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Spatial-Temporal Changes of Soil Organic Carbon During Vegetation Recovery at Ziwuling, China*1

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ABSTRACT

To probe the processes and mechanisms of soil organic carbon (SOC) changes during forest recovery, a 150-year chronosequence study on SOC was conducted for various vegetation succession stages at the Ziwuling area, in the central part of the Loess Plateau, China. Results showed that during the 150 years of local vegetation rehabilitation SOC increased significantly ($P < 0.05$) over time in the initial period of 55–59 years, but slightly decreased afterwards. Average SOC densities for the 0–100 cm layer of farmland, grassland, shrubland and forest were 4.46, 5.05, 9.95, and 7.49 kg C m^{-3}, respectively. The decrease in SOC from 60 to 150 years of abandonment implied that the soil carbon pool was a sink for CO_2 before the shrubland stage and became a source in the later period. This change resulted from the spatially varied composition and structure of the vegetation. Vegetation recovery had a maximum effect on the surface (0–20 cm) SOC pool. It was concluded that vegetation recovery on the Loess Plateau could result in significantly increased sequestration of atmospheric CO_2 in soil and vegetation, which was ecologically important for mitigating the increase of atmospheric concentration of CO_2 and for ameliorating the local eco-environment.

Key Words: soil organic carbon density, spatial-temporal change, vegetation recovery, vegetation succession

Soil functions not only as a nutrient pool for terrestrial plants, soil animals, and microbes, but also as the biggest carbon pool for terrestrial ecosystems (Eswaran *et al.*, 1993; Schlesinger, 1995; Batjes, 1996). Since it could improve degraded soil quality, increase biomass amounts, clean surface water and groundwater, and also reduce the rate of atmospheric CO_2 enrichment (by counteracting CO_2 released from fossil-fuel combustion) (Lal, 2000; Zhao and Zhou, 2002), enhancing soil carbon sequestration was recognized as a win-win strategy. So probing the soil carbon cycle's processes and mechanisms, along with the interaction between soil and vegetation during vegetation restoration, have become key global issues (Cheng *et al.*, 2004; Marland *et al.*, 2004; Zhang *et al.*, 2004). This is also important for accurately assessing and supervising the restoration and reconstruction of degraded ecosystems (Xu and Xu, 2003).

The Loess Plateau is famous for its deep loess and as the cradle of traditional Chinese culture. However, during its history frequent and long-term anthropogenic activities have caused negative impacts on local environments, namely severe degradation of natural vegetation and attendant soil erosion (Peng and Yu, 1995; Shi and Shao, 2000). These have led to a fragile eco-environmental status within the Loess Plateau and have become the main source of sediment in the Yellow River (Zhu, 1999). Due to natural drought conditions and intensive human disturbance, Northwest China, including the Loess Plateau, has become the area with the lowest soil carbon pool in China (Li *et al.*, 2004). Therefore, vegetation rehabilitation is a key step in restoration of degraded ecosystems on the Loess Plateau (Peng, 2001). This will benefit the eco-environmental quality and enhance the soil carbon pool. In this research, it was hypothesized that natural factors such as climate and site conditions were relatively stable over a

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period of 150 years and the process of vegetation recovery was a function of time. Accordingly, it could be hypothesized that change in soil organic carbon (SOC), being closely related to vegetation rehabilitation, was also a function of time. Thus, the objective was to probe the processes and mechanisms of SOC change during forest restoration in the central part of the Loess Plateau of China.

MATERIALS AND METHODS

Study area

The study was conducted in the Ziwuling area ($36°4'$–$6'$ latitude N, $109°7'$–$11''$ longitude E) of Fuxian County, which is in the center of the Loess Plateau, 200 km northwest of Xi'an, the capital of Shaanxi Province, China. The climate is semi-arid with an average annual precipitation of 577 mm, of which 60% falls from June to August; the annual average temperature is 9 °C (Tang *et al.*, 1993); and the natural biome is the northern extended area of a deciduous broadleaf forest zone (Zhu, 1991). To maintain similar and comparable site conditions, investigations were carried out within an area where distances did not exceed 10 km. The landform is a typical loess hilly landscape with relative elevations of less than 200 m and altitudes of 1 200–1 360 m. The loess layer is about 50 m thick, and the soil type is a calcareous loamy soil, classified as an Entisol. Moreover, the spatial distribution of the loessial parent material is uniform and the silty clay loam texture varies little. In the late Qing Dynasty, from 1842–1866, there was a national conflict and local inhabitants largely emigrated from the area. From then on, few inhabitants lived in this area and restoration of secondary vegetation began naturally on the abandoned land (Liu, 1998). Recovery through natural succession suggested that vegetation on abandoned land gradually developed towards higher succession stages with increased restoration time. Thus, today Ziwuling and its adjacent areas have formed a widespread and continuous landscape of secondary forest that the locals call 'Bosquet'. Today the total forest coverage is over 70%. The longest recovery process has lasted almost 150 years with vegetation in some regions reaching the climax community stage dominated by *Quercus liaotungensis*. Nevertheless, in the 1940s–60s, due to famine, war and disasters, people began immigrating to this area in succeeding waves and reclaiming land. So the area's land use has experienced population changes and different stages of natural vegetation can be observed.

Sampling site selection and plant community description

To study the changes in SOC for long-term vegetation recovery, the method of space-for-time substitution or chronosequence (Debussche *et al.*, 1996; Foster and Tilman, 2000; Bonet, 2004) was used to select different sampling plots with various years of abandonment. Sampling plots were selected with similar altitude, slope gradient and direction (Table I). Slope gradient generally varied from 10° to 25°. To avoid the influence of micro-landforms on soil moisture and heat regimes, sampling plots were mostly on the upper or medium part of loess girder slope. A portable GPS was used to determine the longitude and latitude coordinates that are listed in Table I. There were 10 plots selected with four main vegetation succession stages including farmland (1 location), grassland (4 locations), shrubland (2 locations), and forest (3 locations) with fallow time ranging from 0 to 150 years (Table I) and the two plots farthest apart, farmland and forest site 3, were about 5.5 km apart.

To verify lengths of fallow (mainly $\leq$ 60 years), a series of interviews were conducted with local inhabitants. However, for fallow longer than 60 years, exact times were estimated based on annual tree rings and references. Chen (1954) indicated that by the 1950s in the Ziwuling area secondary forests had developed over a large area. This had followed a 100-year period of natural restoration and *Populus davidiana* forest (as a kind of pioneer forest) was the main category, representing 70% of the cover. *Betula platyphylla* forest was also identified as a kind of succession forest (Zhu, 1991). Zou *et al.* (2002) showed that by the beginning of the 21st century most of the 1950s' *P. davidiana* forests had progressed to the *Q. liaotungensis* climax forest stage. This implied that 50 years was needed for *P. davidiana* to

TABLE I

Site conditions and dominant species of plant communities of sampling plots for different succession stages in the Ziwuling area of the Loess Plateau

Vegetation stage	Years of abandonment	Altitude	Slope[a]	Direction	Longitude (E)	Latitude (N)	Dominant species		
							Name[b]	Height	Cover
		m	°					cm	%
Farmland	0	1322	5.0–12.0	N 133	109° 10.5′	36° 5.1′	*Brassica campestris*	–	–
Grassland 1	2	1318	12.0–19.0	N 128	109° 10.5′	36° 5.2′	*Artemisia capillaries*	10.5	67.9
Grassland 2	4	1342	12.5–6.5	N 20	109° 10.8′	36° 5.6′	*Artemisia capillaries*+	10.5	45.9
							Achnatherum extermiorientale	31.7	40.9
Grassland 3	14	1309	8.5–11.5	N 255	109° 9.7′	36° 4.3′	*Artemisia giraldii*+	30.0	22.5
							Stipa bungeana+	14.6	51.5
							Potentilla chinensis	21.3	16.7
Grassland 4	34	1313	15.0–16.5	N 310	109° 10.5′	36° 5.3′	*Themeda triandra* var. *japonica*	92.0	24.6
Shrubland 1	34	1309	19.0–21.5	N 325	109° 10.5′	36° 5.3′	*Acer ginnala*–	338	66.3
							Carex lanceolata	18.8	30.0
Shrubland 2	60	1306	22.0–27.0	N 270	109° 10.9′	36° 4.7′	*Sophora viciifolia*–	147	25.9
							C. lanceolata	13.7	46.7
Forest 1	100	1221	10.0–16.0	N 258	109° 10.1′	36° 4.3′	*Populus davidiana*–	934	90.1
							Spiraea pubescens–	103	11.9
							C. lanceolata	13.2	43.2
Forest 2	100	1220	14.5–24.5	N 18	109° 8.3′	36° 5.9′	*Betula platyphylla*–	940	96.6
							Spiraea pubescens–	86.2	11.5
							C. lanceolata	11.4	25.1
Forest 3	150	1360	14.0–21.0	N 85	109° 7.3′	36° 5.9′	*Quercus liaotungensis*–	901	92.9
							Viburnum schensianum–	127	20.7
							C. lanceolata	10.2	28.7

[a] All sampling plots were on the loess girder slope except for Forest 2, which was in a gully.

[b] Plant species followed by the symbol "+" or "–" indicates that the species and that in the line below it belonged to the same layer or different layers, respectively.

change to a *Q. liaotungensis* forest. So the recovery periods of *P. davidiana* and *B. platyphylla* forests were estimated at 100 years with the *Q liaotungensis* forest being 150 years. Additionally, after long-term cultivation, a steep ladder-like ridge often formed at the border of upper and lower pieces of sloping land. This characteristic could be used to verify whether the selected sampling plots were abandoned fallows or original woodlands.

Of the ten sampling plots selected with different lengths of fallow, representing ten succession stages with fallow time ranging from 0 to 150 years (Table I), a long-term cultivated sloping farmland was chosen as a control relative to the abandoned land; four plots had lengths of fallow ranging from 2 to 34 years and represented grassland community stages; two plots at the shrubland community stage had from 34 to 60 years of fallow; and 3 plots at the forest community stage had from 100 to 150 years of fallow. After the sampling plots were selected, community investigations were first conducted using methods described by Dong (1997). Li and Shao (2003, 2004) have published some of the results. It could be seen from Table I that along with the development of vegetation during recovery from natural succession, the dominant species first changed from annual or biennial to perennial grass, then to shrubs, and finally to trees.

Sample collection and analysis

Three sampling points were randomly selected (as replicates) at the plot of each succession stage. After removing litter and humus layers, the sampling depth was 100 cm sectioned into vertical 20 cm intervals. So, 150 soil samples in total were collected and measured (5 vertical sections per sampling points×3 replicates×10 plots). Soil samples were collected using a soil auger, sorted by hand to remove roots and other foreign materials, and then air-dried in the laboratory. The dry samples were pulverized and sieved through a 0.25 mm sieve. SOC content was determined using the methods described by Walkley and Black (1934) and Nanjing Agricultural University (1981). All measurements were carried out in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau of China and the results were calculated based on air-dried soil. Basic physical and chemical properties of the surface soil (0–20 cm) for four main vegetation stages are presented in Table II.

TABLE II

Physical and chemical properties of the surface soils (0–20 cm) for four main vegetation stages in the Ziwuling area of the Loess Plateau

Vegetation stage	Years of abandon-ment	Bulk density	Mechanical composition			pH	OM	Total N	Total P	Total K	Available N[c)]	Available P	Available K
			> 50 µm	50–2 µm	< 2 µm								
		g cm^{-3}	%				g kg^{-1}	mg kg^{-1}		g kg^{-1}	mg kg^{-1}		
Farmland	0	1.29 a[a)]	10.0 a	63.3 a	26.7 a	8.44 b	10.2 a	828 ab	654 a	16.6 a	20.9 a	8.95 a	104 a
		(0.10)[b)]	(0.8)	(0.3)	(0.6)	(0.04)	(0.53)	(60.1)	(14.8)	(0.23)	(13.4)	(0.34)	(6.0)
Grassland1	2	1.18 a	7.6 b	64.9 a	27.5 a	8.59 c	7.3 a	348 a	592 bc	17.5 a	10.8 a	4.88 b	93.5 a
1		(0.12)	(0.5)	(1.1)	(1.4)	(0.01)	(0.26)	(12.6)	(11.6)	(0.71)	(1.72)	(0.39)	(36.9)
Grassland	14	1.17 a	8.9 a	63.8 a	27.4 a	8.61 c	15.6 a	1018 ab	566 c	17.2 a	13.2 a	1.36 c	127 a
2		(0.10)	(0.3)	(0.4)	(0.6)	(0.01)	(3.20)	(183)	(40.5)	(0.48)	(3.11)	(0.32)	(30.3)
Shrubland	60	1.16 a	2.8 d	67.5 b	29.7 a	8.39 b	38.1 b	1625 b	629 ab	16.6 a	19.6 a	2.92 bc	189 b
2		(0.04)	(0.4)	(1.0)	(1.5)	(0.02)	(7.29)	(875)	(17.8)	(0.30)	(1.17)	(0.46)	(6.8)
Forest 3	150	0.99 b	4.9 c	68.1 b	27.0 a	8.26 a	30.2 b	1513 b	544 c	16.6 a	17.8 a	5.11 b	228 b
		(0.03)	(0.7)	(1.0)	(0.3)	(0.04)	(6.83)	(243)	(34.2)	(0.69)	(4.54)	(2.86)	(41.4)
P value		0.021	0.000	0.004	0.116	0.000	0.000	0.021	0.003	0.195	0.336	0.000	0.001

a) Means with the same letter in the same column are not significantly different at $P < 0.05$ (Duncan's test).
b) Data in parentheses are standard deviations.
c) Available N is the sum of nitrate N and ammonium N.

Soil organic carbon density indicated organic carbon storage per unit area for a certain depth (Jin *et al.*, 2001). It was usually described as total SOC for a 1 m^2 area with units of kg C m^{-2} in 1 m depth or kg C m^{-3} regardless of soil depth. This study used the latter for comparison of vertical changes in SOC with different succession stages. Soil organic carbon density values were evaluated according to Equation 1 (Post *et al.*, 1982; Jin *et al.*, 2001).

$$D = 100 \times cB(1 - \delta_{2\mathrm{mm}}) \tag{1}$$

where D indicates soil organic carbon density (kg C m^{-3}); c indicates SOC content (g kg^{-1}) for a certain soil depth; B indicates soil bulk density (g cm^{-3}); and $\delta_{2\mathrm{mm}}$ indicates the content (%) of soil particles with > 2 mm diameter, including rock debris and calcareous agglomerations.

A one-way analysis of variance (ANOVA) was performed using SPSS11.0 software for all of the data and Duncan's multiple comparison tests or regression analysis were further conducted if the results of ANOVA were significant ($P < 0.05$).

RESULTS AND DISCUSSION

SOC change during the vegetation recovery process

Table III gives the statistical results of SOC density in different layers for different vegetation recovery stages. Fig. 1 shows the change of the average SOC density in the 0–100 cm profile for different succession stages.

TABLE III

Spatial-temporal change of SOC density in different layers during the process of vegetation recovery in the Ziwuling area of the Loess Plateau

Vegetation stage	SOC density				
	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm
	kg C m^{-3}				
Farmland	7.6 ab[a)] (0.39)[b)]	4.96 ab (1.32)	3.44 ab (0.75)	3.23 ab (0.79)	3.09 ab (0.77)
Grassland 1	5.0 a (0.18)	3.64 a (0.58)	2.91 a (0.13)	3.07 a (0.24)	3.05 ab (0.17)
Grassland 2	8.1 ab (1.71)	5.25 abc (1.75)	3.27 ab (0.88)	2.99 a (0.33)	3.01 ab (0.38)
Grassland 3	10.6 abc (2.18)	5.78 abcd (2.21)	3.96 ab (0.72)	3.97 abc (0.35)	3.63 ab (0.65)
Grassland 4	13.0 bcd (1.07)	7.31 bcde (1.61)	4.52 b (0.86)	4.02 abc (0.32)	3.96 bc (0.57)
Shrubland 1	29.4 g (5.61)	9.60 e (0.85)	5.85 c (0.88)	5.05 c (0.59)	5.02 c (0.76)
Shrubland 2	25.7 fg (4.92)	7.65 cde (0.63)	3.93 ab (0.16)	3.69 ab (0.13)	3.55 ab (0.31)
Forest 1	17.0 cde (5.66)	7.50 bcde (1.38)	6.08 c (1.32)	4.21 bc (1.11)	3.94 bc (0.90)
Forest 2	19.7 ef (3.94)	8.31 de (1.36)	3.79 ab (0.90)	2.88 a (0.89)	2.60 a (0.94)
Forest 3	17.3 de (3.91)	7.12 bcde (1.27)	4.21 ab (0.30)	3.99 abc (0.22)	3.80 ab (0.37)
Average	15.4 (8.02)	6.71 (1.78)	4.19 (1.04)	3.71 (0.68)	3.56 (0.69)
CV (%)	52.2	26.5	24.8	18.2	19.2
P value	0.000	0.001	0.001	0.005	0.009

a) Means with the same letter in the same column are not significantly different at $P < 0.05$ (Duncan's test).
b) Data in the parentheses are standard deviations.

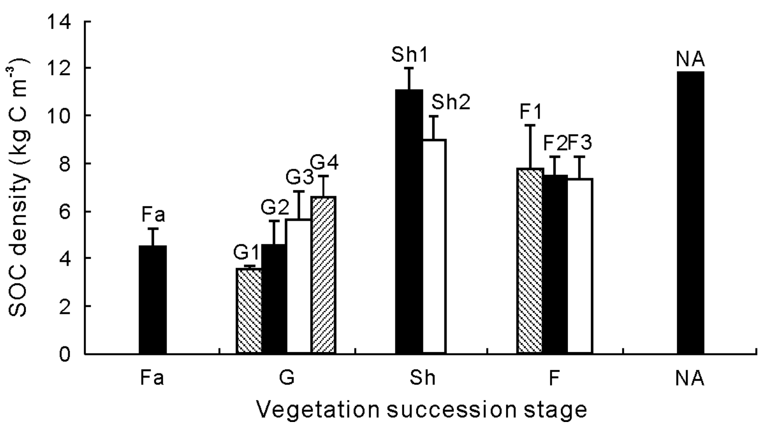

Fig. 1 Change of soil organic carbon density in the 0–100 cm profile for different successional vegetation recovery stages in the Ziwuling area of the Loess Plateau. Fa: farmland; G1–G4: grasslands with abandonment years of 2, 4, 14, and 34 years, respectively; Sh1 and Sh2: shrublands with dominant species of *Acer ginnala* (34 years) and *Sophora viciifolia* (60 years), respectively; F1–F3: forests with dominant species of *Populus davidiana* (100 years), *Betula platyphylla* (100 years) and *Quercus liaotungensis* (150 years), respectively; NA: the national average in soils of China (Wang *et al.*, 2003).

Data showed that changes in SOC density were mostly significant ($P < 0.05$) for the five soil layers among different stages during the process of vegetation rehabilitation. In Grassland 1, the recently abandoned farmland stage (2 years), compared to farmland, SOC density in the surface (0–20 cm) and undersurface layers were slightly reduced though not statistically significant. These changes were attributed to annual and biennial plants, which bloomed in freshly abandoned land and returned little organic matter to the soil, consuming the original mineralized soil organic matter (SOM). However, SOC gradually began to increase with time after a short-term reduction, as a result of the above- and belowground biomass increase (Fang *et al.*, 2003) and corresponding increase of SOM input to soils (Wang, X. B. *et al.*, 2005). For the 0–20 cm depth there was a gradual increase from Grassland 1 to Grassland 4 with Grassland 4 being significantly greater ($P < 0.05$) than Grassland 1 (Table III).

Compared with Grassland 1, which was recovered for only 2 years (5.01 kg C m^{-3}), the topsoil SOC density increased by 62.4%, 112.1%, and 159.5% for Grassland 2 (4 years), Grassland 3 (14 years), and Grassland 4 (34 years), respectively. The profile average increments for 0–100 cm in Grasslands 2, 3, and 4 compared to Grassland 1 increased by 28.2%, 58.2% and 85.6%, respectively, which were somewhat lower than those in the topsoil.

When vegetation developed to the shrubland stage, SOC density showed a sharp elevation (Fig. 1), with Shrubland 1 in the 0–20 cm soil layer being significantly higher ($P < 0.05$) than all the other surface samples (Table III). Shrubland 1 also had 11.0 kg C m^{-3} for the 0–100 cm profile. The increments for Shrublands 1 and 2 relative to Grassland 1 were 488% and 211%, respectively. This change was closely related to the spatial variation of canopy structure and species composition. As grasslands developed into a shrubland stage, vegetation varied not only in community height, but also in an obvious spatial dimension. This subsequently induced some microclimate changes, specifically falling surface temperatures and increased water consumption. To some extent, all these changes resulted in the decline of SOM mineralization rates and accumulation of SOC.

In the meantime, species composition also changed. Shade-tolerant plants such as *Carex lanceolata*, *Rubia cordifolia*, *Lathyrus quinquenervius*, and *Duchesnea indica*, emerged; while sun-loving plants, namely *Themeda triandra* var. *japonica*, *Stipa bungeana*, and *Artemisia giraldii,* began to die and gradually faded from the communities. Species diversity in this stage also reached a climax period attributed to coexistence of plants belonging to different functional groups (Li and Shao, 2004; Bonet, 2004). Due to the death of light-demanding plants, a thick surface layer of litter soon formed, usually with a large biomass. SOC also increased rapidly owing to the death of roots.

However, SOC density declined when vegetation progressed through the shrubland stage and into the forest type. Compared with the *Acer ginnala* shrubland (Shrubland 1), SOC density in the surface soil for all three forest types was significantly less ($P < 0.05$). *Populus davidiana* (Forest 1), *Betula platyphylla* (Forest 2) and *Q. liaotungensis* (Forest 3) forests decreased by 42.3%, 33.0% and 41.2%, respectively. Thus, Forests 1, 2 and 3 compared to Shrubland 1 for the 0–100 cm profile were 29.5%, 32.2% and 33.7% lower, respectively, being also slightly lower than the comparison for surface layer.

Decline of SOC density in the forest stage was attributed to a reduction of litter being directly returned to the soil. Although ground litter under forest was usually thick, it was mostly spread over the surface and only incorporated through indirect ways, such as soil animal activities. Since these actions were generally quite limited, addition of SOC was mainly derived from dead roots, especially herbaceous plant roots. The relatively low biomass of shade-tolerant plants, which dominated the understory communities of forests, resulted in relatively low organic matter input to the soil. On the other hand, microbes gradually decomposed or mineralized the large SOC accumulated during shrub growth, which subsequently resulted in a reduction of SOC density during the forest stage.

SOC density for different layers, as a non-linear function of years of abandonment, for the 0–20, 20–40 and 0–100 cm layers were described as polynomial functions (corresponding regression equations):

$$D_{0\text{-}20\,\mathrm{cm}} = 4.8448 + 0.7662t - 9.6 \times 10^{-3}t^2 + 3.4 \times 10^{-5}t^3 \tag{2}$$

$$D_{20\text{-}40\,\mathrm{cm}} = 4.2904 + 0.1665t - 2.0 \times 10^{-3}t^2 + 6.7 \times 10^{-6}t^3 \tag{3}$$

$$D_{0\text{-}100\,\mathrm{cm}} = 3.6484 + 0.2298t - 3.0 \times 10^{-3}t^2 + 1.1 \times 10^{-5}t^3 \tag{4}$$

where $D_{0\text{-}20\,\mathrm{cm}}$, $D_{20\text{-}40\,\mathrm{cm}}$ and $D_{0\text{-}100\,\mathrm{cm}}$ indicate soil organic carbon density for the 0–20 cm, 20–40 cm and 0–100 cm layers, respectively; t indicates the years of natural vegetation rehabilitation after farmland abandonment, taken as $t = 0$ for farmland for the purpose of analysis. The statistically significant coefficients of determination (R^2) were 0.715 ($P = 0.044$), 0.785 ($P = 0.020$), and 0.750 ($P = 0.031$) for the 0–20, 20–40 and 0–100 cm layers, respectively. However, the regression results were not significant for the layers below 40 cm depth.

Assuming D$'$ (the derivative of D in Equations 2, 3 and 4) = 0, the SOC density recovery times until the climax stage were estimated as 57, 59 and 55 years for the 0–20 cm, 20–40 cm and 0–100 cm layers, respectively. Then, the initial ($t = 0$), maximum ($t = 57$), and final ($t = 150$) values of SOC density during the succession process were calculated to be 4.84, 23.6 and 18.5 kg C m^{-3} in the surface 0–20 cm layer, 4.29, 8.53 and 6.88 kg C m^{-3} for the 20–40 cm layer, and 3.65, 9.04 and 7.74 kg C m^{-3} for the 0–100 cm layer, respectively. Thus, the corresponding maximum net increments of SOC densities calculated were 18.8, 4.24 and 5.39 kg C m^{-3} for the three layers, respectively. So, for fallow period up to nearly 60 years from farmland through shrubland stage, the increment rates of SOC density were 0.33, 0.07, and 0.10 kg C m^{-3} $year^{-1}$ for the three layers. With further succession during the rest of the recorded period (60–150 years), the net decreases of SOC density were 5.08, 1.65, and 1.30 kg C m^{-3} and the declining rates were 0.05, 0.02 and 0.01 kg C m^{-3} $year^{-1}$ for the 0–20, 20–40 and 0–100 cm layers, respectively. So in comparison to the declining rates in the last 90-year period, the SOC density increment prior to shrubland stage was much more rapid. The differences depended on organic matter input and decomposition rates, both above- and belowground. These two factors were closely related to water and temperature status of the sites. So the change of SOC density was not only closely related to vegetation but also limited by the local climatic conditions. Zhou *et al.* (2000) showed that SOC density for forest vegetation in China increased with higher latitudes while carbon density for aboveground vegetation changed in the opposite way. In addition, Wang *et al.* (2002) demonstrated that SOC density was positively related to precipitation but negatively related to temperature. Due to these combined factors, the highest SOC density areas in China were in northeast China, southwest China and the Qinghai-Tibet Plateau (Li and Shao, 2003; Xie *et al.*, 2004a, b). So a wet and cold climate was beneficial to the accumulation of SOC, while a hot and dry climate was beneficial to SOC mineralization and decomposition. Thus, the decrease of SOC density for the period of forest growth in the Ziwuling area was a result of both climate and vegetation.

SOC densities for all stages of succession were highest in the top layers (0–20 cm) and decreased with soil depth (Table III). Based on coefficients of variation (CV) for SOC density, soil depths could be divided into three layers: an intensively variable layer (0–20 cm), a transition layer (20–60 cm), and a relatively steady layer (60–100 cm). Regression analysis with Equation 5 showed that all SOC density values decreased significantly ($P < 0.01$) with depth (Sun *et al.*, 2003):

$$D = ad^{-b} \tag{5}$$

where d indicates the soil depth ranging from 10 to 90 cm, and a and b are the regression coefficients. Equations 6–9 listed below were for the four typical succession stages:

$$D_{\mathrm{Fa}} = 988.11d^{-2.2489} \tag{6}$$

$$D_{\mathrm{G1}} = 3827.9d^{-3.6882} \tag{7}$$

$$D_{\mathrm{Sh1}} = 445.93d^{-1.1404} \tag{8}$$

$$D_{\mathrm{F3}} = 426.46d^{-1.3282} \tag{9}$$

where D_{Fa}, D_{G1}, D_{Sh1}, and D_{F3} indicate the SOC density for the farmland, Grassland 1, Shrubland 1, and Forest 3, respectively. The determination coefficients (R^2) of regression equations were 0.9761, 0.8971, 0.9650, and 0.9645, respectively. Equations 6–9 described well the vertical changes of SOC density. These changes with depth demonstrated that the impacts of vegetation recovery on SOC density mainly occurred in the upper 40 cm depth, especially in the surface layer 0–20 cm (Table III).

Soil carbon pool change in the Ziwuling area and its ecological significance

The above results showed that the soil carbon pool before shrub development increased but fell slightly in the later succession stages (Fig. 1). This demonstrated that SOC density regularly varied with time along the vegetation recovery process and thus confirmed the original hypothesis. It also suggested that soil was a sink for CO_2 in the period from grassland to shrubland stage but became a source during the subsequent succession towards forestry. The carbon pool for a forest eco-system is composed of three closely associated compartments: vegetation, litter, and soil (Zhou *et al.*, 2000). The increase of SOC, as the main component of SOM, was also an important index for improvement of soil quality (Zhao *et al.*, 1997; Sun *et al.*, 1997; Zhou *et al.*, 2003). Data in Table II showed that from grassland to forest (2 to 150 years) soil bulk density and pH significantly ($P < 0.05$) decreased, while organic matter, total nitrogen (N), and available potassium (K) all significantly ($P < 0.05$) increased with vegetation rehabilitation. Therefore, soil properties were being ameliorated. Improvement of soil quality also promoted development of vegetation and accumulation of litter. So, the total carbon pool including litter, above-, and belowground pools for a forest ecosystem increased noticeably more than that of the shrubland stage. This was attributed to the elevated carbon pools associated with vegetation and litter, despite the slight reduction of the soil carbon pool. The higher increasing rate of vegetation productivity and litter accumulation largely concealed the negative influence of soil carbon pool shrinkage in the late period of succession mainly resulting from the control of climate (Wang, S. Q. *et al.*, 2005).

The average values of SOC density of the 0–100 cm profile for the farmland, grassland, shrubland and forest across different plots for the same succession stages were 4.46 (± 0.77), 5.05 (± 1.40), 9.95 (± 1.46), and 7.49 (± 1.11) kg C m^{-3}, respectively. So, in the Ziwuling area, SOC density declined in the order shrubland > forest > grassland > farmland, and SOC density in the Loess Plateau was generally lower than the average, 11.52–12.04 kg C m^{-3}, in China (Wang *et al.*, 2003). In the Ziwuling area, the highest SOC density for *Acer ginnala* shrubland (Shrubland 1 in Fig. 1), 11.0 (± 1.00) kg C m^{-3}, was close to the national average. However, compared with the national average, SOC density was only 42.5% for the farmland and 70% for the climax forest stage. Consequently, the potential of the soil carbon pool was quite limited even if the vegetation was completely recovered or restored. This was attributed to the low vegetation productivity and relatively high decomposition rate under dry climate conditions (Li *et al.,* 2004). Of course, the net increase of SOC density of the 0–100 cm profile for the recovered climax forest was 2.82 kg C m^{-3}, being 63% more than that for farmland (Table III). This is important for improving the sequestration for atmospheric CO_2, and mitigating its negative impacts. Meanwhile, vegetation restoration resulted in effective control of soil and water loss and subsequent amelioration of the eco-environment. These effects could strengthen sustainable development of the Loess Plateau and its surrounding regions.

CONCLUSIONS

The impact of long-term vegetation restoration on the soil carbon pool was significant from farmland through grassland and from shrubland to forest. However, due to changes of community composition, spatial structure and microclimate, this influence varied for the different stages of succession. The soil carbon pool in the central Loess Plateau was a sink for CO_2 before the shrubland stage but became a source of CO_2 in the later periods of succession. However, the negative effect resulting from soil carbon pool shrinkage was largely concealed by the significant increase of aboveground vegetation and carbon litter pools. In addition to benefits from controlling soil and water loss and improving the local eco-environment the possible resulting sequestration of CO_2 was also of importance.

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REFERENCES

Batjes, N. H. 1996. Total C and N in soils of the world. *European Journal of Soil Science.* **47**: 151–163.

Bonet, A. 2004. Secondary succession of semi-arid Mediterranean old-fields in south-eastern Spain: Insights for conservation and restoration of degraded lands. *Journal of Arid Environments*. **56**: 213–233.

Chen, C. D. 1954. The vegetation and its roles in soil and water conservation in the secondary forest area in the boundary of Shaanxi and Gansu Provinces. *Acta Phytoecologica et Geobotanica Sinica* (in Chinese). (2): 152–223.

Cheng, X. F., Shi, X. Z., Yu, D. S., Pan, X. Z., Wang, H. J. and Sun, W. X. 2004. Using GIS spatial distribution to predict soil organic carbon in subtropical China. *Pedosphere*. **14**(4): 425–431.

Debussche, M., Escarrie, J., Lepart, J., Houssard, C. and Lavorel, S. 1996. Changes in Mediterranean plant succession: Old-fields revisited. *Journal of Vegetation Science*. **7**: 519–526.

Dong, M. 1997. Survey, Observation and Analysis of Terrestrial Biodiversities (in Chinese). Standards Press of China, Beijing. pp. 3–23.

Eswaran, H. E., Berg, V. D. and Reich, P. 1993. Organic carbon in soils of the world. *Soil Sci. Soc. Am. J.* **57**: 192–194.

Fang, Y. T., Mo, J. M., Peng, S. L. and Li, D. J. 2003. Role of forest succession on carbon sequestration of forest ecosystem in lower subtropical China. *Acta Ecologica Sinica* (in Chinese). **23**(9): 1 685–1 694.

Foster, B. L. and Tilman, D. 2000. Dynamic and static views of succession: Testing the descriptive power of the chronosequence approach. *Plant Ecology*. **146**: 1–10.

Jin, F., Yang, H., Cai, Z. C. and Zhao, Q. G. 2001. Calculation of density and reserve of organic carbon in soils. *Acta Phytoecologica Sinica* (in Chinese). **38**(4): 522–528.

Lal, R. 2000. Carbon sequestration in drylands. *Annals of Arid Zone*. **39**(1): 1–10.

Li, K. R., Wang, S. Q. and Cao, M. K. 2004. Vegetation and soil carbon storage in China. *Science in China Ser. D Earth Sciences*. **47**(1): 49–57.

Li, Y. Y. and Shao, M. A. 2003. Natural succession and evolution of structural characteristics of forest community in Ziwuling area on the Loess Plateau. *Acta Botanica Boreali-Occidentalia Sinica* (in Chinese). **23**(5): 693–699.

Li, Y. Y. and Shao, M. A. 2004. The change of plant diversity during natural recovery process of vegetation in Ziwuling area. *Acta Ecologica Sinica* (in Chinese). **24**(2): 252–260.

Liu, L. P. 1998. Arborum et Fruticum Ziwu Montium (in Chinese). Lanzhou University Press, Lanzhou. pp. 2–6.

Marland, G., Garten, Jr. C. T., Post, W. M. and West, T. O. 2004. Studies on enhancing carbon sequestration in soils. *Energy*. **29**: 1 643–1 650.

Nanjing Agricultural University (ed.). 1981. Analysis of Soil and Agro-Chemistry (in Chinese). 2nd Edition. Agricultural Press, Beijing. pp. 29–39.

Peng, L. and Yu, C. Z. 1995. Nutrient losses in soils on Loess Plateau. *Pedosphere*. **5**(1): 83–92.

Peng, S. L. 2001. Restoration of degraded ecosystem and restoration ecology. *Chinese Foundation Sciences* (in Chinese). (3): 18–24.

Post, W. M., Emanuel, W. R., Zinke, P. J. and Stangenberger, A. G. 1982. Soil carbon pools and world life zone. *Nature*. **298**: 156–159.

Schlesinger, W. H. 1995. An overview of the global carbon cycle. *In* Lal, R. *et al.* (eds.) Soil and Global Change. CRC, Boca Raton, FL. pp. 9–25.

Shi, H. and Shao, M. A. 2000. Soil and water loss from the Loess Plateau in China. *Journal of the Arid Environments*. **45**: 9–20.

Sun, B., Zhao, Q. G. and Zhang, T. L. 1997. Soil quality and sustainable environment: II. Quality assessment and carbon and nitrogen index. *Soils* (in Chinese). **29**(4): 169–175, 184.

Sun, W. X., Shi, X. Z. and Yu, D. S. 2003. Distribution pattern and density calculation of soil organic carbon in profile. *Soils* (in Chinese). **35**(3): 236–241.

Tang, K. L., Zheng, F. L., Zhang, K. L., Wang, B. K., Cai, Q. and Wang, W. L. 1993. Research subjects and methods of relationship between soil erosion and eco-environment in the Ziwuling forest area. *Memoir of Northwestern Institute of Soil and Water Conservation, China* (in Chinese). (17): 3–10.

Walkley, A. and Black, I. A. 1934. An examination of the Degtjarrtt method for determining soil organic matter and proposed modification of chromic acid titration method. *Soil Science*. **37**: 29–38.

Wang, S. P., Zhou, G. S., Lu Y. C. and Zou, J. J. 2002. Distribution of soil carbon, nitrogen and phosphorus along Northeast China transpect (NECT) and their relation with climate factors. *Acta Phytoecologica Sinica* (in Chinese). **26**(5): 513–517.

Wang, S. Q., Liu, J. Y. and Yu, G. R. 2003. Error analysis of estimating terrestrial soil organic carbon storage in China. *Chinese Journal of Applied Ecology* (in Chinese). **14**(5): 797–802.

Wang, S. Q., Yu, G. R., Zhao, Q. J., Niu, D., Chen, Q. M. and Wu, Z. F. 2005. Spatial characteristics of soil organic carbon storage in China's croplands. *Pedosphere*. **15**(4): 417–423.

Wang, X. B., Cai, D. X., Hoogmoed, W. B., Oenema, O. and Perdok, U. D. 2005. Scenario analysis of tillage, residue and fertilization management effects on soil organic carbon dynamics. *Pedosphere*. **15**(4): 473–483.

Xie, X. L., Sun, B., Zhou, H. Z. and Li, A. B. 2004a. Soil organic carbon storage in China. *Pedosphere*. **14**(4): 491–500.

Xie, X. L., Sun, B., Zhou, H. Z., Li, Z. P. and Li, A. B. 2004b. Organic carbon density and storage in soils of China and spatial analysis. *Acta Pedologica Sinica* (in Chinese). **41**(11): 35–43.

Xu, Q. F. and Xu, J. M. 2003. Changes in soil carbon pools induced by substitution of plantation for native forest. *Pedosphere*. **13**(3): 271–278.

Zhang, S. R., Sun, B., Zhao, Q. G., Xiao, P. F. and Shu, J. Y. 2004. Temporal-spatial variability of soil organic carbon stocks in a rehabilitating ecosystem. *Pedosphere*. **14**(4): 501–508.

Zhao, Q. G., Sun, B. and Zhang, T. L. 1997. Soil quality and sustainable environment: The definition of soil quality and assessment method. *Soils* (in Chinese). **29**(3): 113–120.

Zhao, Q. G. and Zhou, J. M. 2002. Making a new contribution to innovation and development of 21st century soil science—A review of the 17th World Congress of Soil Science. *Soils* (in Chinese). **34**(5): 237–256.

Zhou, Y. D., Wu, J. S., Zhao, S. W., Guo, S. L. and Lu, P. 2003. Change of soil organic matter and water holding ability during vegetation succession in Ziwuling region. *Acta Botanica Boreali-Occidentalia Sinica* (in Chinese). **23**(6): 895–900.

Zhou, Y. R., Yu, Z. L. and Zhao, S. D. 2000. Carbon storage and budget of major Chinese forest types. *Acta Phytoecologica Sinica* (in Chinese). **24**(5): 518–522.

Zhu, X. M. 1999. Rapid and overall recovery of vegetation cover is the foundation of eliminating river disasters. *Soil and Water Conservation in China* (in Chinese). (10): 29–31.

Zhu, Z. C. 1991. Features of vegetation zones in Qinling Mountain and its northern loess area. *Scientia Geographica Sinica* (in Chinese). **11**(2): 157–163.

Zou, H. Y., Liu, G. B. and Wang, H. S. 2002. The vegetation development in the North Ziwuling forest region in last fifty years. *Acta Botanica Boreali-Occidentalia Sinica* (in Chinese). **22**(1): 1–8.