C sequestration (Fig. 5). The increasing SOC and soil C stock with vegetation succession cannot be explained by changes in C inputs from litter and fine roots – the changes in their quality and decomposition rate may be more important controls than total litter and fine root production for soil C sequestration (Zhang et al., 2013). Montané et al. (2010) also demonstrated that litter quality, not quantity, drove the SOC accumulation after shrub encroachment into mountain grasslands in the Alt Pirineu Natural Park of the Pyrenees. Litter quality may control soil C sequestration by influencing microbial composition and activity, chemical transformations during humification, and synthesis of new compounds that are more resistant to decay (Marín-Spiotta et al. 2008; Montané et al., 2010). Therefore, more focus should be on the effect of litter and fine root quality on soil C sequestration along with the process of vegetation restoration on the Loess Plateau.

5. Conclusions

Land use stages, soil layers and restoration age significantly affected SOC and soil C stocks. The SOC and soil C stocks in the 0–60 cm soil profile rapidly increased in long-term natural vegetation succession from abandoned farmland to natural climax forest. The topsoils had higher SOC and soil C stock than subsoils in the five land use stages from AF to NF in both 2005 and 2015. Moreover, land use stages and soil layers also had significant effects on the rate of SOC change and soil C sequestration rate. During 2005–2015, litter and fine root production increased with restoration age along with natural vegetation succession. Because litter and fine roots are the main input source of C to soil, so they had a significant positive effect on SOC and soil C sequestration. More focus should be on the effect of litter and fine root quality on soil C sequestration along with the process of vegetation restoration on the Loess Plateau.

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