Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China

Yafeng Wang, Bojie Fu^{*}, Yihe Lü, Liding Chen

State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, PR China

ARTICLE INFO

Article history:

Received 1 October 2010

Received in revised form 17 November 2010

Accepted 17 December 2010

Keywords:

Semi-arid environment

Cesium-137

Loess plateau

Vegetation cover

Multiple scales

Soil organic carbon

Ecological restoration

Soil erosion

ABSTRACT

Soil organic carbon (SOC) sequestration by vegetation restoration is the theme of much current research. Since 1999, the program of “Grain for Green” has been implemented in the semi-arid Loess Plateau, China. Its scope represents the largest vegetation restoration activity in China. However, it is still unclear for the SOC sequestration effects of vegetation cover change or natural succession promoted by the revegetation efforts at different scales under the semi-arid conditions. In this study, the changes in SOC stocks due to the vegetation restoration in the middle of Loess Plateau were estimated at patch, hill slope transect and small watershed scale from 1998 to 2006. Soil samples were taken from field for the determination of cesium-137 (¹³⁷Cs) and SOC contents. Vegetation cover change from 1998 to 2006 at the small watershed scale was assessed using Geographic Information System. The results showed that cropland transforming to grassland or shrubland significantly increased SOC at patch scale. Immature woodland, however, has no significant effect. When vegetation cover has no transformation for mature woodland (25 years old), SOC has no significant increase implying that SOC has come to a stable level. At hill slope scale, three typical vegetation cover patterns showed different SOC sequestration effects of 8.6%, 24.6%, and 21.4% from 1998 to 2006, and these SOC increases mainly resulted from revegetation. At the small watershed scale, SOC stocks increased by 19% in the surface soil layer at 0–20 cm soil depth from 1998 to 2006, which was equivalent to an average SOC sequestration rate of 19.92 t C y^{−1} km^{−2}. Meanwhile, SOC contents showed a significant positive correlation ($P < 0.001$) with the ¹³⁷Cs inventory at every soil depth interval. This implied significant negative impacts of soil erosion on SOC sequestration. The results have demonstrated general positive effects of vegetation restoration on SOC sequestration at multiple scales. However, soil erosion under rugged topography modified the spatial distribution of the SOC sequestration effects. Therefore, vegetation restoration was proved to be a significant carbon sink, whereas, erosion could be a carbon source in high erosion sensitive regions. This research can contribute to the performance assessment of ecological rehabilitation projects such as “Grain to Green” and the scientific understanding of the impacts of vegetation restoration and soil erosion on soil carbon dynamics in semi-arid environments.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Soil organic carbon (SOC) is a dynamic component of terrestrial systems, with both internal changes and external exchanges with the atmosphere and the biosphere (Zhang and McGrath, 2004). Restoring soil carbon is essential to enhancing soil quality, sustaining and improving food production, maintaining clean water, and reducing increases in atmospheric CO₂ (Lal, 2004). SOC plays important roles in enhancing crop production (Stevenson and Cole, 1999) and mitigating greenhouse gas emissions (Post and Kwon, 2000). SOC is related to

atmospheric CO₂ levels with soils having the potential for C release or sequestration, depending on vegetation cover, land management and climate (Lal, 2004). Developing technologies to reduce the rate of increase of atmospheric CO₂ concentration is an important issue of the 21st century (Lal, 2008).

Terrestrial ecosystems play a significant role in the global carbon cycle because soils contain a stock of carbon that is about twice as large as that in the atmosphere and about three times that in vegetation (Smith et al., 2008). In semi-arid areas, which are characterized by fragile ecological systems, soil organic carbon is greatly susceptible to environment changes, especially to vegetation cover change. During the past two centuries, vegetation cover practices, such as deforestation and tillage, have resulted in a net loss of soil carbon to the atmosphere. Another crucial process that can drastically alter the soil C stock at the catchment scale is land cover change. In recent years, many studies have been conducted to estimate the

^{*} Corresponding author. State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, P. O. Box 2871, Beijing 100085, PR China. Tel./fax: +86 10 62923557.

E-mail address: bfu@rcees.ac.cn (B. Fu).

effects of land cover changes on soil carbon stocks. During land cover change, soil may act either as a carbon source or as a carbon sink, depending on the ratio between the carbon of inflows and outflows. Studies addressing SOC dynamics when land is converted from one cover type to another would be valuable in improving our understanding and increasing our predictive capability over both short and long timescales (Post and Kwon, 2000). The review of Guo and Gifford (2002) indicated a decrease of 59% in SOC due to a change from pasture to cropland. The highest losses recorded for the conversion from pasture to crops were found in areas where precipitation range is 400–500 mm. They also found an up to 53% increase of SOC after the change from crop to secondary forest. Other studies indicated that after 20 years of afforestation the total amount of soil C increased by 23% in the first 10 cm of soil in humid Mediterranean conditions (Galdo et al., 2003). Wang et al. indicated that it is only in 5 cm depth of soil surface that SOC contents are significant for different land covers at semi-arid climate of the hilly Loess Plateau of China (Wang et al., 2010). Reductions of 10% to 40% of the soil C in cultivated soils compared with the non-cultivated soils have been reported in China with the highest losses from the semi-arid and subhumid areas (Wu et al., 2003). In central Spain, results show extensification using longer-term pasture rotations (e.g. 5-year) could increase SOC levels (Boellstorff, 2009). Therefore, sequestering additional soil C can be achieved through improved management techniques on current agricultural lands and by the transformation of cultivated soils to forest or grassland ecosystems (Guo and Gifford, 2002; Guo et al., 2004; Heath et al., 2003).

Recent concerns about rising carbon dioxide (CO₂) concentrations in the atmosphere have led to speculation that a large amount of carbon may be sequestered in the soil. This may happen through forestation and other vegetation restoration driven by land use conversions (DeGryze et al., 2004).

At regional (Esser, 1995; Fang et al., 2001; Fearnside and Imbrozio Barbosa, 1998; Houghton, 1999; Kerr et al., 2003; Liu et al., 2008; Smith et al., 2000; Tan et al., 2009) and global scales (Esser, 1987; Houghton, 1999), many efforts have been carried out in determining the changes of SOC storage induced by land cover change. However, because of the high inherent natural variability in the world's soils and variable dynamics of carbon loss under different land cover types and change trajectories, accurate estimates of the historic loss are usually hampered by the lack of the required baseline data on soils (Lal, 2009). More accurate estimates on the size of the current SOC storage and the human-induced changes at patch, a piece of land which has

uniform land cover and topography, typical comparable hill slope, and watershed scale are highly needed, especially based on dynamic data. This would provide a basis for a better understanding of the dynamic spatial–temporal variations of SOC.

China's Loess Plateau, covering approximately 58×10^4 km², is known for its long agricultural history and serious soil erosion. Since the 1950s substantial efforts in soil erosion control and ecological rehabilitation have been made by Chinese government, for example, extensive tree plantation in the loess plateau in the 1970s, integrated soil erosion control at the watershed scale in the 1980s and 1990s. Check-dams have been built in hilly and gully region since 1970s. Despite these efforts, soil erosion was still intensive, and vegetation had not grown up well by the late 1990s. In 1999, another project, Grain-to-Green, was initiated for soil erosion control and land quality improvement using widespread conversion of sloping cropland to forest and grassland on the Loess Plateau. In this project, it was suggested to convert all croplands with slopes of over 25° to green land covered with forest or grass, while the local farmers would receive grain and cash subsidy from the government for the loss of food due to cropland decrease (Chen et al., 2007).

Understanding the effect of vegetation restoration on soil carbon sequestration is valuable in estimating the potential of human in climate change adaptation. This is also one of the important pathways to evaluate the performance of ecological restoration efforts. Meanwhile, understanding landscape structure and functioning requires multiscale information, and scaling functions are the most precise and concise way of quantifying multiscale characteristics explicitly (Wu, 2004). Therefore, the objectives of the present study were: (1) to estimate SOC change responding to vegetation restoration at patch (single vegetation cover) and hill slope (combinations of different vegetation types) scales from 1998 to 2006; (2) to reconstruct the dynamics of SOC inventories at watershed scale; (3) to interpret the mechanism and implications of SOC sequestration in Loess Plateau along with vegetation restoration driven by vegetation cover conversion.

2. Materials and methods

2.1. Study area

The study area is the Yangjuangou catchment (36°42'N, 109°31'), which located in the middle part of the loess plateau in northern Shaanxi Province, China (Fig. 1). It is 14 km east to Yan'an city

Fig. 1. Location of Yangjuangou catchment and soil sampling locations. (Elevation contours are 10 m interval).

and covers an area of 2.02 km². There are significant topographic variations within the loess hills and gully landforms of the study area. The maximum altitude difference from hill top to gully bottom is 225 m. The gully density is 2.74 km km⁻². The region has a semi-arid continental climate with an average annual rainfall of 535 mm. The rainfall is concentrated mainly between July and September and varies greatly from year to year. The soil in the study area is mainly derived from loess, which is fine silt to silt in texture and weakly resistant to erosion. The erosion rate is severe with an average soil loss of 8979 t km⁻² y⁻¹ between 1991 and 1996 (Li et al., 1997). The natural vegetation has been destroyed by cultivation, and after several years of rehabilitation, many changes have taken place in the agricultural landscape.

2.2. Soil sampling and laboratory analysis

In 1998, three transects with typical vegetation structures in existence for about 15 years were selected on the hill slopes of the

Yangjuangou catchment. The vegetation cover patterns from foot to top of the slope were (Fig. 2):

- (I) naturally recovered grass/cultivated crops/forest plantation (Fig. 2a);
- (II) cultivated crops/naturally recovered grass/forest plantation (Fig. 2b);
- (III) cultivated crops/forest plantation/naturally recovered grass (Fig. 2c).

The grasses were mainly *Artemisia* Linn, couch grass and small weeds, and the shrubs were *Prunus armniaca* and *Hippophae rhamnoides* in the mature forest and *Robinia pseudoacacia* in the young forest. They were developed from former sloping farmland. The shape and gradient of the three vegetation cover types are identical. The slope gradients range from 10° to 30° from the hill foot to the upper slope. Nutrient levels were determined for the surface soil samples at 0–20 cm depth. Three samples were taken from each vegetation cover type. About 10 samples were taken from each

Fig. 2. Three vegetation cover patterns in the study area. (left is in 1998, right is in 2006).

transect, resulting a total of 32 from the three transects (Fu et al., 2000).

In 2006, the second samplings were taken, 105 locations were selected in the watershed. Soil was collected to 30 cm depth with a soil core auger (Eijkelkamp, diameter 60 mm), and divided in 0–5 cm, 5–10 cm, 10–20 and 20–30 cm intervals. 3 cores taken within a 1 m × 1 m square were combined in one sample. At least three different positions from top, middle and bottom were selected under each vegetation cover type. These sites were distributed throughout the catchment according to different topographic positions and vegetation covers, including those three transects sampled in 1998.

2.3. Laboratory analysis

Soil samples were analysed at State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. After being air-dried in the laboratory and sieved through a 2 mm screen, the samples were weighed. Using HPGe co-axial detectors coupled to a multi-channel analyzer, soil ^{137}Cs was measured. In order to minimize the uncertainties associated with the precision of ^{137}Cs measurements, ^{137}Cs was detected at 662 keV with counting times of about 30 000 s. This provides results with a counting error less than 10% at the 95% confidence level. Specific activity is gained by reference to comparative standard sources. In this study, the reference site its altitude is the highest in the region, where built up an old temple 60 yrs ago and without human activity. Therefore it is rational to present the reference value for ^{137}Cs , the average is 1755.2 Bq m^{-2} (Fu et al., 2009).

Soil erosion can be estimated using the simplified mass balance model (SMBM) (Zhang et al., 1990), which has widely been applied to the Loess Plateau, was used to estimate soil redistribution at Yangjuangou from the ^{137}Cs measurements:

$$A = A_{\text{ref}} \left(1 - \frac{h}{H} \right)^{(T-1963)}$$

Where A is the area activity of sampling point ^{137}Cs ($\text{Bq} \cdot \text{m}^{-2}$), A_{ref} is the ^{137}Cs background value of the study area (Bq m^{-2}), h is the depth of soil loss every year (cm), H is the depth of cultivated layer (cm), and T is the year of sampling.

SOC was determined using the dichromate oxidation method (external heat applied) (Liu et al., 1996). The sample was weighed and placed in 150 mL Erlenmeyer flasks; 5 mL of chromous mixture (using 0.2 M potassium dichromate solution in diluted (1:1) sulphuric acid) was added. Wet combustion was performed according to the thermostat. Combustion time was measured from the moment when the temperature in the thermostat rose to 160°C for 30 min. After cooling, the content of the flasks was transferred to 50 mL measuring flasks and diluted. And finally SOC was measured using a calibrated burette to add the titrant. For an individual profile with the layers, total organic carbon by volume (SOC, C kg m^{-2}) is given by:

$$\text{SOC}_d = \sum_{i=1}^k \text{OC}_i \times \text{BD}_i \times D_i \times (1 - S_i)$$

Where SOC_d is the total amount of organic carbon (C kg m^{-2}) above depth d , BD_i (Mg m^{-3}) is the dry bulk density of layer i , OC_i is the concentration of organic carbon (C%) in layer i , D_i is the thickness of this layer (cm), and S_i is the volume of the fraction of fragments $> 2 \text{ mm}$. In this study, the loess particle size is not greater than 2 mm, so S_i value was 0.

The total SOC pool (P_{oc}) of topsoil is calculated as:

$$P_{\text{oc}} = \sum_i^n S_i \times \sum_{ij}^{nm} \text{SOC}_{ij} \times \text{BD} \times H_j \times 10^{-1}$$

Where j is the different depth of topsoil (1 = 0–5 cm, 2 = 5–10 cm, 3 = 10–20 cm); S_i is the total area (ha) of a given land-use type i ; and BD is soil bulk density (g cm^{-3}). The soil bulk density used here is the mean value of loess (1.25 g cm^{-3}). SOC concentration in 20–30 cm does not calculate in order to compare with those of 1998.

2.4. Vegetation/land cover mapping and change analysis

Aerial photograph interpretation and field survey techniques were used to classify vegetation cover type for land use mapping in 1998 (Fu et al., 2000). Land use for Yangjuangou was extracted from a 10-m resolution ALOS satellite image taken in 2006. Arcgis9.2 was used for analysis of land cover change in the study area between 1998 and 2006.

2.5. Statistical analyses

Figures were made by Origin8.0 and Excel2003 software. Linear regression analysis was carried out to test the correlation between SOC and ^{137}Cs . Two Sample T -test was adopted to compare SOC changes for the three transects from 1998 to 2006. One-way analysis of variance (ANOVA) was used to compare concentrations of ^{137}Cs at different slope positions. For all data, all differences reported in the text were tested and considered significant at $\alpha = 0.05$.

3. Results

3.1. SOC change at patch scale

In 1998, the vegetation cover types were mainly cultivated crops, natural recovered grass and forest plantation in the catchment, which were included by those three typical vegetation cover patterns of the slope transects. At patch scale, vegetation cover changes are from cultivated crops to natural grass, or scrub, or immature forest. Meanwhile, vegetation cover with no conversion is mature forest plantation. Tables 1 and 2 respectively showed SOC contents change under the situation of conversion and no conversion.

Different types of vegetation conversions result in dissimilar trends of SOC changes. As for vegetation cover pattern (I): When vegetation cover changed from cultivated crops to immature forest, the SOC had almost no increase was detected from 1998 to 2006. After 8 yrs, the SOC concentration under grass cover increased by 27.5%, from 3.41 g kg^{-1} to 4.35 g kg^{-1} , and the SOC under forest had no evident change (Fig. 3a). For vegetation cover pattern (II): Cultivated crops was converted to scrubs, the SOC showed increased tendency, similar trends were obtained for grassland and forestland (Fig. 3b). For vegetation cover pattern (III): it is evident that the conversion from cultivated crops to grass cover has higher capacity for SOC

Table 1

Descriptive statistics of SOC on conversion of sloping cropland to grassland/woodland (Units: g kg^{-1}).

Vegetation cover conditions	n	V _{average}	S.E.	S.D.	min	max	Confidence (95.0%)
Before conversion	11	2.95	0.08	0.28	2.50	3.41	0.19
After conversion	13	4.13	0.35	1.25	3.05	6.76	0.76

Table 2

Descriptive Statistics of SOC under no vegetation cover conversion in field from 1998 to 2006 (Units: g kg^{-1}).

No conversion	n	V _{average}	S.E.	S.D.	min	max	Confidence (95.0%)
1998	21	4.38	0.31	1.43	2.59	8.02	0.65
2006	22	4.84	0.22	1.03	2.66	6.88	0.46

Fig. 3. SOC concentration change in different vegetation cover type from 1998 to 2006 (a, b, c respectively mean three selected transects: (I); (II); and (III). Where C = Cropland, G = Grassland, S = shrubland, I = immature forestland, F = Forestland; different letter indicate vegetation cover changed).

sequestration than other vegetation cover changes. When sloping cropland was abandoned, SOC was significantly increased ($t=3.04$, $P=0.006$) owing to vegetation restoration. The concentration of SOC increased from 2.839 g kg^{-1} to 5.262 g kg^{-1} . The SOC changes were not significant under forest and grass cover (Fig. 3c).

Fig. 4. Change of SOC contents in the three hillslope transects.

At patch scale, vegetation cover change can affect the SOC concentration. The conversion from cultivated crops to natural grass cover, showed the highest potential for SOC sequestration. Under the conversion from cultivated crops to immature forest, SOC content indicated no evident increase possibly due to high consumption of soil nutrients for biomass accumulation and the restriction of grass cover establishment under the high density canopy coverage.

3.2. SOC change at hill slope scale

Comparing the SOC contents of the three types of vegetation cover pattern (Fig. 4), it is clear that the SOC increased from 1998 to 2006. Compared with 1998, The SOC contents of these vegetation cover patterns increased by 8.6%, 24.6%, and 21.4%, respectively. After vegetation cover conversion, the vegetation cover patterns II and III represented higher potential for SOC sequestration.

Under the vegetation pattern change in the three transects, the effectiveness of SOC sequestration correlated with slope position (Fig. 5a, b, and c). The results demonstrated that under different slope transects, SOC distribution trends were very similar at all slope

Fig. 5. SOC contents under different transects at different slope position in 1998 and 2006.

Table 3
Descriptive statistics of SOC in catchment from 1998 to 2006 (Units: g kg^{-1}).

	mean	S.E.	S.D.	square	min	max	No.	Confidence (95.0%)
1998	3.89	0.24	1.35	1.82	2.50	8.02	32	0.49
2006	4.66	0.18	1.20	1.43	2.52	11.01	105	0.23

S.E. means standard error, and S.D. means Standard deviation.

Table 4
SOC storage and density (0–20 cm) of different vegetation cover type in Yangjuangou watershed in 1998.

	Forestland	Grassland	Orchard	Slope Cropland	Total
Area (ha)	30	87.3	27.4	34.1	178.8
Percent Area (%)	16.8	48.8	15.3	19.1	100
D_{oc} (tC ha^{-1})	12.43	9.60	8.90	7.38	9.54 ^a
P_{oc} (tC)	372.75	838.08	243.86	251.49	1706.18
Percent P_{oc} (%)	21.85	49.12	14.29	14.74	100

^a Is SOC density of land-use area-weighted; D_{oc} means soil organic carbon density; P_{oc} means soil organic carbon pool.

Table 5
SOC storage and density (0–20 cm) of different vegetation cover type in Yangjuangou watershed in 2006.

	Forestland	Grassland	Immature forestland	Orchard land	Cropland terraced	Total
Area (ha)	26.8	77.5	39.7	18.0	15.6	177.6
Percent Area (%)	15.1	43.67	22.35	10.12	8.76	100
D_{oc} (tC ha^{-1})	12.09	11.94	10.84	11.7	8.66	11.41 ^a
P_{oc} (tC)	324.13	925.83	430.24	210.13	134.66	2025.00
Percent P_{oc} (%)	16.01	45.72	21.25	10.38	6.65	100

^a Is SOC density of vegetation cover area-weighted; D_{oc} means soil organic carbon density; P_{oc} means soil organic carbon pool.

positions. Soil with low organic carbon content was mostly from middle slope position, but the higher SOC content was found on the upper slope position. From 1998 to 2006, SOC content significantly

increased at down slope position for these transects. The SOC sequestration effect is more consistent for the transect II slope.

3.3. SOC change at catchment scale

At catchment scale, for ascertaining the SOC change, the reference levels of SOC were those derived from the 32 samples in 1998 (Table 3). The results indicated that SOC concentration increased from $3.89 \pm 0.24 \text{ g kg}^{-1}$ to $4.66 \pm 0.12 \text{ g kg}^{-1}$. The SOC contents increased 19.7% from 1998 to 2006 at watershed scale.

Vegetation covers have an effect on SOC density (Tables 4 and 5). The SOC density of different Vegetation cover types followed the order of forest plantation>orchard>naturally recovered grass>immature forest>cultivated crops on terraces. The SOC density under forest, grass and orchard increased by 29%, 28% and 28%, respectively, compared to that of the sloping cropland. In this sense, the carbon sequestration effects of the above three vegetation covers are nearly the same in spite of their different ages of succession (over 20 yrs for forest and orchard; 7 yrs for natural grass restoration).

Vegetation cover pattern changed significantly (Fig. 6) in the Yangjuangou watershed from 1998 to 2006 driven by economic, environmental, and policy factors. The most significant change was vegetation restoration on sloping croplands. The percent of sloping cropland has declined from 16.9% in 1998 to 0.11% in 2006. Forest cover retained relative stable level above 15.0%. Immature forest increased rapidly from 0.19% in 1998 to 22.35% in 2006. The estimated SOC stock of the top soil (0–20 cm) in Yangjuangou watershed were 1706.18 tC in 1998 and 2025 tC in 2006, respectively. The overall effect of SOC sequestration in the surface soil layer (0–20 cm) amounted to 19% at the catchment scale from 1998 to 2006 as the result of vegetation restoration. This implied that the Yangjuangou catchment has acted as a C sink during the vegetation restoration Process. Due to relatively good vegetation cover, less disturbance and the stable SOC input and output in this area, SOC stock per unit area in the topsoil layer in this study was at the moderate level.

Fig. 6. Vegetation cover map at Yangjuangou catchment in 1998 and 2006.

4. Discussion

4.1. SOC sequestration potentials as affected by vegetation Restoration pathways and ecological succession

There are many factors and processes that determine the direction and rate of change in SOC content along with the changes of vegetation and soil management practices (Post and Kwon, 2000). The present study indicated that different vegetation restoration pathways and ecological successions had different potentials for SOC sequestration. There were three vegetation restoration pathways including cultivated crops to grass, cultivated crops to scrubs, and cultivated crops to immature forest plantation (Fig. 3). The former two pathways increased SOC significantly with grass cover as the more effective one in SOC sequestration. This implied a comparative high effectiveness of grass cover on SOC sequestration at early stages of cropland abandonment for natural vegetation restoration (Kucharik et al., 2001). However, the effects of SOC sequestration under well structured shrub and forest communities can exceed those under grass covers (De Kovel et al., 2000; Goberna et al., 2006; McClaran et al., 2008).

Vegetation cover types including grass and forest experienced no changes along the three hill slope transects (Fig. 3). The ecological succession of the grass communities had a significant effect on SOC sequestration, whereas, no such effect was detected for the forest communities. This can be attributed to a shorter life cycle of grass as compared with trees, contributing to larger C cycling coming from leaves and roots in superficial soil (Dube et al., 2009). For forest communities, however, there are time thresholds corresponding to the environmental conditions for significant enhancement of soil quality and Specifically SOC sequestration. For example, in Mediterranean semiarid areas SE Spain, SOC was three times higher in former shrubland than in former barley field. Meanwhile, the incorporation of organic matter into the soil was probably delayed by the quality of recalcitrant pine litter and the unfavorable semiarid climate (Ruiz-Navarro et al., 2009); Soil C sequestration with improved soil management is highly time-dependent; the effect lasted for only 20–80 years. Generally, practicing no-tillage causes higher rate and longer sustainability of soil C sequestration than only increasing crop residue into soils (Yan et al., 2007). The SOC was increased consistently and rapidly during the first 17 years of forest development in the Loess Plateau of China (Jia et al., 2005). Beyond the thresholds, the effects of SOC sequestration would change to more stable states. In the present study, the forest plantation was about 25 years old in 2006 and there were no significant increase in SOC under the forest cover after 1998. This suggests that it may take about 17–18 years for the forest plantations to achieve the most potential in SOC sequestration in semi-arid loess plateau.

From the above analysis, it can be proposed that the sloping cropland (or marginal cropland) set aside approach is viable and cost-effective for ecological restoration with objectives of carbon sequestration and soil quality enhancement at early stages. After the nursery stage of grass cover, shrub or forest species would be much easier to establish for either natural colonization or planting.

4.2. Carbon sequestration and soil erosion

It is no doubt that soil erosion, as a wide spread transport process in terrestrial ecosystems, can have important implications for the dynamics of the soil carbon pool. However, the roles that soil erosion can play as a carbon source or sink are still a scientific subject of hot debate (Lal, 2005; Quine and van Oost, 2007). An ecological and geomorphologic perspective on organic C movement through landscapes can contribute significantly to the resolution of this contested subject (Kuhn et al., 2009).

Fig. 7. Plot of the relationship between ^{137}Cs (Bq kg^{-1}) and soil organic carbon (%) in 0–20 cm soil depths at Yangjuangou watershed.

In the present study, SOC inventory was strongly and significantly correlated with ^{137}Cs inventory (Bq m^{-2}) at high significance levels ($R^2 = 0.4424$, $P < 0.001$), for 0–20 cm soil depths (Fig. 7). This relationship implied that SOC inventories increases with decreasing soil erosion at the watershed scale. This result is consistent with those studies by Ritchie and McCarty (2003) and Zhang et al. (2006), suggesting that soil erosion can result in net losses of SOC from the soil carbon pool. The underlying mechanism of this effect is the selective removal of the most labile fraction of SOC in water erosion process (Zhang et al., 2005; Zhang et al., 2006).

At the slope scale, the above correlation between soil erosion and SOC still hold. For the slope transects I and III, the soil erosion intensity was higher at middle-up slope more than down and summit slope (Fig. 8). And the down slope position, with gentler slope and improved soil cover by vegetation restoration and ecological succession, more deposition and soil quality improvement could be expected (Fig. 9). With vegetations being restored on middle and upper slope position, soil erosion was also decreased when cover crops were converted to grass or forest cover. It is propitious to SOC accumulation

Fig. 8. Distribution of soil erosion intensity (EI) in typical slope: (a) transect I; (b) transect III.

Fig. 9. Characteristics of cesium-137 concentration at different slope position.

because of increased biomass and vegetation cover and decreased erosion intensity (Gregorich et al., 1998; Li et al., 2006).

Except for the erosive rainfall events, topography is one of the major factors controlling erosion and deposition processes. Therefore, many studies under different environmental conditions correlated SOC stocks to topographic features and attributed this correlation to the influence of topography on water dynamics (Arrouays et al., 1998; Awasthi, 2004; Chaplot et al., 2001; Pennock and Kessel, 1997; Thompson et al., 1997). Lower positions as well as low slope gradients or curvatures were shown to associate with high SOC stocks due to the decrease in the velocity of the running water coming from upslope, thus allowing the deposition of eroded organic C (Gregorich et al., 1998). Another main process leading to greater SOC stocks at downslope or summit positions may be the lower mineralization potential (Janzen, 2006).

Even soil erosion and the loss of SOC correlate positively, the net loss of SOC during erosion processes does not necessarily result in net source of carbon to the atmosphere (Smith et al., 2005). Lal (2005) addressed this uncertainty from the perspectives of different disciplines and called for the measuring and monitoring of SOC in eroded landscapes to understand the fate of eroded SOC. Multiple factors are needed to be considered (Quine and van Oost, 2007) in the monitoring and analysis.

5. Conclusion

The assessment of ecological restoration efforts on the enhancement of ecosystem services is crucial for gauging the restoration success (Benayas et al., 2009). This assessment is of a multi-attribute analysis with SOC as one of the important indicators for ecological process or ecosystem function (Laggoun-Défarge et al., 2008; Ruiz-Jaen and Aide, 2005). We can conclude from the present study that vegetation restoration can significantly enhance the SOC stock of surface soil (0–20 cm). The trends of SOC change are similar at patch, hill slope, and watershed scales. At the watershed scale, the average rate of SOC enrichment in the surface soil layer amounted to 19% after revegetation of sloping croplands and ecological succession from 1998 to 2006. Vegetation patterns or combinations can make difference at the slope transect scale with the SOC enhancement rates from 8.6% to 24.6%. With the growth of above ground vegetation and the underground SOC accumulation, vegetation restoration in the semi-arid Loess Plateau makes a significant carbon sink. In this sense, the vegetation restoration efforts are effective. However, afforestation in the semi-arid Loess Plateau can lead to water shortage problem (Cao et al., 2009). This further iterates the multidimensionality of restoration success evaluation, for which the trade-offs between ecosystem services and disservices brought about by ecological restoration efforts are indispensable. The trade-off analysis should incorporate spatial covariance, spatiotemporal scales, and scaling (Anderson et al., 2009; Rodriguez et al., 2006).

Soil erosion by water can modify the effects of SOC sequestration significantly in semi-arid and topographically complex landscapes as indicated by this study via the correlation analysis between ^{137}Cs inventory and SOC stock. The net effect of erosion on SOC is the integration of sources and sinks of SOC at the landscape scale during the erosion process. Whether soil erosion functions as source or sink for atmospheric carbon pool still remains an open scientific question because many intricate processes are involved in carbon dynamics during soil erosion. It is still too early to draw concrete and general conclusions on this scientific issue until long term monitoring and enough scientific understandings of these complex and interacting processes are being made.

Acknowledgments

The research was supported by the National Basic Research Program of China (No. 2009CB421104), National Natural Science Foundation of China (Nos. 40925003, 40930528 and 40901098), China Postdoctoral Science Foundation (No. 20090450597) and the CAS/SAFEA International Partnership Program for Creative Research Teams of “Ecosystem Processes and Services”.

References

- Anderson, B.J., Armsworth, P.R., Eigenbrod, F., Thomas, C.D., Gillings, S., Heinemeyer, A., Roy, D.B., Gaston, K.J., 2009. Spatial covariance between biodiversity and other ecosystem service priorities. *J. Appl. Ecol.* 46, 888–896.
- Arrouays, D., Daroussin, J., Kicin, J.L., Hassika, P., 1998. Improving topsoil carbon storage prediction using a digital elevation model in temperate forest soils of France. *Soil Sci.* 163, 103–108.
- Awasthi, K.D., 2004. Land use change effects on soil degradation, carbon and nutrient stocks and greenhouse gas emission in mountain watersheds. C821192 Thesis, Norges Landbrukskole (Norway), Norway, pp. 148.
- Benayas, J.M.R., Newton, A.C., Diaz, A., Bullock, J.M., 2009. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science* 325, 1121–1124.
- Boellstorff, D.L., 2009. Estimated soil organic carbon change due to agricultural land management modifications in a semiarid cereal-growing region in Central Spain. *J. Arid Environ.* 73, 389–392.
- Cao, S.X., Chen, L., Yu, X.X., 2009. Impact of China's Grain for Green Project on the landscape of vulnerable arid and semi-arid agricultural regions: a case study in northern Shaanxi Province. *J. Appl. Ecol.* 46, 536–543.
- Chaplot, V., Bernoux, M., Walter, C., Curmi, P., Herpin, U., 2001. Soil carbon storage prediction in temperate hydromorphic soils using a morphologic index and digital elevation model. *Soil Sci.* 166, 48–60.
- Chen, L.D., Gong, J., Fu, B.J., Huang, Z.L., Huang, Y.L., Gui, L.D., 2007. Effect of land use conversion on soil organic carbon sequestration in the loess hilly area, loess plateau of China. *Ecol. Res.* 22, 641–648.
- De Kovel, C.G.F., Van Mierlo, A.E.M., Wilms, Y.J.O., Berendse, F., 2000. Carbon and nitrogen in soil and vegetation at sites differing in successional age. *Plant Ecol.* 149, 43–50.
- DeGryze, S., Six, J., Paustian, K., Morris, S.J., Paul, E.A., Merckx, R., 2004. Soil organic carbon pool changes following land-use conversions. *Glob. Change Biol.* 10, 1120–1132.
- Dube, F., Zagal, E., Stolpe, N., Espinosa, M., 2009. The influence of land-use change on the organic carbon distribution and microbial respiration in a volcanic soil of the Chilean Patagonia. *For. Ecol. Manag.* 257, 1695–1704.
- Esser, G., 1987. Sensitivity of global carbon pools and fluxes to human and potential climatic impacts. *Tellus* 39B, 245–260.
- Esser, G., 1995. Contribution of Monsoon Asia to the carbon budget of the biosphere, past and future. *Plant Ecol.* 121, 175–188.
- Fang, J., Chen, A., Peng, C., Zhao, S., Ci, L., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* 292, 2320–2322.
- Fearnside, P.M., Imbrozio Barbosa, R., 1998. Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *For. Ecol. Manag.* 108, 147–166.
- Fu, B.J., Chen, L.D., Ma, K.M., Zhou, H.F., Wang, J., 2000. The relationships between land use and soil conditions in the hilly area of the loess plateau in northern Shaanxi, China. *Catena* 39, 69–78.
- Fu, B.J., Wang, Y.F., Lu, Y.H., He, C.S., Chen, L.D., Song, C.J., 2009. The effects of land-use combinations on soil erosion: a case study in the Loess Plateau of China. *Prog. Phys. Geogr.* 33, 793–804.
- Galdo, I.D., Six, J., Peressotti, A., Cotrufo, M.F., 2003. Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable C isotopes. *Glob. Change Biol.* 9, 1204–1213.
- Goberna, M., Sánchez, J., Pascual, J.A., García, C., 2006. Surface and subsurface organic carbon, microbial biomass and activity in a forest soil sequence. *Soil Biol. Biochem.* 38, 2233–2243.
- Gregorich, E.G., Greer, K.J., Anderson, D.W., Liang, B.C., 1998. Carbon distribution and losses: erosion and deposition effects. *Soil Till. Res.* 47, 291–302.

- Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. *Glob. Change Biol.* 8, 345–360.
- Guo, R.B., Liang, X.M., Chen, J.P., Wu, W.Z., Zhang, Q., Martens, D., Kettrup, A., 2004. Prediction of soil organic carbon partition coefficients by soil column liquid chromatography. *J. Chromatogr. A* 1035, 31–36.
- Heath, L.S.K., John, M., Birdsey, Richard A., Lal, Rattan, 2003. The potential of U.S. forest soils to sequester carbon and Mitigate the Greenhouse Effect. CRC Press, Boca Raton, pp. 385–394.
- Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus* 51B, 298–313.
- Janzen, H.H., 2006. The soil carbon dilemma: shall we hoard it or use it? *Soil Biol. Biochem.* 38, 419–424.
- Jia, G.M., Cao, J., Wang, C.Y., Wang, G., 2005. Microbial biomass and nutrients in soil at the different stages of secondary forest succession in Ziowulin, northwest China. *For. Ecol. Manag.* 217, 117–125.
- Kerr, S., Liu, S., Pfaff, A.S.P., Hughes, R.F., 2003. Carbon dynamics and land-use choices: building a regional-scale multidisciplinary model. *J. Environ. Manag.* 69, 25–37.
- Kucharik, C.J., Brye, K.R., Norman, J.M., Foley, J.A., Gower, S.T., Bundy, L.G., 2001. Measurements and modeling of carbon and nitrogen cycling in agroecosystems of southern Wisconsin: potential for SOC sequestration during the next 50 years. *Ecosystems* 4, 237–258.
- Kuhn, N.J., Hoffmann, T., Schwanghart, W., Dotterweich, M., 2009. Agricultural soil erosion and global carbon cycle: controversy over? *Earth Surf. Process. Land.* 34, 1033–1038.
- Laggoun-Défarge, F., Mitchell, E., Gilbert, D., Disnar, J.-R., Comont, L., Warner, B.G., Buttler, A., 2008. Cut-over peatland regeneration assessment using organic matter and microbial indicators (bacteria and testate amoebae). *J. Appl. Ecol.* 45, 716–727.
- Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627.
- Lal, R., 2005. Soil erosion and carbon dynamics. *Soil Till. Res.* 81, 137–142.
- Lal, R., 2008. Carbon sequestration. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 815–830.
- Lal, R., 2009. Challenges and opportunities in soil organic matter research. *Eur. J. Soil Sci.* 60, 158–169.
- Li, Y., Yang, J., Zhu, Y., 1997. Using ^{137}Cs and ^{210}Pb to assess the sediment sources in a dam reservoir catchment on the Loess Plateau, China. *China Nuclear Sciences and Technology Report*. Atomic Energy Press, Beijing, pp. 1–15.
- Li, Y., Zhang, Q.W., Reicosky, D.C., Bai, L.Y., Lindstrom, M.J., Li, L., 2006. Using ^{137}Cs and ^{210}Pb for quantifying soil organic carbon redistribution affected by intensive tillage on steep slopes. *Soil Till. Res.* 86, 176–184.
- Liu, G.S., Jiang, N.H., Zhang, L.D., Liu, Z.L., 1996. Soil Physical and chemical analysis and description of soil profile. China Standardization Publishing House, Beijing, pp. 131–134 (In Chinese).
- Liu, J., Liu, S., Loveland, T.R., Tieszen, L.L., 2008. Integrating remotely sensed land cover observations and a biogeochemical model for estimating forest ecosystem carbon dynamics. *Ecol. Model.* 219, 361–372.
- McClaran, M.P., Moore-Kucera, J., Martens, D.A., van Haren, J., Marsh, S.E., 2008. Soil carbon and nitrogen in relation to shrub size and death in a semi-arid grassland. *Geoderma* 145, 60–68.
- Pennock, D.J., Kessel, C.V., 1997. Effect of agriculture and of clear-cut forest harvest on landscape-scale soil organic carbon storage in Saskatchewan. *Can. J. Soil Sci.* 77, 211–218.
- Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. *Glob. Change Biol.* 6, 317–327.
- Quine, T.A., van Oost, K., 2007. Quantifying carbon sequestration as a result of soil erosion and deposition: retrospective assessment using caesium-137 and carbon inventories. *Glob. Change Biol.* 13, 2610–2625.
- Ritchie, J.C., McCarty, G.W., 2003. ^{137}Cs and soil carbon in a small agricultural watershed. *Soil Till. Res.* 69, 45–51.
- Rodriguez, J.P., Beard Jr., T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., Dobson, A.P., Peterson, G.D., 2006. Trade-offs across space, time, and ecosystem services. *Ecol. Soc.* 11 (1), 28.
- Ruiz-Jaen, M.C., Aide, T.M., 2005. Restoration success: how is it being measured? *Restor. Ecol.* 13, 569–577.
- Ruiz-Navarro, A., Barberá, G.G., Navarro-Cano, J.A., Albaladejo, J., Castillo, V.M., 2009. Soil dynamics in *Pinus halepensis* reforestation: effect of microenvironments and previous land use. *Geoderma* 153, 353–361.
- Smith, W.N., Desjardins, R.L., Pattey, E., 2000. The net flux of carbon from agricultural soils in Canada 1970–2010. *Glob. Change Biol.* 6, 557–568.
- Smith, S.V., Sleezer, R.O., Renwick, W.H., Buddemeier, R.W., 2005. Fates of eroded soil organic carbon: Mississippi basin case study. *Ecol. Appl.* 15, 1929–1940.
- Smith, P., Fang, C.M., Dawson, J.J.C., Moncrieff, J.B., 2008. Impact of global warming on soil organic carbon. *Advan. Agron.* 97, 1–43.
- Stevenson, F.J., Cole, M.A., 1999. Cycles of soil: carbon, nitrogen, phosphorus, sulfur, micronutrients/F.J. Stevenson and M.A. Cole. Wiley, New York.
- Tan, Z., Liu, S., Tieszen, L.L., Tachibana, E., 2009. Simulated dynamics of carbon stocks driven by changes in land use, management and climate in a tropical moist ecosystem of Ghana. *Agric. Ecosyst. Environ.* 130, 171–176.
- Thompson, J.A., Bell, J.C., Butler, C.A., 1997. Quantitative soil-landscape modeling for estimating the areal extent of hydromorphic soils. *Soil Sci. Soc. Am. J.* 61, 971–980.
- Wang, Y.F., Fu, B.J., Lü, Y.H., Song, C.J., Luan, Y., 2010. Local-scale spatial variability of soil organic carbon and its stock in the hilly area of the Loess Plateau, China. *Quatern. Res.* 73, 70–76.
- Wu, J.G., 2004. Effects of changing scale on landscape pattern analysis: scaling relations. *Landscape Ecol.* 19, 125–138.
- Wu, H., Guo, Z., Peng, C., 2003. Land use induced changes of organic carbon storage in soils of China. *Glob. Change Biol.* 9, 305–315.
- Yan, H., Cao, M., Liu, J., Tao, B., 2007. Potential and sustainability for carbon sequestration with improved soil management in agricultural soils of China. *Agric. Ecosyst. Environ.* 121, 325–335.
- Zhang, C.S., McGrath, D., 2004. Geostatistical and GIS analyses on soil organic carbon concentrations in grassland of southeastern Ireland from two different periods. *Geoderma* 119, 261–275.
- Zhang, X.B., Higgitt, D.L., Walling, D.E., 1990. A preliminary assessment of the potential for using caesium-137 to estimate rates of soil erosion in the Loess Plateau of China. *Hydrol. Sci. J.* 35, 243–252.
- Zhang, J.H., Liu, S.Z., Zhong, X.H., 2005. Distribution of soil organic carbon and phosphorus on an eroded hillslope of the rangeland on the northern Tibet Plateau, China. *Eur. J. Soil Sci.* 57, 365–371.
- Zhang, J.H., Quine, T.A., Ni, S.J., Ge, F.L., 2006. Stocks and dynamics of SOC in relation to soil redistribution by water and tillage erosion. *Glob. Change Biol.* 12, 1834–1841.