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ORIGINAL ARTICLE

The effects of ecological construction and topography on soil organic carbon and total nitrogen in the Loess Plateau of China

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Abstract

The construction of terraces and vegetation restoration in the hillslope are major soil and water conservation measures on the Chinese Loess Plateau and contributed to the distribution patterns of soil organic carbon (SOC) and soil total nitrogen (STN). Topography influences soil erosion and changes SOC and STN contents. However, little information is available regarding the effects of ecological construction and topography on SOC and STN. A study was undertaken in the Loess Plateau, to evaluate the effects of land use conversion and topographic factors on the topsoil SOC and STN content at three hillslope positions (upper, middle, and foot slopes) under four land uses types: artificial forest, grassland, terraced fields, and sloping cropland. The results showed that land use conversion from sloping cropland to artificial forest and grassland improved the SOC and STN content. Slope position was an important topographic factor governing the SOC and STN distribution at the slope scale in artificial forest, grassland, and sloping cropland, with the foot slope having the highest SOC and STN content, followed by the upper slope, while the middle slope had the lowest values. SOC and STN showed positive correlation with Caesium-137 (^{137}Cs) content. Land use types, slope position, and soil erosion had significant relationships with SON and STN. The results suggested that vegetation restoration of sloping cropland will contribute to soil carbon (C) and nitrogen (N) sequestration in the loess hilly region. The quantitative estimation of land use change and topography effects on SOC and STN could improve the accuracy of SOC and STN predictions in the region with a complex topography.

Keywords Land use conversion · ^{137}Cs · Slope position · Soil nitrogen · Soil organic carbon

Introduction

Soil organic carbon (SOC) and total nitrogen (STN) have a significant influence on soil quality (Zhang et al. 2013; Zhao et al. 2015). SOC and STN play important roles in maintaining adequate levels of plant nutrients and improving crop production (Wang et al. 2011). Recently, attention has been focused on the biogeochemical cycling of C and N in terrestrial ecosystems because of its critical relationship with global climate change (Lacoste et al. 2015). Soil has the largest C stock in the terrestrial ecosystem, with more than 2000 Pg of C stored in the top 2 m of soils, which is about twice as much as the amount of C in the atmosphere and three times the amount stored in vegetation. The soil C stock is related to atmospheric carbon dioxide (CO_2), with approximately 4% of soils C pool released into the atmosphere each year (Li et al. 2014). Furthermore, soil is the main emission source of another important greenhouse gas, with 10.2 Tg of nitrous oxide from agricultural and natural soils each year (Saikawa et al. 2014). Minor changes in the soil C and N pools can have significant impacts on global temperature changes.

Land use changes are known to significantly affect SOC and STN (Li et al. 2017). Soils act as sources or sinks of C and N. Different land uses can affect the SOC and STN content by altering the inflow and outflow of C and N. For

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example, forestation or reforestation has been widely found to increase SOC and STN, and a conversion to cropland decreases the SOC and STN content (Chen et al. 2007; Chang et al. 2014). The C and N sequestration mechanisms under different land uses may vary due to the presence of organic residues, soil microbial activity, agricultural tillage, and soil erosion (Tesfaye et al. 2016; Wang et al. 2016). Land use is sensitive to human activities and monitoring the SOC and STN content under different land uses is important for estimating soil C and N sequestration and distribution.

Topography factors, such as position, gradient, and altitude, are environmental factors determining the SOC and STN content and distribution (Schwanghart and Jarmer 2011; Sun et al. 2015). Topographic position influences the SOC and STN contents by controlling soil erosion and sediment deposition processes (Sun et al. 2014). In eroded areas, SOC and STN transported by runoff and sediment are redistributed over the landscape. The topography also affects plant litter production and decomposition, which is related to vegetable distribution and soil environmental conditions (Fernández-Romero et al. 2014). Therefore, topography may have a significant influence on SOC and STN sequestration, particularly in areas with complex topography.

The Loess Plateau of China, with a total area of 62.4×10^4 km^2, is characterized by a complex topography. Typical landforms in this region are loess Liang and Mao, which is characterized by hilly and gully landscapes. The complex topography changed soil erosion process. The Loess Plateau is known to have a serious soil erosion problem because of its high levels of soil erodibility and intensive human activity (Chang et al. 2012). Since the 1950s, many soil and water conservation measures have been implemented by the Chinese government, for example, terrace, check-dams, and vegetation rehabilitation (Zhao et al. 2013). To control soil erosion, the Grain for Green Project (GGP) was initiated in 1999 by converting sloping cropland to forestland and grassland (Chen et al. 2007). Understanding the effect of these land use conversions and the topography on soil C and N sequestration is essential for determining the global C and N cycles. The objectives of this study were therefore to: (1) study the influence of soil erosion on SOC and STN contents; (2) quantify the effects of ecological construction and topographical factors on SOC and STN distribution.

Materials and methods

Study area

This study was conducted at Qiaozi Watershed (105°42′–43′E, 34°34′–35′N), which is a major branch of the Luoyugou Watershed located in the southwest of the Loess Plateau of China (Fig. 1). The total area of the Qiaozi Watershed is 2.86 km^2, with an altitude that ranges from 1330 to 1707 m above sea level. The topography in the watershed is characterized by hills and gullies, including the two catchments of Qiaozi West and Qiaozi East (Table 1). The watershed has a typical semi-arid climate, with an average annual air temperature of 10.7 °C, and the average annual

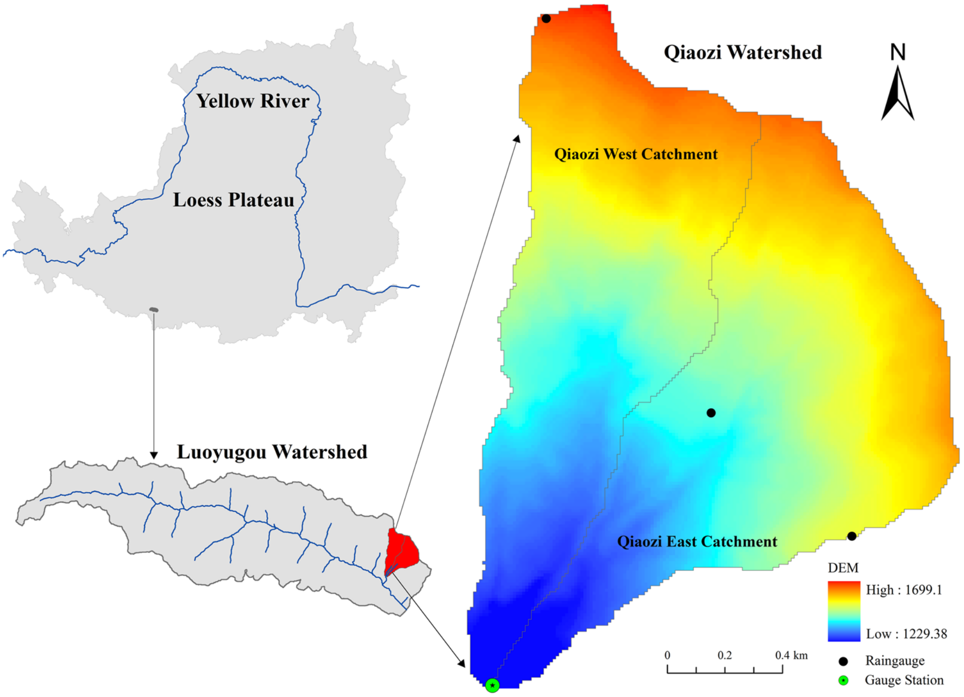

Fig. 1 The location of study area in the Loess Plateau of China

Table 1 The topography characters in the study area

Catchment	Area (km^2)	Shape	Length (km)	Width (km)	Shape factor	Channel gradient (%)	Relative difference in elevation (m)	Gully density (km km^{-2})
Qiaozi West	1.09	Fearthing	2.18	0.50	0.23	8.0	377	5.09
Qiaozi East	1.36	Half-sallop	2.00	0.68	0.34	8.0	377	5.13

mean precipitation is 542.5 mm (Li et al. 2017). Soil types in this area are dominated by CalcaricRegosol, which originated from a calcareous loess parent material. The soil in the study area has a weak resistance to erosion and soil erosion is around 1.85–5.47 × 10^6 kg km^{-2} a^{-1}.

Sloping cropland was the main land use type before the 1980s in the Qiaozi Watershed. Since the late 1990s, the land use in the study watershed has changed substantially (Table 2). Specifically, after the GGP was initiated in 1999, a large area of sloping cropland changed to forest and terraced field. The study area is presently covered by cropland, wild grassland, artificial forest land, and terraced field. The major crops grown in the area are maize (*Zea mays* L.), wheat (*Triticumaestivum* L.), and potatoes (*Solanumtuberosum* L.). The major grasses include *Elymusdahuricus, Artemisia gmelinii, Roegneriakanoji, Stipacapillata* Linn. and *Pedicularis*. Artificial plantations are *Robiniapseudoacacia* and *Populusdavidiana*.

Soil sampling and analysis

Before soil sampling, we conducted a land use history investigation in the watershed based on the field survey. Four land use types were selected: sloping cropland with wheat (*T. aestivum* L.), forest land (*R. pseudoacacia* and *S. capillata* Linn.), grassland (*A. gmelinii*), and terraced fields (*Z. mays*). Three transects of each of the typical land uses were established on the hill slopes of Qiaozi Watershed: sloping cropland, artificial forest, grassland, and terraced fields. Soil samples were collected along the slope transects from the following three positions: the upper slope, the middle slope, and the foot slope. At each site, a 1 × 1 m plot was established for surface soil sampling. Five randomly selected cores were taken to a 0–20 cm depth using a soil auger (Eijkelkamp, diameter 60 mm) and were combined in one sample. Topography factors including slope gradient, position, aspect, and altitude were surveyed at each site (Table 3).

Soil samples were air-dried and sieved through a 2-mm screen in the laboratory. Soil ^{137}Cs, an indicator of soil erosion intensity, was measured by HPGe co-axial detectors coupled to a multi-channel analyzer. The reference value for ^{137}Cs in this study area was presented, the average of which was 1476.42 Bq m^{-2}. SOC was analyzed using a colorimetric determination (Sims and Haby 1971). STN was determined with an Vario EL III elemental analyzer (Shi et al. 2015). Soil pH was determined using a Crison GLP 21 pH meter (Cavalli et al. 2017).

Statistical analysis

To identify the effects of land use and topography on the SOC and STN contents, statistical analysis were conducted using SPSS 16.0. One-way ANOVA was used to evaluate the variances in SOC, STN, and ^{137}Cs under different land use types and slope positions at 0.05 levels by the least significant differences. Pearson correlation was used to analyse relationships between environmental factors (land use types, slope position, slope gradient, slope aspect, altitude, and ^{137}Cs content) with SOC and STN. Because of the changed microtopography during the terrace construction, this land use type was not in the Pearson correlation. To quantify the relationship between land use types with SOC and STN, grassland, artificial forest, and sloping cropland were assigned to 1, 2 and 3, respectively. Three sloping positions including upper, middle, and foot were assigned to 10,

Table 2 Land use types in 1986 and 2004 in the Qiaozi watershed

Land use type	1986		2004		Area change (%)
	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	
Forest	31.25	8.32	79.18	21.08	+ 12.76
Grassland	19.41	5.17	19.41	5.17	0.00
Sloping cropland	276.15	73.52	148.65	39.58	− 33.95
Terraced fields	4.5	1.20	75.33	20.06	+ 18.86
Bare land	15.85	4.22	15.85	4.22	0.00
Residential land	28.43	7.57	37.17	9.90	+ 2.33

Table 3 Topography information of the sampling sites

Land use type	Sampling sites	Slope gradient (°)	Slope aspect (°)	Altitude (m)	Slope position
Artificial forest	AF-U	10.02 ± 1.66	224.51 ± 23.06	1589 ± 26	Upper
	AF-M	12.72 ± 0.88	228.15 ± 25.83	1545 ± 30	Middle
	AF-F	10.78 ± 0.82	227.76 ± 32.29	1490 ± 42	Foot
Grassland	GL-U	15.28 ± 0.44	237.99 ± 16.45	1488 ± 18	Upper
	GL-M	16.01 ± 1.73	240.97 ± 16.97	1482 ± 19	Middle
	GL-F	12.60 ± 0.45	245.18 ± 3.97	1471 ± 17	Foot
Terraced field	TF-U	11.68 ± 3.24	229.08 ± 44.47	1464 ± 32	Upper
	TF-M	13.84 ± 3.75	271.80 ± 30.36	1411 ± 12	Middle
	TF-F	13.62 ± 1.88	225.37 ± 45.15	1402 ± 10	Foot
Sloping cropland	CL-U	12.56 ± 2.76	245.78 ± 35.50	1485 ± 30	Upper
	CL-M	14.06 ± 0.70	246.51 ± 29.49	1478 ± 27	Middle
	CL-F	11.24 ± 3.55	244.78 ± 37.38	1465 ± 21	Foot

50, and 100 m, respectively (the distance to the peak). Origin 8.5 software was used to produce the figures.

Results

Changes in soil properties of different land use types

Land use changes had a significant effect on soil properties (Table 4). Artificial forest and grassland had a higher SOC and STN than the other land uses ($P < 0.05$). The highest SOC concentration was obtained in the grassland transect (5.50 g kg^{-1}), and artificial forest had a similar SOC content (5.21 g kg^{-1}). Terraced field and sloping cropland had SOC concentrations of 3.55 and 3.88 g kg^{-1}, respectively. Grassland had the highest STN content (0.61 g kg^{-1}), followed by artificial forest (0.55 g kg^{-1}), while it was lowest in terraced fields and sloping cropland (both of which were 0.35 g kg^{-1}). The content of ^{137}Cs significantly varied with land use types. The higher ^{137}Cs was observed in artificial forest (902.24 Bq m^{-2}) and grassland (853.15 Bq m^{-2}), followed by terraced fields (482.32 Bq m^{-2}) and then sloping cropland (326.80 Bq m^{-2}). This finding was consistent with the variations of SOC and STN. The pH was highest in terraced fields, whereas both were lowest in sloping cropland.

The effect of slope position on SOC and STN

The highest concentration of SOC was found on the foot slope (5.40, 6.27, 4.04, and 4.88 g kg^{-1} for artificial forest, grassland, terraced fields, and sloping cropland, respectively) compared with other slope positions (Fig. 2). Specially, in the grassland and sloping cropland transects, the SOC content was significantly lower on the upper and middle slopes (5.18 and 5.06 g kg^{-1} for grassland, and 3.68 and 3.06 g kg^{-1} for sloping cropland, respectively) than that on the foot slope ($P < 0.05$). The SOC content was lowest on the middle slope of the artificial forest, grassland, and sloping cropland transects (5.08, 5.06, and 3.09 g kg^{-1}, respectively). The SOC content in the terraced fields transect increased from the upper slope to the foot slope, following the order of upper (3.23 g kg^{-1}) < middle (3.38 g kg^{-1}) < foot (4.04 g kg^{-1}).

The STN content had a similar distribution to that of SOC in the artificial forest, grassland, and sloping cropland transects. Generally, these three transects had higher STN concentrations on the foot slopes than that on the upper and middle slopes. The highest STN concentration was obtained on the foot slope in the grassland transect (0.82 g kg^{-1}), which was significantly higher than on the upper slope (0.59 g kg^{-1}) and the middle slope (0.55 g kg^{-1}). The middle slope had the lowest STN compared to the upper and foot slopes in artificial forest, grassland, and sloping cropland

Table 4 Soil pH, soil organic carbon, soil total nitrogen, and ^{137}Cs contents in the 0–20 cm soil layer for different land use types

Land use type	pH	SOC (g kg^{-1})	STN (g kg^{-1})	^{137}Cs (Bq m^{-2})
Artificial forest	8.20 ± 0.02 a	5.21 ± 0.33 a	0.55 ± 0.05 a	902.24 ± 47.72 a
Grassland	8.13 ± 0.01 b	5.50 ± 0.45 a	0.61 ± 0.13 a	853.15 ± 59.33 a
Terraced fields	8.23 ± 0.02 a	3.55 ± 0.71 b	0.35 ± 0.07 b	482.32 ± 47.31 b
Sloping cropland	8.11 ± 0.01 b	3.88 ± 0.49 b	0.35 ± 0.10 b	326.80 ± 54.84 c

Values followed by the same letter are not significantly different at the 0.05 level among various land use types

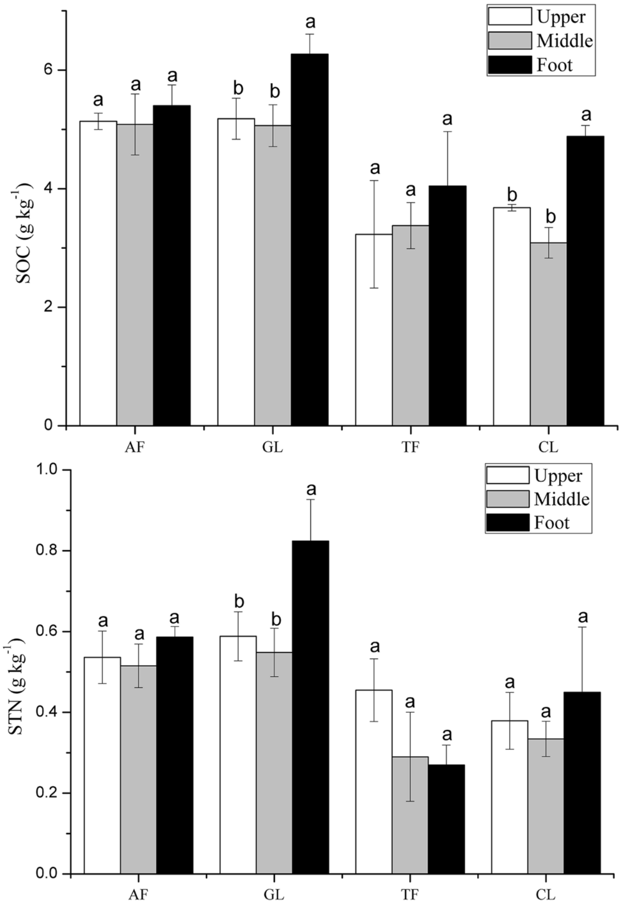

Fig. 2 The soil organic carbon (SOC) and soil total nitrogen (STN) contents at three slope positions under different land use types. Values followed by the same letter above standard error are not significantly different at the 0.05 level among various slope positions

transects. The lowest STN was observed on the foot slope of the terraced fields transect, which was only 0.27 g kg^{-1}, while there was no significant difference among the three slope positions. The amount of ^{137}Cs varied in the following order: middle slope < upper slope < foot slope in soils of the artificial forest and sloping cropland (Fig. 3). The increasing trend of ^{137}Cs was found down the slope in the grassland.

The relationships between SOC, STN, and environmental factors

Land use types, slope position, and ^{137}Cs content had significantly correlations ($P < 0.01$) with SOCin the Pearson correlation analysis, with the correlation coefficients of −0.528, 0.412, and 0.418, respectively (Table 5). Similarly, correlations between land use types, slope position, and ^{137}Cs content with STN were −0.497, 0.499, and 0.423, significant at 0.01 level. Slope gradient was negatively correlated with SOC and STN. Slope aspect and altitude had positive correlations with SOC and STN.

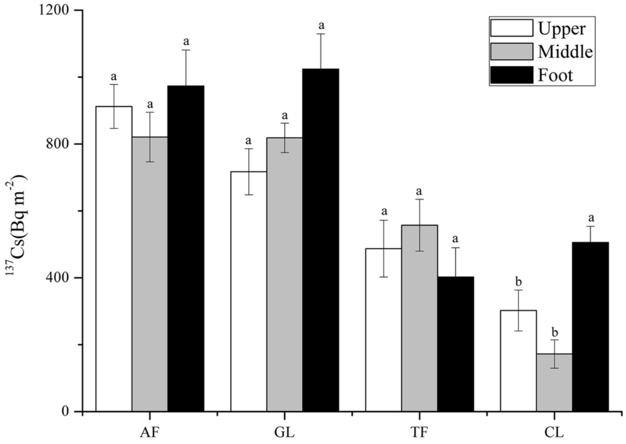

Fig. 3 The ^{137}Cs content at three slope positions under different land use types. Values followed by the same letter above standard error are not significantly different at the 0.05 level among various slope positions

Discussion

The effects of ecological construction on the SOC and STN content

It is usually assumed that land use conversions have a significant effect on the SOC content (Conti et al. 2016; Poeplau and Don 2013; Ostle et al. 2009). A previous meta-analysis showed that the soil C stock increased by 53 and 19% after land use changed from sloping cropland to forestland and pasture, respectively (Guo and Gifford 2002). In the current study, compared with sloping cropland, the SOC content in the surface soil increased by 34.2% when it was converted into forestland, and by 41.7% when it was converted into grassland (Table 4). This suggested that changing cropland to land with perennial vegetation would improve the SOC and soil quality (Chen et al. 2007). Vegetation restoration affects soil C storage by increasing the input of litter and altering the decomposition of organic matter inputs. Llorente et al. (2010) found that 67% of soil C was lost after forest was converted into cropland, whereas the SOC content was greatly increased after reforestation. The extensive fine root system of natural vegetation may also be responsible for the higher SOC content, because it would substantially increase the C input to soil and indirectly decrease soil erosion (King et al. 2001). The ^{137}Cs content of all soil sampling sites was lower than the reference value in the present study. The results indicated that land uses experienced considerable net erosion before ecological constriction. The amount of ^{137}Cs of sloping cropland was the lowest, and the ^{137}Cs value of artificial forest and grassland was higher than sloping cropland. The forest and grasses have much lower

Table 5 Pearson correlation between SOC and STN with environmental factors

	Land use types	Slope position	Slope gradient	Slope aspect	Slope altitude	^{137}Cs
SOC	−0.528**	0.412**	−0.144	0.088	0.120	0.418**
STN	−0.497**	0.499**	−0.166	0.114	0.104	0.423**

**Means correlation is significant at 0.01 level

soil erosion rates (Fu et al. 2009). Vegetation cover could slow down the movement of surface runoff and reduce sediment transportation. SOC was positively and significantly correlated with ^{137}Cs content ($R^2 = 0.418$, $P < 0.01$, as shown in Table 5). This result is consistent with those of studies by Wang et al. (2011) and Li et al. (2017), suggesting that SOC inventory increases with decreasing soil erosion. Soil carbon losses during soil erosion processes, SOC transfer and mineralization are associated with soil detachment, sediment transport, and deposition (Nadeu et al. 2014). The present study indicated that ecological construction of sloping cropland changed to forest and grasses could effectively control soil erosion and improve soil carbon pool.

The STN content in the topsoil under the different land uses was similar to the SOC content. Compared with sloping cropland, artificial forest, and grassland had a significantly higher STN content in the 0–20 cm profile. The result was consistent with that reported by Puget and Lal (2005), who found that STN in the top 5 cm layer of grassland and forest was higher than in cultivated soils. Wang et al. (2016) indicated that the topsoil STN content of forestland was 46.2% higher than that of cropland. This result may be largely due to the lower organic matter (such as root or litter biomass) input to soil and the high erosion rate in the cropland (Anh et al. 2014; Jafarian and Kavian 2013).STN showed positive correlation with ^{137}Cs content ($R^2 = 0.423$, $P < 0.01$, as shown in Table 5). The amount of soil nitrogen is mainly concentrated in the surface soil layer, and agricultural cultivation increases the risk of soil N losses by water erosion processes.

Terraces are considered to be an effective agricultural management practice to reduce soil erosion and are ubiquitous in hill-slope regions (Wei et al. 2016). However, terraces had a lower SOC and STN content than revegetated land in our study. During terrace construction, the fertile topsoil was removed leading to a significant impact on soil properties (Posthumus and Stroosnijder 2010). Previous studies have shown that approximately 20% of the SOC is lost within 10–20 years after the soil is first cleared and cultivated (Monreal and Janzen 1993; Zhang et al. 2015). Restoration of a soil system to high productivity requires a period of several years after the initial disturbance. Long-term restoration (more than 10 years) should be considered to improve the soil quality in terraces in the arid and semi-arid regions (Xue et al. 2011).

Changes in the SOC and STN content with slope position

The earth's surface acts as the template, on which C and N fluxes occur (Schwanghart and Jarmer 2011). Some studies have indicated that topography is related to soil properties (Tsui et al. 2004; Wei et al. 2010). Landscape position has been proposed as an important topographic factor governing the distribution of SOC and STN (Fernández-Romero et al. 2014). In this study, the SOC and STN content in the artificial forest, grassland, and sloping cropland transects was highest on the foot slope, followed by the upper slope, and lowest on the middle slope. This result was similar to that reported by Li et al. (2017), who found that the distribution of SOC and STN on a hillslope was lowest on the middle slope, and demonstrated a 'V' shape distribution. The reason that slope position influenced the SOC and STN contents maybe due to soil erosion and water content, which resulted in material redistribution (Hao et al. 2002). ^{137}Cs inventories can reflect changes in SOC and STN induced by water erosion in the hillslope (Ritchie and McCarty 2003). Distribution pattern of ^{137}Cs varied in different slope positions (as shown in Fig. 3). The higher ^{137}Cs content was found in the foot position of artificial forest, grassland, and sloping cropland compared to other slope positions. The result indicates that soil erosion intensity was higher at upper and middle slopes than that at down slope. Fine particles combined with organic matter and N in the surface soil of the upper and middle slope positions were carried away by runoff during erosion and deposited on the foot slope position (Liang et al. 2012; Khormali et al. 2009). The foot slope is a sink for sediment deposition, and the SOC and STN content was enriched in this location. The middle slope position had a lower SOC and STN content than upper and foot slopes, probably because of the uniform distribution of soil erosion at the slope scale. This was consistent with previous studies, which suggest that the SOC and STN content followed the order of lower-slope and upper-slope > mid-slope (Li et al. 2015; Polyakov and Lal 2004). Fu et al. (2009) discovered that the trend of soil erosion intensity from the upper to lower slopes varied, with an inverted 'V' pattern. Wang et al. (2011) found that the soil C pool had a strong relationship with topography and the high soil erosion intensity on the middle slope resulted in net losses of SOC.The higher SOC and STN contents in the lower slope may also be attributed to the soil water accumulation along the altitudinal transect

(Tsui et al. 2004).Increasing soil water content at lower slope position affects vegetation growth and litter production and contributes to changes in SOC and STN contents (Gregorich et al. 1998).

Land management and recommendations

The GGP, initiated by the Chinese government in 1999 to halt soil erosion, is the largest revegetation program in China (Chen et al. 2015). A cropland area of 1.21×10^6 ha in the steeply sloping Loess Plateau was converted into forest and grassland (Chen et al. 2007). In the fragile ecological system of the Loess Plateau, soil C and N concentrations are extremely susceptive to changes in environmental conditions, especially to land use changes (Zhang et al. 2013). The results of this study have demonstrated that the reconversion of sloping cropland into forestland and grassland contributed to an increase in the SOC and STN content. Similarly, a meta-analysis indicated that the GGP led to a large increase in SOC, with an increase of 48.1% at a soil depth of 0–20 cm (Song et al. 2014). The Chinese government has approved a future expansion of the GGP to convert 2.83×10^6 ha of sloping cropland to forest and grassland by 2020. Large-scale land use changes under the GGP in the loess hilly area will contribute to soil C and N accumulation in terrestrial ecosystems. This will help to balance levels of global greenhouse gases. Terraces had a lower SOC and STN content, probably due to soil disturbance during construction and conventional tillage in the terraced field. Wang et al. (2010) found that a terraced field had a lower SOC density than forest and grassland. Soil management practices, such as no-tillage and organic manure applications, should be considered to restore terraced field soil fertility. The Loess Plateau of China is characterized by a complex topography. Slope position affects soil erosion and sediment distribution, which contributes to the significant variations in SOC and STN. However, important topographic factors have generally been ignored in hill and gully areas (Sun et al. 2015). Understanding the contribution of topography on the SOC and STN distribution will enable the effects of ecological construction to be assessed. In addition, these results provide a valuable reference for ecological policy planning in the Loess Plateau.

Conclusions

Ecological construction and topographic factors strongly affect the distribution of SOC and STN in hillslope regions of the Loess Plateau. The SOC and STN content in the artificial forest and grassland was significantly higher than in the sloping cropland, indicating that land use conversions from sloping cropland to forest and grassland will improve the SOC and STN content, and decrease soil erosion. Terrace had lower SOC and STN contents than other land use types; therefore, appropriate soil management practices should be undertaken to restore soil quality. Topography influences the SOC and STN contents by changing the processes of soil erosion and deposition. The SOC and STN had a similar distribution at the slope scale of artificial forest, grassland, and sloping cropland, following the order of foot slope > upper slope > middle slope. These results indicate that the return of sloping cropland to forest and grassland is the optimal choice in the loess hilly area to control soil erosion and increase soil C and N sequestration. Moreover, topographic factors should be considered during ecological construction.

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