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SOIL QUALITY INDICATORS IN RELATION TO LAND USE AND TOPOGRAPHY IN A SMALL CATCHMENT ON THE LOESS PLATEAU OF CHINA

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ABSTRACT

Better understanding of how the loess soils respond to topography and land use under catchment-scale vegetation restoration is needed to enable science-based land management interventions for the policy-driven “Grain-for-Green” eco-restoration program in the Loess Plateau of China. The objective of this study was to characterize the relationships of four selected soil quality indicators to land use under vegetation restoration and topography for a small catchment (0·58 km^2) in the Loess Plateau. The major land uses established in the catchment are cropland, fallow (i.e., natural revegetation), grassland, and jujube orchard. The four soil quality indicators were soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and mean root zone soil water content during the wet season (MRZSWwet). SOC, STN, and MRZSWwet were significantly different ($p < 0{\cdot}05$) for different land uses. Grassland showed the highest values for these three properties, whereas cropland had relatively low values for SOC and STN. Land use had no effect on STP, although the lowest value was observed in grassland. Spatial analysis showed that various relations between soil quality indicators and topography (slope and elevation) were observed. These relations were generally weak for most of them, and they varied with land uses. Further analyses indicated that land uses, slope, and elevation had significant effects on the relations between different soil quality indicators. The results here should provide useful information for the further development of “Grain-for-Green” program. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: soil quality; land use; Grain-for-Green; Loess Plateau

INTRODUCTION

The Loess Plateau of China extends from about 34 to 41°N latitude and 102 to 114°E longitude. The mean rainfall decreases with latitude from about 800 mm in its southeast portion to about 100 mm in the northwest portion. The mean annual temperature varies in the same manner from 15 °C to −7 °C. Deforestation of land for grain production in the hilly areas of the Loess Plateau has resulted in severe land and ecological degradation.

Restoring vegetative cover is critical to remediate severely eroded and degraded land and to achieve sustainable redevelopment of the hilly areas of the Loess Plateau of China (Wu *et al*., 2003). The long-term, policy-driven “Grain-for-Green” eco-restoration program was initiated in 1999 to promote vegetation restoration at the catchment level of barren or low-yielding farmland. The program promotes planting orchard trees, fallow (natural restoration), and grassland to restore soil fertility, decrease soil erosion, and improve soil quality at catchment scale. Over the decade since its inception, the program has successfully increased the vegetation cover in the Chinese Loess Plateau (Zhao *et al*., 2009; Zhang *et al*., 2011). Understanding how the different vegetation covers affect the ecology and economic development in the Loess Plateau is essential for science-based land management practices and the continued success of the program. Specifically, understanding the relationship between vegetation restoration practices and soil quality at the catchment scale would help to refine such practices and to assess their effects on ecology, soil erosion, and environmental quality (Cambardella *et al*., 1994; Tang, 2004).

Soil organic carbon (SOC) is a key indicator of soil quality (Gregorich *et al*., 1994) and overall soil productivity (Lal, 2004) and increases cation exchange capacity, aggregation, and water retention (Lee *et al*., 2009). Soil total nitrogen (STN) and soil total phosphorus (STP) are closely related to soil productivity (Lu *et al*., 2007; Wang *et al*., 2009), and they are also suitable indicators of soil quality in the Loess Plateau (Jia *et al*., 2006; An *et al*., 2008; Wang *et al*., 2009). The arid and semiarid climate makes the Loess Plateau prone to drought especially during dry season (Zhao *et al*., 2009). Root zone soil water storage during the wet season is essential to sustain vegetation restoration and crop growth during the dry season (Wilcox and Newman, 2005) and can be characterized by the mean root zone soil water content during the wet season (MRZSWwet).

Parent material, climate, and geological history are major factors affecting the distribution of soil properties at continental scale (Mclauchlan, 2006), whereas land use, land

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use history, and topography are the dominant controls at smaller scales such as catchment scale (Wang *et al*., 2001; Liu *et al*., 2006; Schulp and Verburg, 2009; Wang *et al*., 2009; Fang *et al*., 2012). In field experiments, Zhao *et al*. (2005) found that converting grassland to cropland resulted in significant soil degradation through loss of fine soil particles, SOC, and nutrients. SOC and STN gradually increased over time after it was returned to grassland. Wei *et al*. (2010) found increases in SOC and STN 28 years after afforestation of grassland. In addition to land use, Wang *et al*. (2003) and Wang *et al*. (2009) found that SOC, STN, and STP varied with topography in terms of slope and elevation.

These studies suggest that land use changes affect soil properties and soil quality indicators. Vegetation restoration at the catchment scale would significantly change the land use patterns. An important question is whether soil quality indicators are different for the different land uses established under the Grain-for-Green vegetation restoration program in the Loess Plateau. The objective of this study was to quantify how soil quality indicators (SOC, STN, STP, and MRZSWwet) are related to topography and land use associated with catchment-scale vegetation restoration in the Loess Plateau.

MATERIALS AND METHODS

Study Site

The study site was a small catchment (Yuanzegou catchment 37°15′N, 118°18′E) with an area of 0·58 km^2 located in Qingjian County of Shaanxi Province in the north central part of the Loess Plateau, China (Figure 1). This site has a semiarid continental climate with a mean annual precipitation of 505 mm, 70 per cent of which falls during late summer and early autumn (August–October); a mean annual temperature of 8·6 °C, with mean monthly temperatures ranging from −6·5 °C in January to 22·8 °C in July. The elevation of the catchment ranges from 865–1105 m with slope ranging from 0–40 degrees. The loess soil texture is predominantly silt loam (Inceptisols, USDA), and the detailed information of soil texture was shown in Figure 2. Almost all samples fell within the range of 10 to 30 per cent sand, 60 to 70 per cent silt, and 10 to 25 per cent clay content. The surface bulk density (0–20 cm) ranges from 1·17–1·33 g · cm^{-3}. The field capacity and permanent wilting point of the loess in this study site is 24·3 and 8·8 per cent (volumetric water content, hereafter), respectively.

The current land uses established in the catchment under the Grain-for-Green eco-restoration program are jujube (*Zizyphus jujuba*) orchard of 3–8 years of age, cropland,

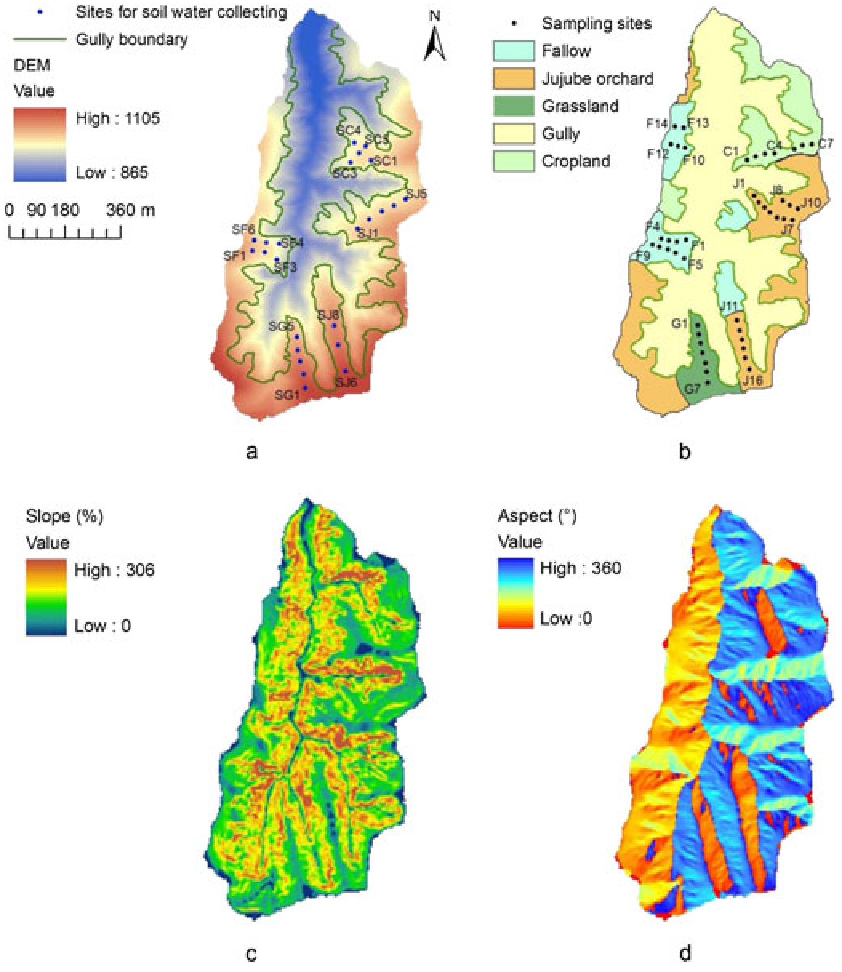

Figure 1. Soil sampling and water measurement locations in the Yuanzegou catchment. The DEM (a), the land use types (b), the slopes (c) and the aspect (d) of the catchment were also shown. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

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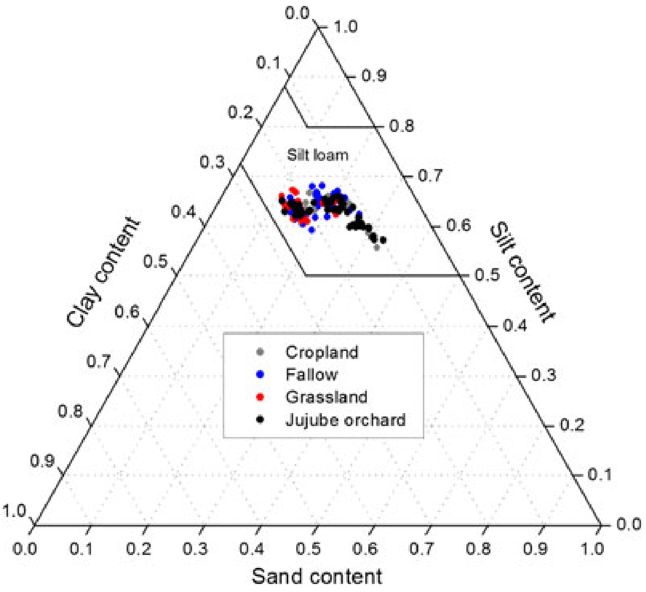

Figure 2. Soil texture triangle showing the range of textures for different land uses. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

fallow of 4–9 years of age, and grassland of ~20 years of age (Figure 1b). Prior to the current land uses, cropland dominated the entire catchment in addition to gullies. Jujube trees were planted with a density of about 1650 trees per hectare with no cover crop. A small amount of manure was applied to the trees in late March of every year since they were planted. For mature trees, about 0·2–0·3 kg urea were added at bloom in late May and during fruit development in early August every year. Rainfed millet (*Panicum miliaceum*) and beans (*Phaseolus vulgaris*) were grown on cropland areas with little or no fertilizer application. Dominant grassland species were Gmelin's wormwood (*Artemisia gmelinii*), Yellow Bluestem (*Bothriochloa ischemum*), and Lespedeza (*Lespedeza davurica*). Redstem Wormwood (*Artemisia scoparia*), Wild Rye (*Leymus secalinus*), and Bunge Needlegrass (*Stipa bungeana*) were the main species under fallow.

Soil Sampling and Measurements

From 18 to 28 September 2010, soils for each land use were sampled at the upper, middle, and lower positions of the catchment slope. For each land use, the number of sampling locations varied depending on the area and topography (Figure 1). There were seven sampling locations for cropland and grassland, 14 for fallow, and 16 for jujube orchard. At each sampling location, three borings were made with a hand auger ($\Phi = 40$ mm) and composite samples taken for the 0–20, 20–40, and 40–60 cm depths. The composite samples were air dried and the <1 mm sieved fraction was used for soil particle size distribution analysis using a Mastersizer2000 particle size analyzer (Malvern Instrument, Malvern, Britain). The <0·25 mm fraction was used for SOC, STN, and STP analysis.

Soil organic carbon was determined by hot oxidation with potassium dichromate and sulfuric acid (Yeomans and Bremner, 1988). STN was determined using the Kjeldahl digestion procedure (Bremner and Tabatabai, 1972), and STP was determined using molybdenum antimony blue colorimetry (Murphy and Riley, 1962).

The field soil volumetric water content was measured at five equal intervals over the 0–100 cm depth several times during the wet season (August–October) using a portable time domain reflectometer (TRIME-PICO IPH/T3, IMKO, Ettlingen, Germany). Measurements were made eight times in 2009 and ten times in 2010. Similar to soil sampling, the number of soil water measurement locations for each land use varied according to the area and topography. There were five locations in cropland and grassland, six in fallow, and eight in jujube orchard (Figure 1a). The MRZSWwet for a given land use is therefore an overall mean for the 0–100 cm depth taken over all times ($j = 1, 2, \ldots, T$) and all locations ($i = 1, 2, \ldots, N$). The mean of soil volumetric water content over the 0–100 cm depth at location i and time j was calculated by trapezoid integration as $\bar{\theta}_{ij} = \frac{1}{100}\sum_{k=1}^{k=m}\left(\theta_{ijk}d_k\right)$ where θ_{ijk} is a single measurement at time i and location j at the kth depth interval, and d_k is the midpoint of the given depth interval. The mean over all locations for a given time was calculated as $\bar{\theta}_j = \frac{1}{N}\sum_{i=1}^{i=N}\bar{\theta}_{ij}$. Finally, the MRZSWwet over all time for a given land use was calculated as

$$\mathrm{MRZW}_{\mathrm{wet}} = \frac{1}{T}\sum_{j=1}^{j=T}\bar{\theta}_j.$$

Land Use Slope and Elevation

Slope and elevation for each land use was derived from a 5-m resolution DEM of the Yuanzegou catchment using the software package ArcGIS 9·3 (ESRI, Redland, CA). According to the slope classification on the Loess Plateau by Tang (2004), the slope was divided into five classes, that is, <10 per cent (slight slope, S1), 10–25 per cent (gentle slope, S2), 25–45 per cent (moderate slope, S3), 45–70 per cent (steep slope, S4), and very steep slope (>70 per cent, S5). Elevation was also categorized into five classes, that is, <980 m (E1), 981–1000 m (E2), 1001–1030 m (E3), and >1031 m (E4), on the basis of the elevation distribution of sampling locations.

Statistical Analysis

One-way analysis of variance was used to determine the effect of land use on soil quality indicators, and the least significant difference method was used for multiple comparison analysis. All the analysis was performed with SPSS16·0 (SPSS Inc., Chicago, USA).

RESULTS AND DISCUSSION

Soil Quality Indicators in Relation to Land Use

Q-Q plots showed that all of the datasets were normally distributed (not shown). One-way ANOVA showed a

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significant effect ($p < 0·05$) of land use on SOC, STN, and STP for each sampling depth. Means for each depth were separated using least square difference (LSD) (Table I).

The overall mean values of all SOC and STN for all sampling locations and land uses tended to decrease with increasing depth. The overall mean SOC values in the 20–40 cm and 40–60 cm depths were, respectively, 22 and 27 per cent lower than the value of 4·33 g kg^{-1} for the 0–20 cm depth. Corresponding values for STN were 25 and 28 per cent of 0·318 g kg^{-1}. Overall means for STP did not change markedly with depth. Values were 0·305, 0·292, and 0·300 g kg^{-1} for the three depths.

This study site showed lower SOC content than other areas such as New Zealand (Percival *et al*., 2000), Argentina (Urioste *et al*., 2006), Germany (Spielvogel *et al*., 2009), USA (Schilling *et al*., 2009), and Laos (Chaplot *et al*., 2010). It was also lower than other sites in the hilly areas of the Loess Plateau (e.g., Fang *et al*., 2012). Compared with other studies, the low SOC in our site is probably due to the relatively low vegetative cover and the severe soil erosion associated with intensive human disturbance, and very little fertilizer application were used in the study catchment.

The highest SOC content was detected in grassland and the lowest value was in cropland for each depth. The low SOC content in cropland could be attributed into the relatively serious soil erosion, whereas the relatively high vegetation coverage and thick litter fall are helpful to reduce soil erosion and accumulate SOC. This is consistent with the findings of previous studies conducted at the small catchment scale in the Loess Plateau (Wang *et al*., 2003; Fang *et al*., 2012). On the other hand, for the whole Loess Plateau, Liu *et al*. (2011) found that cropland had higher SOC content than grassland at the 0–40 cm. This suggests that land use effects on SOC depend on spatial scale of observations.

Fallow land showed higher SOC values than cropland but lower values than grassland for different depths, which was consistent with the results reported by Fang *et al*. (2012). This implies that in short term (4–9 years after cessation of cultivation disturbances), there would be increase of SOC content especially at the 0–20 cm for the different land uses under vegetation restoration. Surface litter may contribute to the higher SOC content in grassland and fallow land in the 0–20 cm, whereas organic fertilizer application most likely increased the surface SOC content in jujube orchard.

Grassland had the highest STN content and cropland had the lowest (Table I). A similar finding was reported by Wang *et al*. (2003). Jujube orchard exhibited relatively high STN as compare with fallow land and cropland, which was probably attributed to fertilizer and manure applications in jujube orchard. The highest STN for grassland could be attributed to the thick litter layer, the highest SOC content, and the highest C:N (14·8 for grassland, 14·4 for fallow land, 12·9 for jujube orchard, and 11·5 for cropland). There was no difference in STN between fallow and cropland, especially for subsurface layers where very similar values were observed. This implies that short term vegetation restoration may have little influence on STN.

Analysis also showed a significant effect ($p < 0·05$) of land use on MRZSWwet in both 2009 and 2010 (Table I). The MRZSWwet values in 2009 were significantly greater than in 2010 due to the greater precipitation in 2009 (242 mm in 2009 and 213 mm in 2010). For both years, grassland stored significantly more soil water in the 0–100 cm compared with other land uses. This result agrees with the findings of previous studies in the Loess Plateau (Qiu *et al*., 2001; Fu *et al*., 2003; Gao *et al*., 2011). The relatively high MRZSWwet in grassland in the Yuanzegou catchment was probably because of the north-facing spatial location (Figure 1b) and the higher clay and SOC content. In 2010, MRZSWwet in cropland was higher, although not significantly, than in fallow land and jujube orchard. The relatively low MRZSWwet in fallow land may be because of the appearance of the lichen on surface soils, which could reduce the infiltration of precipitation, especially the initial infiltration rate (Eldridge *et al*., 2000).

Table I. Soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), saturated soil hydraulic conductivity (*K*s), and mean root zone soil water content during the wet season (MRZSWwet) at 0–20 cm for various land uses in the Yuanzegou catchment

SOC (g kg^{-1})	Cropland	Fallow	Grassland	Jujube
0–20 cm	3·34 ± 0·24 c	4·51 ± 0·53 ab	5·12 ± 0·79 a	4·21 ± 1·17 b
20–40 cm	2·66 ± 0·31 b	3·29 ± 0·54 b	4·43 ± 0·28 a	3·35 ± 1·13 b
40–60 cm	2·52 ± 0·38 b	3·07 ± 0·59 b	4·23 ± 0·36 a	3·02 ± 0·89 b
STN (g kg^{-1})				
0–20 cm	0·290 ± 0·019 b	0·312 ± 0·038 ab	0·345 ± 0·043 a	0·325 ± 0·068 ab
20–40 cm	0·216 ± 0·037 b	0·217 ± 0·023 b	0·281 ± 0·037 a	0·256 ± 0·064 a
40–60 cm	0·197 ± 0·024 b	0·203 ± 0·029 b	0·275 ± 0·057 a	0·247 ± 0·070 a
STP (g kg^{-1})				
0–20 cm	0·309 ± 0·012 a	0·307 ± 0·018 a	0·283 ± 0·028 b	0·312 ± 0·012 a
20–40 cm	0·297 ± 0·009 a	0·290 ± 0·026 a	0·266 ± 0·021 a	0·303 ± 0·016 a
40–60 cm	0·295 ± 0·011 ab	0·306 ± 0·034 a	0·281 ± 0·015 b	0·306 ± 0·014 a
MRZSWwet (per cent, v/v)				
2009	—	25·6 ± 2·24 b	27·3 ± 1·80 a	25·2 ± 2·80 b
2010	22·1 ± 2·81 ab	21·6 ± 2·73 ab	23·6 ± 3·63 a	21·4 ± 3·13 b

For each row, values followed by lowercase letters are significantly different for $p < 0·05$ using the LSD method.

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Soil Quality Indicators in Relation to Slope and Elevation

Figure 3 shows the relationships between soil quality indicators for different land uses and slope and elevation. Note that only soil properties within 0–20 cm (except for MRZSWwet) were used for analysis because our preanalysis results showed stronger relations existed in the 0–20 cm (data not shown here). Clearly, the majority of soil sampling locations were located in moderate slopes (S3, 25–45 per cent) and steep slopes (S4, 45–75 per cent). Overall, SOC content increased with slope, whereas different behaviors were observed for different land uses (Figure 3a). In particular, for jujube orchard, relatively low values were observed for moderate slopes (S3) compared with slight slopes (S2) and steep slopes (S4). A possible explanation is that the human activities (e.g., fertilizer application) changed this relationship. In general, STN behaved similarly with SOC when slope increased (Figure 3c). However, it is difficult to characterize the relations between slope and STP as well as MRZSWwet because weak relations existed between them (Figure 3e, g, and i). This means that slope had weak effects on STP and MRZSWwet. Our results agreed with some of previous findings but disagreed with others. For instance, Fang *et al*. (2012) also found SOC increased with slope, and much higher values were observed where slopes exceeded 45 per cent. Comparing the study sties between ours and Fang *et al*. (2012), a possible explanation for this difference was that grassland at which higher SOC existed more often located at steeper slopes. However, Wang *et al*. (2009) found slope had weak effects on SOC content, whereas Liu *et al*. (2006) found that SOC content decreased with slope because of the stronger soil erosion at higher slopes. At the regional scale, Chaplot *et al*. (2010) also observed larger SOC stocks at steeper slopes,

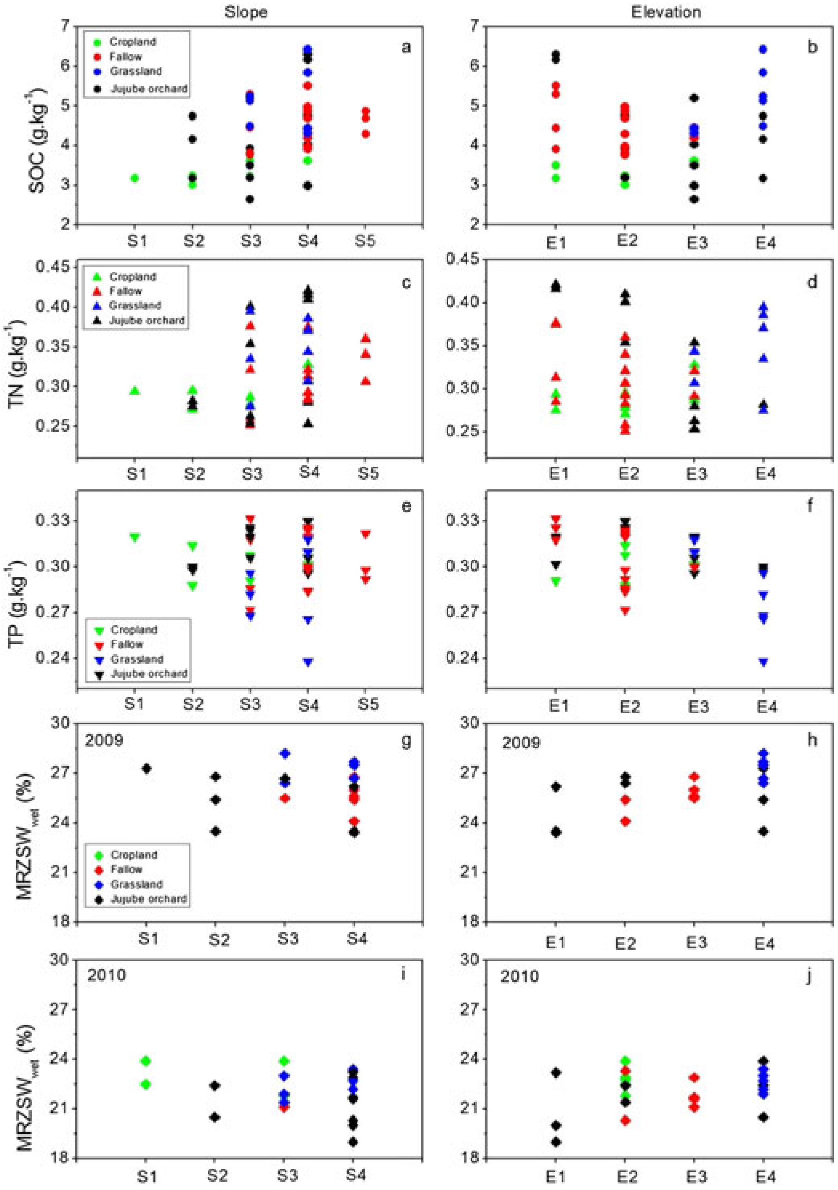

Figure 3. The relations between soil properties for different land uses and topography (slope and elevation). (a), (c), (e), (g) and (i) showed the relations between slopes and SOC, TN, TP, MRZSWwet in 2009 and 2010, respectively; (b), (d), (f), (h) and (g) showed the relations between elevation and those soil quality indicators, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

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whereas Liu *et al.* (2011) found no significant difference among various slope gradients. For STN and STP, Wang *et al.* (2009) found that no significant difference existed among slope gradients.

As to the elevation, overall, SOC showed relatively low values at moderate elevations (E2 and E3, i.e., 981–1030 m), and different SOC versus elevation relationship was observed for different land use. SOC for jujube orchard and fallow decreased, whereas that for grassland increased when elevation increased. However, SOC for cropland changed little with elevation.

A similar but weak relation was observed between STN and elevation compared with SOC, and relatively low values existed for elevations between 1001 and 1030 m (E3). In general, significant ($p < 0{\cdot}05$) and negative relation existed between STP and elevation, whereas SOC for cropland showed opposite behaviors. For both years, MRZSWwet increased with elevation. This may be also because grassland at which highest values were observed was located at high elevations. Our results partly accorded with several previous findings in the Loess Plateau. For example, Wang *et al.* (2009) found that STN and STP decreased with slope within a small catchment. At the regional scale, Liu *et al.* (2011) found that the lowest SOC density at the 0–40 cm located at elevations of 1000–1500 m. However, Fang *et al.* (2012) found that weak relations existed between elevation and SOC.

Land use, slope, and elevation also affect the relations between soil properties. Figure 4 shows the Pearson correlation coefficients between different soil properties at the 0–20 cm for various land use, slope gradients, and elevation intervals. Overall, the degree of correlations between soil properties was highly dependent on these environmental variables. The highest correlation coefficient ($R = 0{\cdot}86$) between SOC and STN existed in fallow land (Figure 4a); for SOC versus STP and for STN versus STP, the highest values existed in grassland and jujube orchard, respectively (Figure 4b and c). Note that we reclassified the slope gradients because only one and three sampling locations existed in slight slope (S1) and very steep slope (S5), respectively. The results showed that negative correlation between SOC and STN existed for relatively gentle slope (S1and S2), whereas a transition to positive correlation existed for steeper slopes (S3, S4, and S5). For SOC versus STP, very weak correlation existed for S1 and S2, whereas negative and stronger correlations existed for steep slopes. The highest correlation between STN and STP was observed at moderate slope (S3). For different elevation intervals, strong and positive correlation ($R = 0{\cdot}995$) was observed at low elevation (E1), whereas very weak correlation ($R = 0{\cdot}017$) at relative high elevation (E3). Weak relations between

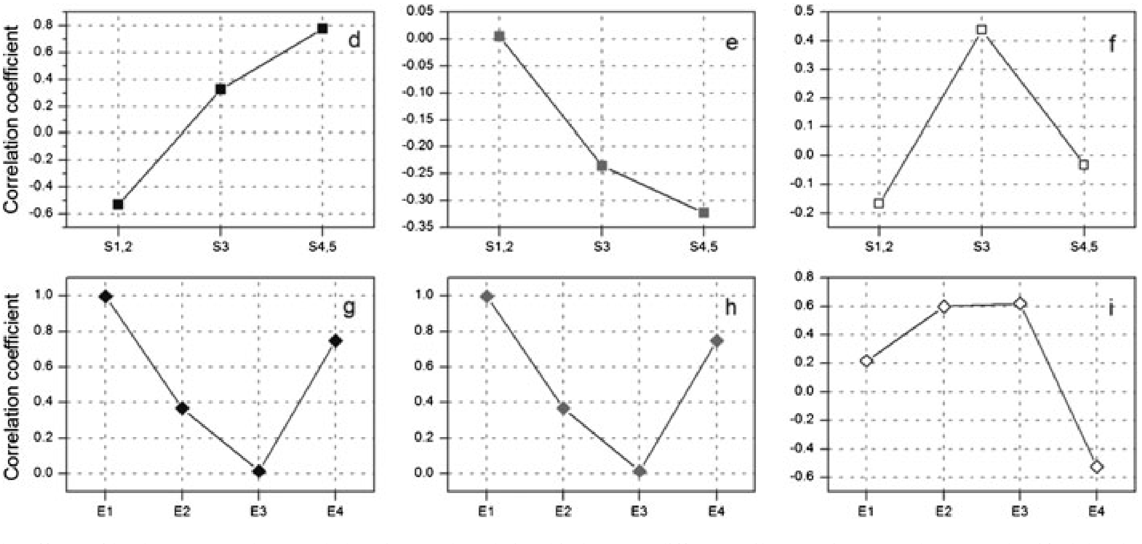

Figure 4. The effects of land use types, slope, and elevation on the relationship between different soil properties. Note that we reclassified the slope gradients into three classes: S1 and S2 (<25 per cent), S3 (25–45 per cent), and S4 and S5 (>45 per cent) (a)-(c): the correlation coefficients between soil properties for various land uses; (d)-(f): the correlation coefficients between soil properties for various slope gradients classes; (g)-(i): the correlation coefficients between soil properties for various elevation classes..

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SOC and STP existed at relatively low elevations (E1, E2, and E3), whereas strong and negative correlation existed at the highest elevation interval (E4). Similarly, negative correlation was also observed for E4.

CONCLUSIONS

We analyzed the spatial variations of four soil quality indicators for different land uses under catchment-scale vegetation restoration in the Loess Plateau of China. The relations of these soil properties to topography (slope and elevation) were characterized. On the basis of the results and analyses, the following conclusions could be drawn:

- Soil organic carbon, STN, and MRZSWwet were significantly different ($p < 0{\cdot}05$) for different land uses. Grassland indicated the highest values for these three soil properties, whereas cropland showed relatively low values. However, grassland showed the lowest STP, suggesting that vegetation restoration had little effect on STP. Overall, this study shows that soil quality indicators can be used to effectively monitor long-term changes associated with the "Grain-for-Green" program on the Loess Plateau of China.
- Different relations between soil quality indictors and topography were observed. Overall, SOC and STN increased with slope, whereas STP and MRZSWwet showed weak relations to slope. SOC and STN showed relatively low values at moderate elevations (E3); STP decreased with elevation, whereas MRZSWwet increased with elevation. Moreover, these relations varied with land uses. Furthermore, land use types, slope, and elevation showed significant effects once the correlation coefficients of different soil quality indicators.

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