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Local-scale spatial variability of soil organic carbon and its stock in the hilly area of the Loess Plateau, China

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ABSTRACT

Soil organic carbon (SOC) is one of the key components for assessing soil quality. Meanwhile, the changes in the stocks SOC may have large potential impact on global climate. It is increasingly important to estimate the SOC stock precisely and to investigate its variability. In this study, Yangjuangou watershed was selected to investigate the SOC distribution under different land uses. We found that SOC concentration decreased with increasing soil depth under all land uses and was significantly different across the vertical soil profile ($P<0.01$). However, considering effect of land use on SOC, it is only significant ($P<0.01$) in the topsoil (0–5 cm) layer. This indicated that land use has a large effect on the stocks of SOC in the surface soil. The stratification ratio of SOC >1.2 may mean that soil quality is improving. The order of the SOC density (0–30 cm) under different land uses is forestland>orchard land>grassland>immature forestland>terraced cropland. The SOC stock is found to be as large as 2.67×10^3 t (0–30 cm) in this watershed. Considering time effect of restoration, the slope cropland just abandoned is more efficient for SOC accumulation than trees planted in the semi-arid hilly loess area.

Introduction

Soil organic carbon (SOC) has an important influence on the chemical and physical properties of soil and can release its contained nutrients through mineralization in forms available to plants. Thus one of the key components for assessing soil quality is SOC appraisal (Gregorich et al., 1994; Lal, 2004). On the other hand, with an increasing concern about the increase of atmospheric CO_2 concentration and the role of SOC in carbon sequestration, field experiments carried out on different land uses are widely employed to develop options for increasing soil carbon sequestration (Follett, 2001). SOC stock in surface soils worldwide has been estimated to around 2011 Pg (2.011×10^{18} g) C, twice the value in either living vegetation or atmospheric carbon (IPCC, 2000). As one of the most important carbon stocks, SOC has large potential to affect global climate (IPCC, 2000; Pan et al., 2003). Measuring the quantity and spatial distribution of SOC is essential for evaluating soil function and understanding soil carbon sequestration processes (Venteris et al., 2004).

A series of studies to estimate the soil carbon stock and distribution patterns at the global, continental, country and regional scales have been conducted and reported. However, due to varied data sources, a lack of complete inventory data, and the inherent spatial variability of SOC, estimation of SOC stock at large scale has varied from one study to another (Xie et al., 2004). For example, Bohn (1976) estimated a figure of 3000 Pg for global SOC storage, whereas Bolin (1977) estimated a figure of 710 Pg. There is similar uncertainty for SOC estimates in China. Fang et al. (1996) estimated the SOC storage in China at 185.7 Pg, while Pan et al. (2002) estimated SOC storage at a significantly lower figure of only 50 Pg. Therefore, the selection of the type of SOC database, the land use and/or soil map, the mapping resolution, reference depth, bulk density or other information can have a great influence on the final SOC stock estimation. To reduce the uncertainty of SOC stock estimation, site and local scale monitoring and assessments are necessary.

Arid and semi-arid regions have been regarded as potential carbon sinks recently (Squires, 1998; Lal, 2002; Ardö and Olsson, 2003; Grünzweig et al., 2003). The Loess Plateau, the important cradle of traditional Chinese culture, is typically semi-arid and famous for its deep loess. However, during its history frequent and long-term anthropogenic activities have caused negative impacts on local environments, namely severe degradation of natural vegetation and serious soil erosion (Peng and Yu, 1995; Shi and Shao, 2000). The amount of annual soil erosion is estimated to be over 2.2 Pg (National Environmental Protection Bureau, 2000). A large quantity of fine surface soil that has eroded from the loess area is transported into the Yellow River, which has been described as the most turbid river in the world, with some 1.6 Pg of sediment being transported each year and a sediment concentration of 35 kg m^{-3} (Zhang, 2005). These have resulted in a fragile environmental status within the Loess Plateau and have become the main source of sediment in the Yellow River (Zhu, 1999). Due to natural drought conditions, intensive human disturbance and severe erosion, the Loess Plateau has become the lowest in soil carbon pool in China (Li et al., 2004). Since the

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1950s, large efforts on soil erosion control and ecosystem restoration have been made by the Chinese Government (Fu et al., 2002) and other stakeholders. However, vegetation remained poor and soil erosion was still out of control until late 1990s. In 1999, the “Grain-for-Green” project was initiated in western China including the Loess Plateau by the Chinese Government for ecological rehabilitation, through converting sloping cropland into other land cover types (Chen et al., 2007a,b).

This paper focuses on the land use effects on SOC and spatial variation of SOC at the small watershed scale. The objectives are: (1) to reveal the spatial heterogeneity of SOC distribution; (2) to assess the degree of soil quality improvement under the current naturally rehabilitated states by stratification ratio of SOC; and (3) to estimate SOC density of a small watershed in Loess Plateau.

Geographical setting

The study area is the Yangjuangou watershed (36°42′N, 109°31′E), which is located in the middle part of the loess plateau in northern Shaanxi Province of China (Fig. 1). It is 14 km north to Yan'an city and covers an area of 2.02 km^2. There are important 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}. It has a semi-arid continental climate with an average annual rainfall of 535 mm. The rainfall is mainly concentrated between July and September with large inter-annual variations. The soil is mainly derived from loess with texture ranging from fine silt to silt and vulnerable to erosion (Fu et al., 2000). The erosion rate is high with an average soil loss of 8979 t km^2 yr^{-1} (8.979×10^6 kg km^2 yr^{-1}) between 1991 and 1996 (Li et al., 1997). The natural vegetation has been destroyed by cultivation, and many changes have taken place in the agricultural landscape after several years of rehabilitation.

Materials and methods

Soil sampling and laboratory methods

105 sites were sampled according to land use (Table 1) and slope transects in July 2006. A portable GPS receiver was used to locate the sampling sites (Fig. 1). The sampling depth was 30 cm with four layers

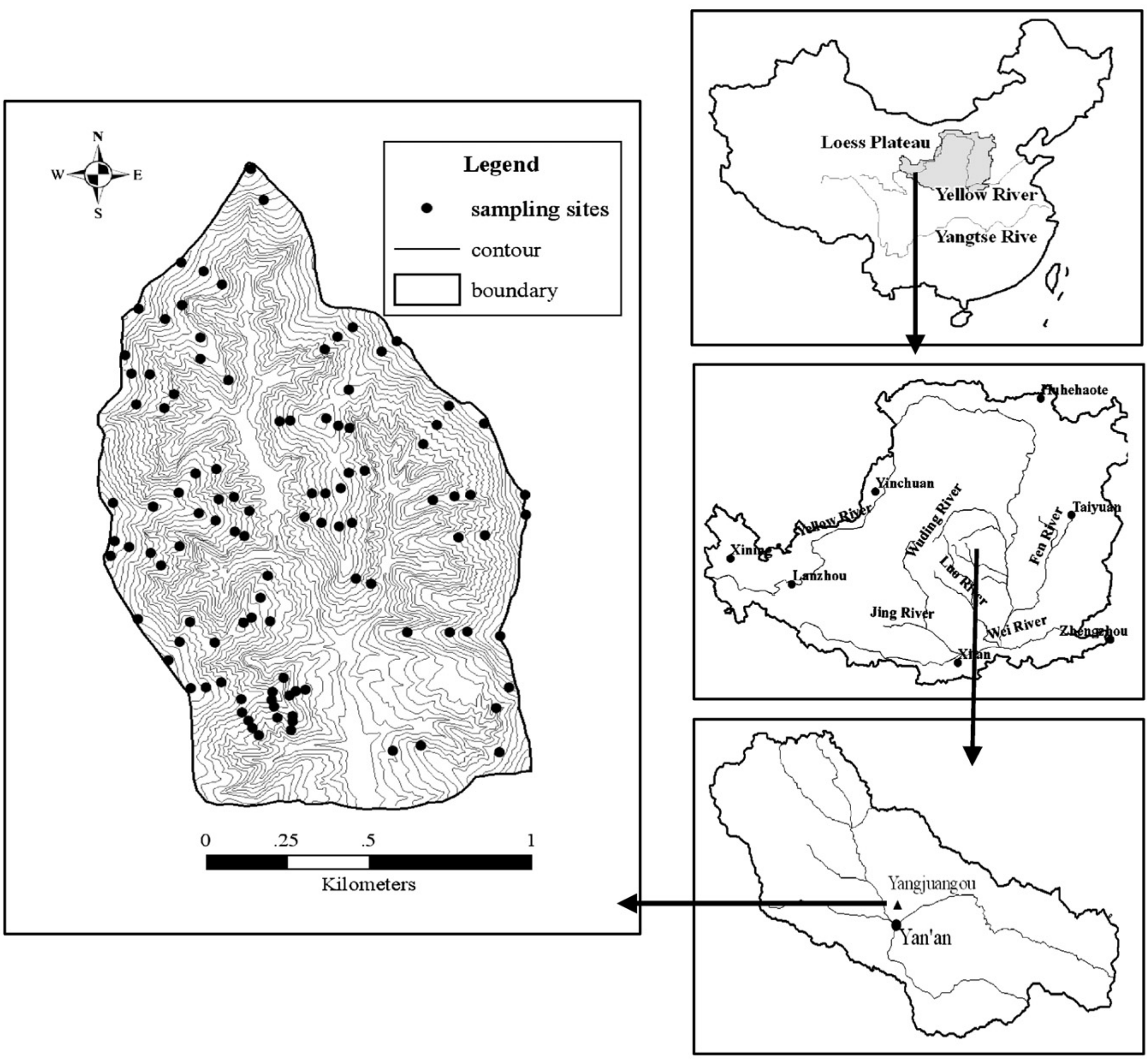

Figure 1. Location of Yangjuangou watershed, Loess Plateau.

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Table 1
Main types of plant on different types of land use.

Land-use types	Main vegetation cover	Age (yr)
Forestland	Locust tree (*Robinia pseudoacacia* L.)	25
Grassland	Annual grass: wormwood, small shrub	7
Immature forest land	Almond (*Prunus armniaca* L), Locust (*Robinia pseudoacacia* L.)	7
Orchard	Apple tree (*Malus pumila mill*), (*Jugians regia* L.)	23
Terraced cropland	Potato (*Solanum tuberosum*), miller (*Panicum miliaceum* L.)	20

(0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm). Three replicated samples were homogenized by hand mixing and were sieved for the determination of SOC after being air-dried. SOC was determined using the dichromate oxidation method (external heat applied) (Liu et al., 1996). The inverse distance weighted approach (IDW) was used to produce the spatial distribution map of SOC content.

Calculation of stratification ratio of SOC

The stratification ratio is defined as a soil property at the soil surface divided by the same soil property at a lower depth according to Franzluebbers (2002). It can be used as an indicator to assess dynamic soil quality. In this study, the stratification ratio of SOC was surface soil SOC content at 0–5 cm depth divided by that of 10–20 cm depth.

Calculation of C density and pool

Although many researchers have assumed the thickness of topsoil to be 30 cm (Bernoux et al., 2002; Bhatti et al., 2002) or considered the upper 20–25 cm when estimating C pools (Li & Zhao, 2001), we used the measured thickness 30 cm to estimate the C pool. The SOC density of a single layer was calculated by using the equation similar to that used by Schwager & Mikhailova (2002):

$$D_{oc} = \mathrm{SOC}\times\gamma\times H\times(1-\delta_{2nm}/100)\times10^{-1}$$

where D_{oc} and *SOC* are the density (t ha^{-1}) and content (g kg^{-1}) of organic C, respectively; γ is the bulk density (g cm^{-3}); *H* is the soil layer thickness (cm); and δ2 mm is the fraction (%) of >2 mm soil particle size. Since loess soil particle size in China was mostly below 2 mm, this fraction was not calculated.

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

$$P_{oc} = \sum_{i}^{n} S_i\times\sum_{ij}^{nm}\mathrm{SOC}_{ij}\times\mathrm{BD}\times H_j\times10^{-1}$$

where *j* is the different depth of topsoil (1 = 0–5 cm, 2 = 5–10 cm, 3 = 10–20 cm, 4 = 20–30 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}).

Statistical data analysis

Some main statistical parameters, generally accepted as indicators of the central trend and of the data trend, were analyzed. They include description of the mean, standard deviation, variance, and the extreme maximum and minimum value. Coefficient of variation (*Cv*) was calculated for the mean SOC to show the variation of individual calculation for each layer. *Cv*, the ratio of the standard deviation to the mean, is a measure of dispersion of a probability distribution.

Table 2
The statistic parameters of SOC in different soil layers.

Variables	0–5 cm	5–10 cm	10–20 cm	20–30 cm
Cv	0.3186	0.2619	0.2684	0.2929
P of Kolmogorov-Smirnov test	0.039	0.02	0.178	0.073
S.D.	2.004	1.243	1.039	0.913
Variance	4.016	1.545	1.079	0.833

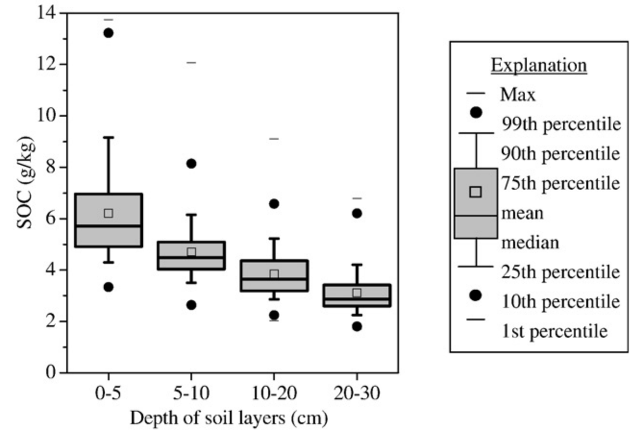

Figure 2. Box-plot showing the SOC content for four soil layers.

$$C_v = \frac{\mathrm{S.D.}}{\overline{X}}$$

$$\mathrm{S.D.} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i-\overline{X})^2}$$

where *Cv* is the coefficient of variation; *S.D.* is the standard deviation; $\overline{X}$ is the mean value; X_i is the value of the *i*th sample; n is number of samples. Kolmogorov-Smirnov test was used to check the normal distribution of data; ANOVA was performed to assess differences in distribution of organic carbon content for soil depth and land use, respectively.

Results

Descriptive statistics for SOC

The statistic parameters of SOC in different soil layers are shown in Table 2. The SOC in four layers have a relatively higher coefficient of variation (*Cv*) ranging between 0.25 and 0.35, which could be linked to the heterogeneity of land use, soil depth and other factors. From the results of Kolmogorov-Smirnov test (Table 2), it is clear that the statistical distribution of the raw SOC data in the 0–5 cm and 5–10 cm layers is positively skewed ($P<0.05$), and the data in the 10–20 cm and 20–30 cm is of normal distribution ($P>0.05$). The log-transformed data in the 0–5 cm and 5–10 cm layers present the normal distribution character with the *P* value of Kolmogorov-Smirnov at 0.525 and 0.315 for 0–5 cm and 5–10 cm, respectively. The box-plot was used to show the distribution range of SOC content for the four soil layers (Fig. 2). It is obvious that SOC decreased with the soil depth. For the four layers,

Table 3
SOC of soil profiles ($n>9$) in the five land-use types (± standard deviation) g kg^{-1}.

Depth (cm)	Forestland	Grassland	Immature forestland	Orchard land	Cropland terraced
0–5	6.96 ± 2.16aA	6.25 ± 2.08aAB	5.59 ± 1.58aBC	5.32 ± 0.86aBC	3.76 ± 0.46aC
5–10	4.69 ± 1.05bA	4.93 ± 1.65bA	4.47 ± 1.02bA	5.00 ± 0.59bA	3.52 ± 0.22bA
10–20	3.85 ± 0.91cA	3.96 ± 1.30cA	3.64 ± 0.90cA	4.20 ± 0.80cA	3.29 ± 0.20cA
20–30	3.16 ± 1.08dA	3.14 ± 0.94dA	2.92 ± 0.64dA	3.36 ± 0.61dA	3.01 ± 0.33dA

Means with different small letters are significantly different of SOC in different soil depth at the 0.05 level of probability.

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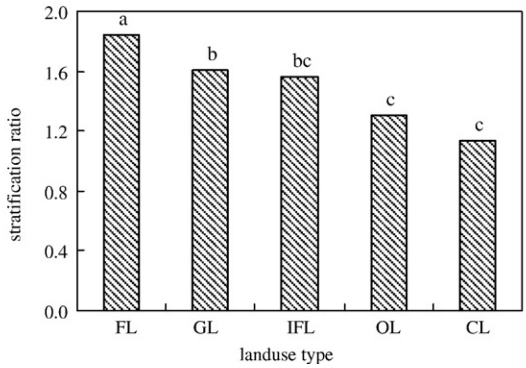

Figure 3. Stratification ratio of SOC under different land-use type (FL is forestland, GL is grassland, OL is orchard land, IFL is immature forest land, CT is cropland terraced). Means with different small letters are significantly different at 0.05 level.

0–5 cm, 5–10 cm, 10–20 cm and 20–30 cm, the 50% SOC contents lie between 1.96–6.97 g kg^{-1}, 4.40–5.15 g kg^{-1}, 3.19–4.39 g kg^{-1}, and 2.59–3.44 g kg^{-1}, respectively.

Vertical distribution of SOC under different land-use types

SOC concentration decreased with increasing soil depth under all land-use types (Table 3) with significant difference across different soil depth ($P<0.01$). At the surface layer (0–5 cm), SOC was variably distributed under five land-use types. SOC of forestland was significantly different from those under other land uses except for grassland ($P<0.05$). This indicated that forestland and grassland are more effective in SOC accumulation than other land-use types.

When soil depth is below 5 cm, SOC contents in orchards showed the maximum values among all the land uses. This is related to the management practices in orchards. Farmers are accustomed to fertilizing orchards with organic manure and tillage operations as well. Therefore, the subsurface soil in orchard gets more residue and manure and reserves more SOC than others.

Effect of land use on stratification ratio

The stratification ratio of SOC varies from 1.14 to 1.85 under different land-use types (Fig. 3). For forestland, it is significantly different from those values of other land uses ($P<0.01$). The order of SOC stratification ratio is forestland>grassland>immature forestland>orchard land>terraced cropland. For grassland and immature forestland, the ratios are similar, but they are both significantly different from those of orchard and terraced cropland ($P<0.05$). Meanwhile, the distribution of stratification ratio was created by the IDW method (Fig. 4) to estimate the spatial variation of this indicator at the watershed scale.

The SOC spatial distribution and stock estimation

The spatial distribution of SOC content in the four soil layers is shown in Figure 5. The spatial distribution of SOC in Figure 5(a) is closely related to land-use distribution (Fig. 6), in that high-level SOC contents usually correspond to grassland and forestland. It is clear that the SOC distribution character is similar for every layer across the land-use types. On the whole, the SOC contents in the north and west are, respectively, higher than those in the south and east. After the implementation of the Grain-for-Green project, the southern area became the base of food supplies and human activities in this part were intensified accordingly. It has already been reported (McGrath and Zhang, 2003) that SOC levels were significantly lower in highly disturbed areas such as those with more frequent tillage.

Land use also had an effect on SOC density (Table 4). The SOC density of different land-use types followed the order of forestland>orchard land>grassland>immature forestland>terraced cropland. The SOC density in forestland, grassland and orchard increased by 29%, 28% and 28%, respectively, compared to that of terraced cropland. In this sense, the carbon sequestration effects of the above three land uses are nearly the same in spite of their different ages of succession (over 20 yr for forest and orchard; 7 yr for natural grass restoration).

Finally, the SOC stock of the top soil (0–30 cm) in Yangjuangou watershed is estimated to 2.67×10^3 tC. 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 is at a moderate level.

Discussion

Land use change and carbon sequestration

SOC content change resulting from land-use change is meaningful for C cycling. Increasing the SOC content means increasing the carbon input. Switching from conventional agriculture to other land uses with higher carbon inputs or reduced disturbance (e.g., conversion to grassland, natural regeneration) will increase soil carbon stocks. To a certain extent, increased SOC can result in decreasing atmospheric CO_2 level and mitigating global warming.

However, different land use or vegetation cover has different potential to increase SOC. In this study, forest plantation with an age of 25 yr accumulated the highest level of SOC among all land-use types. Seven-yr-old, naturally rehabilitated grassland dominated by local herbaceous species, however, reached a SOC level almost similar to that of forestland. This indicated that natural vegetation restoration

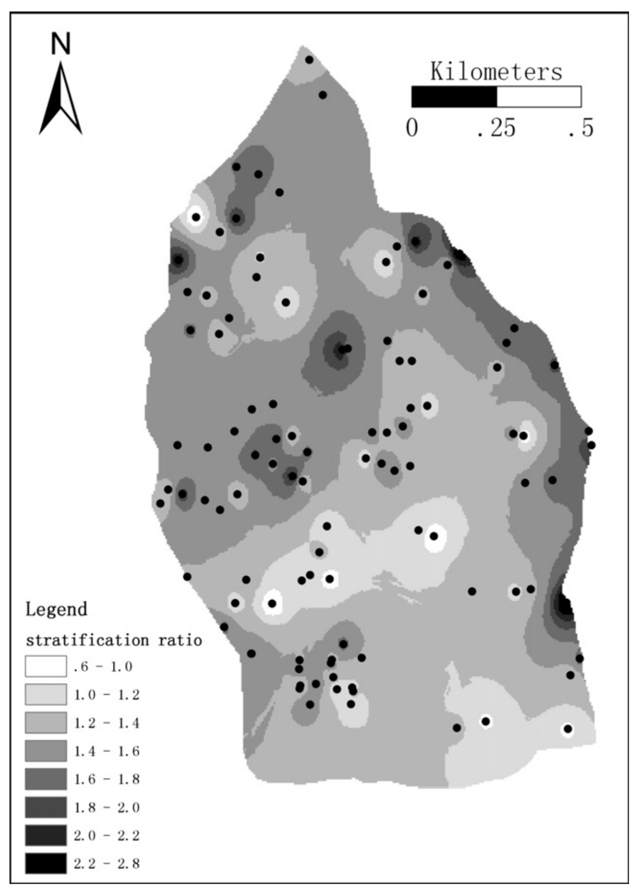

Figure 4. Spatial distribution of SOC stratification ratio.

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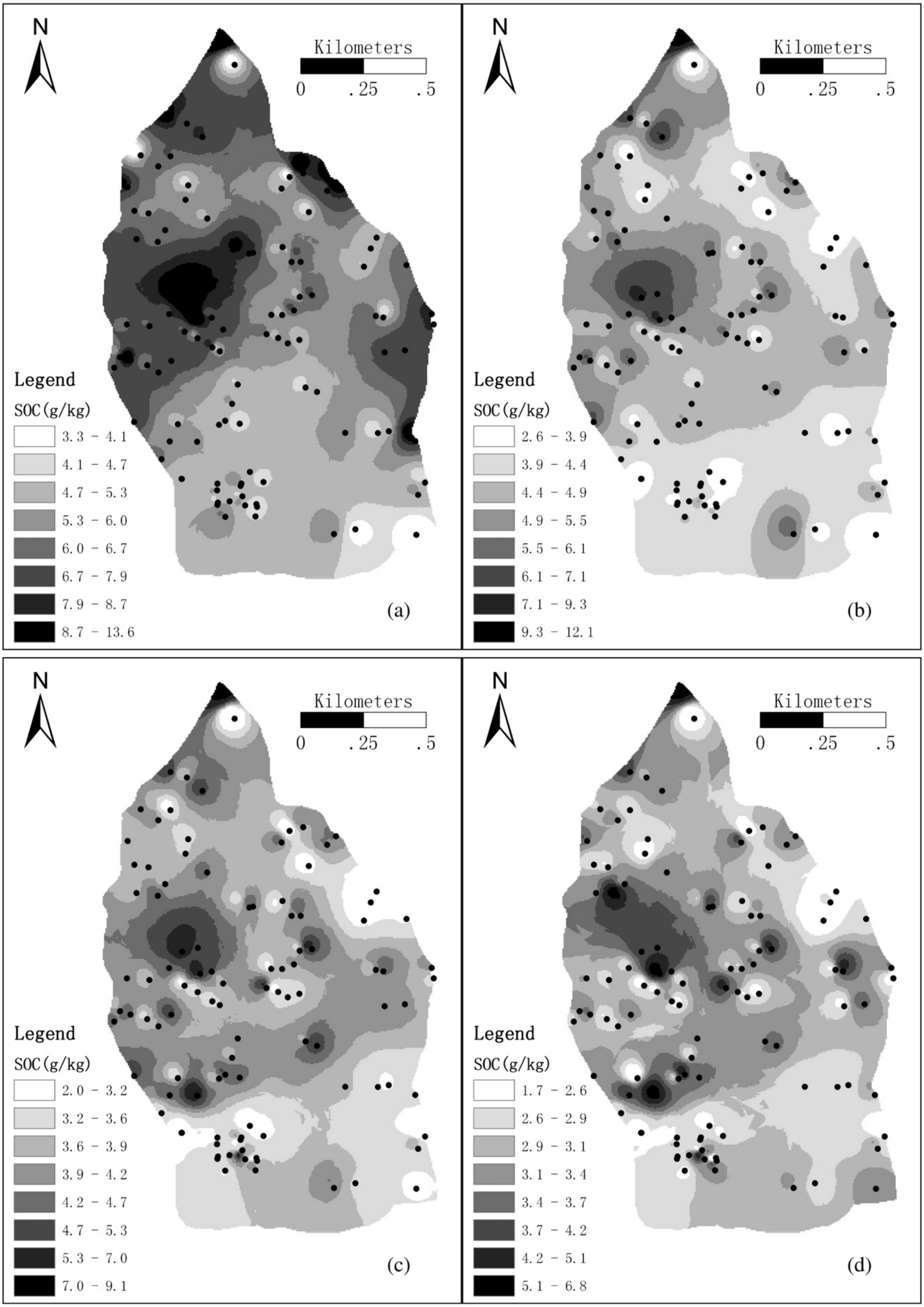

Figure 5. Spatial distribution of SOC concentration. (a) 0–5 cm; (b) 5–10 cm; (c) 10–20 cm; (d) 20–30 cm.

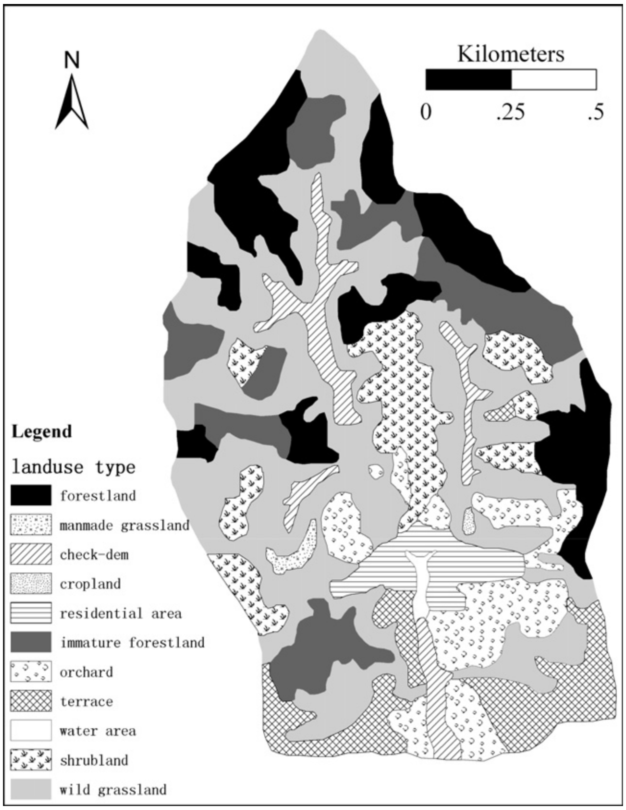

Figure 6. Distribution of land use in Yangjuangou watershed.

has great potential for improving soil quality due to increasing surface SOC. This was due to the high residue input in the surface soil (Li et al., 1992; Wu et al., 2004; Liu et al., 2005). The topsoil (0–5 cm) layers of all the land-use types were significantly different on SOC, which indicated that the topsoil was very important for SOC accumulation. At the same time, the effects of land use on soil carbon sequestration occur mainly in the topsoil layer. Factors including vegetation coverage, the amount of liter fall and root impact, and disturbance or management regime can contribute to the significant variation of surface soil SOC across different land uses (Franzluebbers et al., 1998; McCarty et al., 1998; Pascual et al., 2000; Degryze et al., 2004; Chen et al., 2007a,b). Accordingly, the large and rapid changes in the SOC density after land-use conversion indicated that there is considerable potential to enhance soil carbon sequestration in the loess hilly area of China. This can result in improving topsoil quality and increasing SOC storage.

SOC stratification ratio as an indicator of ecological rehabilitation

The concept of soil organic matter stratification is suggested as an alternative soil quality assessment tool to overcome the inherent differences in soil capability for carbon sequestration among varied environments. It is used to detect management-induced changes in dynamic soil quality. So in this article, we introduced the indicator to illustrate dynamic soil quality under different land-use types. It is considered that the extent of stratification can be used as an indicator of soil quality or soil ecosystem functioning, because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients (Franzluebbers, 2002).

Franzluebbers (2002) indicated that stratification ratio of soil organic C pool >2 would be an indication that soil quality might be improving under no tillage. In this study, it is not suitable to use 2 as index to assessing the loess quality. If SOC in cropland and orchard were used as reference, a stratification ration of SOC >1.2 would be an indication that denotes the soil quality might be improving in the process of Grain-for-Green. In Figure 4, the spatial distribution trend of SOC stratification ratio showed similar pattern with vegetation restoration pattern. This indicated that stratification ratio was an effective indicator for soil quality rehabilitation in this region. Further study is still needed at broader scales to clarify whether this indicator can be applied to the whole Loess Plateau.

Local scale monitoring vs. large scale estimation of SOC

Based on soil type data from the Second National Soil Survey and soil type map, Xu et al. (2003) calculated soil organic carbon density and stocks of topsoil (0–20 cm) in the Loess Plateau. Their results showed that soil organic carbon density varied from 0.6 to 12.18 kg C m^{-2} in the Loess Plateau, mostly ranging from 1 to 4 kg C m^{-2} with a mean value of 2.49 kg C m^{-2}, and totaled to be 1068 Tg C. Meanwhile, SOC density tends to decrease from the east to the west in the Loess Plateau.

In this study, we thought about main influencing factors on SOC, for example, land-use type, soil depth and topography. We based the research at small watershed scale to estimate SOC stocks. We calculated by weighted area of different land-use type that SOC density was 15.06 kg C m^{-2} (0–30 cm). It is still significantly higher than 2.49 kg C m^{-2}(0–20 cm) even though different soil depths were considered. The loess hilly area covers approximately half of the loess plateau with about 204.7×10^4 ha of steep cropland (slopes >15°) planned to be reforested during the Grain-for-Green project (Xu and Tian, 2004). If all the croplands with slopes over 15° were converted into other land uses in the loess hilly area, SOC sequestration in the soil layer (0–30 cm) would be 30.82 Tg C at the rate found in this study.

Conclusions

The SOC content decreases along with the increase of soil depth, and the degree of SOC content variance is relatively high in the study area. The impact of long-term vegetation restoration on the soil carbon pool is significant in this region; land use is a significant factor influencing the SOC at 0–5 cm soil depth, and the surface soil (0–5 cm) is very important for the SOC accumulation.

The stratification ratio of SOC is an indicator to assess soil quality dynamics. After rehabilitation, both grassland and forestland have higher stratification ratio than other land uses. Considering time effect of rehabilitation, grassland showed great potential to improve soil quality.

The order of SOC density of surface soil (0–30 cm) is: forestland>orchard land>grassland>immature forestland>cropland terraced. The stock of the top soil (0–30 cm) in this study is at a moderate level of 2.67×10^3 t. Based on the results of this study, it is clear that the ongoing Grain-for-Green project aiming to reduce soil erosion and improve land quality will also raise C sequestration in the soil.

Large uncertainty exists on the estimation of soil carbon stock due to environmental heterogeneity and ecological complexity on various scales. The integration of data and information from different scales and scaling are necessary to reduce this kind of uncertainty.

Table 4
SOC storage and density of different land-use type in Yangjuangou watershed.

	Forestland	Grassland	Immature forestland	Orchard land	Cropland terraced	Total
Area(ha)	26.81	77.54	39.69	17.96	15.55	177.55
Percent area (%)	15.10	43.67	22.35	10.12	8.76	100
D_{oc}(tC ha^{-1})	16.04	15.86	13.50	15.91	12.43	15.06[a]
P_{oc} (tC)	429.90	1229.73	535.62	285.67	193.21	2674.13
Percent P_{oc} (%)	16.10	46.07	20.22	10.86	7.12	100

[a] is SOC density of land use area-weighted.

Small-scale monitoring and large-scale spatiotemporal modelings are both integral parts of carbon cycling research. It is, therefore, necessary for researchers to get more site or local-scale evidence according to some environmental gradient to raise the accuracy of the estimation. In this sense, the present study provides important small-scale for large-scale SOC stock estimation.

Acknowledgments

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