Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China

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Abstract
Accurate knowledge of regional soil organic carbon (SOC) stocks and the effects of environmental factors on SOC is crucial, both from the perspective of regional carbon budgets and appropriate landscape management of SOC. However, little information is available regarding the regional SOC stocks in the Loess Plateau region in China. Thus, the objectives of this study were to estimate the current regional SOC stocks and to analyze the relationship between SOC and pertinent environmental factors, i.e. precipitation, temperature, elevation, slope gradient, clay plus silt content (<20 μm) and land use. We investigated upper (0–20 and 20–40 cm) and deeper (0–100 and 100–200 cm) soil layers at 382 sampling sites across the entire Loess Plateau region (620,000 km²). Regional spatial distribution of soil organic carbon density (SOCD) was depicted in a map and SOC stocks were calculated for different soil depths using a geostatistical method. Analysis of variance (ANOVA) was used to analyze the effects of environmental factors on SOCD. Results showed that the mean SOCD was 2.64 kg C m⁻² in the 0–20 cm soil layer and 4.57 kg C m⁻² in the 0–40 cm soil layer, and it was estimated that 1.64 and 2.86 Pg (1 Pg = 10¹⁵ g) of organic carbon were stored in these soil layers, respectively. Estimates for deeper soil layers indicate that mean SOCD in the 0–100 and 0–200 cm soil layers was 7.70 and 12.45 kg C m⁻², respectively, while the total organic carbon stocks amount to 4.78 Pg C (0–100 cm) and 5.85 Pg C (0–200 cm), respectively. Precipitation, temperature, elevation, clay plus silt contents and land use showed significant regional impacts on SOCD. Generally, SOC contents are higher in soils on mountains (with relatively high elevations and low temperatures) and valleys (with low elevations and high precipitation). The results also show that human activities have heavily affected SOC accumulation. Measured SOCD under cropland was relatively higher than under grassland and forestland. The study provides an overview of the current spatial pattern and stocks of SOC, as well as the effects of environmental factors on SOCD, across the entire Loess Plateau region and may be of further use in optimizing strategies for ecological restoration and regional SOC dynamic modeling as an important initial input.

1. Introduction

Soil organic carbon (SOC) is an important soil component that plays key roles in the functions of both natural ecosystems (greatly influencing soil structure, fertility, and water-holding capacity) and agricultural systems, in which it also affects food production and quality (Lal, 2004a). Recently, attention has focused on organic carbon pools in soils because of its critical role in the global carbon cycle and its potential for mitigating or exacerbating atmospheric levels of greenhouse gases (Raich and Potter, 1995; Davidson and Janssens, 2006). The global SOC stock has been estimated to be about 1400–1500 Pg C in the upper 100 cm soil layer (Post et al., 1982; Eswaren et al., 1993; Batjes, 1996), which is approximately twice the amount of C in the atmosphere and three times the amount stored in terrestrial vegetation (Smith, 2004). Thus, slight reductions in SOC contents due to changes in land-use, soil management, or rates of soil erosion, could significantly raise the CO₂ concentration in the atmosphere. However, soils have the potential to mitigate increasing atmospheric CO₂ concentrations through C sequestration with maximum potential global sequestration estimates ranging from 0.45 to 0.9 Pg C year⁻¹ (Batjes, 1999; Bruce et al., 1999; Lal, 2004b).

Soil carbon sequestration may be of a major role in attempts to meet the aims of the United Nations Frame-
work Convention on Climate Change to limit rises in atmospheric CO₂ thereby mitigating their potential effects (Schlesinger, 2000; Ingram and Fernandes, 2001). Accurate assessment of the spatial pattern and stocks of SOC, especially at national and sub-national scales, is an indispensable step when evaluating sequestration potentials. Therefore, SOC stock inventories have been widely established: at a global level (Eswaran et al., 1993; Sombroek et al., 1993; Batjes, 1996), and in North America (Lacelle et al., 1997), South America (Batjes, 2000), various European countries (Arrouays et al., 2001; Batjes, 2002; Krogh et al., 2003), India (Bhattacharyya et al., 2000), Brazil (Bernoux et al., 2002) and China (Fang et al., 1996; Pan, 1999; Wang et al., 2000; Jin et al., 2001; Li et al., 2003; Xie et al., 2004; Yu et al., 2007a,b).

Stocks of SOC have also been investigated in various sub-national regions, including northern (Zha et al., 2006b), eastern (Li et al., 2001b, 2002), southwestern (Zhang et al., 2008) and south-eastern (Zhao et al., 1997) regions of China. However, most of these studies focused on humid or semi-humid areas of China, and there is little information on either regional SOC stocks or their relationships with pertinent environmental factors in the large-scale arid and semiarid inland regions, which have been regarded as major potential carbon sinks (Squires, 1998; Lal, 2002; Ardö and Olsson, 2003). The Loess Plateau region (620,000 km²) in China, which is typically arid or semiarid, has deep loess soils and is subject to severe soil erosion (Shi and Shao, 2000). Due to natural drought conditions, intensive human disturbance and severe soil erosion, the region has the lowest soil organic carbon density (SOCD) in China (Yu et al., 2007a). However, it is possible to increase organic carbon content, as well as to sequester more carbon, in this region’s soils through appropriate reforestation of degraded soils and ecosystems whose resilience capacity is intact (Lal, 2004a; Pan, 2008).

To acquire accurate estimates of regional SOC stocks, reliable datasets providing information on pertinent soil variables in all of the areas, or types of sites, within the entire region are required. Several areal distributions of SOC in China, Chinese regions and other countries have been estimated by scaling up estimates obtained from soil sampling points and maps showing the distributions of related variables (soil type, land-use type, soil polygons or vegetation type) (Krogh et al., 2003; Yu et al., 2007b). A serious concern with this approach is that the division of areas according to classified types is based on Boolean logic, ignoring the spatial continuity between the plots and spatial variability within the plots (Zhu, 1997). Thus, both the accuracy and the reliability of the area datasets are questionable (Pan, 1999). Furthermore, previous large-scale evaluations of SOC stocks in China have generally been based on soil data (including soil profile records, soil bulk density, SOC concentration and proportions of rock fragments) gathered by the Second National Soil Survey of China (1979–1983) (Wang et al., 2000; Li et al., 2001a, 2002; Zhao et al., 2006b; Zhang et al., 2008). These estimates were based on decades old information, which may have subsequently changed significantly, and it was not possible to establish a baseline year. To better understand the SOC reservoir, it is necessary to update regional SOC information with intensive and contemporary measurements and to use a geostatistical method to avoid dependence on various maps having artificial boundaries.

The SOC content varies from place to place, controlled by a series of environmental factors at different spatial scales (Powers and Schlesinger, 2002), such as climate variables (Ganuza and Almendros, 2003; Dai and Huang, 2006; Davidson and Janssens, 2006), topography (Rezaei and Gilkes, 2005; Liu et al., 2006), soil texture (Hassink, 1996; Percival et al., 2000; Hevila et al., 2003), vegetation and land-use types (Su et al., 2006; Wang et al., 2009), and human management (Sainju et al., 2008). However, large-scale studies on the relationship between SOC and affecting factors are not sufficient (Lal, 2004b; Chaplot et al., 2010) and a good understanding on this issue is essential to develop suitable management strategies to enhance carbon sequestration.

Therefore, the two objectives of the study presented here were: (1) to acquire contemporary measurements of SOCD and a database of pertinent environmental factors, and then to use a geostatistical method to evaluate the SOC stocks in various layers of soils in China’s Loess Plateau region; and (2) from a large-scale perspective, to analyze the effects of those environmental factors on SOC stocks.

2. Materials and methods

2.1. Study area

The Loess Plateau region, as defined here and illustrated in Fig. 1a, is located in northwestern China within latitudes 33°43′–41°16′N and longitudes 106°54′–114°33′E, between the upper and middle reaches of the Yellow River, covering a total area of 620,000 km², about 6.5% of the area of China. The region is surrounded by the mountains of the Yinshan, Qinling, Taihang and Riyue-Helan Mountains to the north, south, east and west, respectively, and it has highly complex topography, including sub-plateaus, basins, hills and gullies, with altitudes ranging from 200 to 3000 m. The region is dominated by a temperate, arid and semi-arid continental monsoon climate. The mean annual temperature ranges from 3.6 to 14.3 °C, and the mean annual precipitation ranges from 150 to 800 mm, most (55–78%) of which falls between June and September, and decreases along a southeast to northwest transect (Yang and Shao, 2000). The soils are mainly derived from loess, and are of diverse types. The most widespread soil is clay–loam in texture, with sandier soils in the northwest and clayey soils in the southeast (Wang et al., 2010b). The natural vegetation has been largely destroyed by deforestation and cultivation. Much of the region (280,000 km²) is subject to severe soil erosion (Shi and Shao, 2000). A large quantity of the eroded mass is transported into the Yellow River, which carries a sediment load of about 16.4 × 10⁶ t year⁻¹ (SSCCWRA, 1989). Land degradation, desertification, soil erosion and declining soil fertility threaten the environment. However, since the 1950s the Chinese Government has made efforts to control soil erosion and restore the ecosystem and, in 1999, an extensive ecological rehabilitation program, designated “Grain-for-Green,” was initiated in the Loess Plateau region. The program has now been operating for about 10 years and the natural environment in parts of the Plateau is improving as annual crops are replaced by perennial plants.

2.2. Estimation of soil organic carbon density (SOCD)

2.2.1. Field sampling and laboratory analysis

In order to obtain updated SOCD data, 382 sampling sites were investigated throughout the Loess Plateau region, from April to November, 2008 (Fig. 1b). In the field, the approximate location of each sampling site was controlled by the spacing distance (30–50 km) between sites, which was measured by a vehicle’s milometer during travelling. Furthermore, the actual sampling sites were randomly selected to represent the main topography, land-uses and vegetation types within the range of vision; a global positioning system (GPS) (5-m precision) was then used to identify the site’s longitude, latitude and elevation. Notes were made of land-use type, vegetation species and coverage by observation; aspect and slope measured with a geological compass; and information on human activities (irrigation, fertilizer use and crop yield) collected from surveys of the local inhabitants.

Disturbed soil samples were collected with a 5-cm diameter soil auger, extracted in 10-cm incremental subsamples that were
then mixed together by hand. Soil samples representing the upper soil layers were collected from the 0–20 cm and 20–40 cm depths at five different places randomly selected within a 10-m radius at each site; for each layer, the five samples were then mixed by hand to form one representative sample for that layer at the site. Soil samples representing deeper soil layers were collected from 0–100 cm and 100–200 cm depths from one place at each site. In total, 1528 soil samples were collected to determine SOC concentrations, i.e., one sample from four soil layers (0–20, 20–40, 0–100 and 100–200 cm) at each of the 382 sampling sites. In addition, undisturbed soil cores from the 0–20 cm and 20–40 cm soil layers were collected and sealed in air-tight containers for measurements of bulk density.

All disturbed soil samples were air-dried, sealed in air-tight bags and taken to the laboratory. Samples passed through a 0.25-mm mesh were used to determine SOC concentration (g kg⁻¹), using the Walkley-Black method (Nelson and Sommers, 1982). The extraction efficiency of SOC by the Walkley-Black method varies between 60 and 86%, with a mean recovery of 76% (Walkley and Black, 1934). In this study, the SOC data were adjusted with a correction factor of 1.32 to estimate 100% organic C recovery (Meersmans et al., 2009; Wei et al., 2010). Samples passed through a 2-mm mesh were used

![Map of Loess Plateau region and sampling sites](image-url)
to determine soil mechanical composition (%) by laser diffraction using a Mastersizer 2000 (Malvern Instruments, Malvern, England) (Liu et al., 2005). Soil bulk density (g cm$^{-3}$) was determined by measuring the original volume of each soil core and the dry mass of it after oven-drying at 105 °C.

2.2.1. Calculation of SOC

SOC (kg C m$^{-2}$) was calculated using the following equation (Zhang et al., 2008):

$$\text{SOC}_h = \frac{\sum_{i=1}^{n} L_i \times SOC_i \times \rho_{bh} \times (1 - F_i/100)}{100}$$

where SOC$_h$ is the total amount of soil organic carbon between the soil surface and depth $h$ per unit area (kg C m$^{-2}$); $n$ is the number of layers considered; $i$ is the $i$th layer and $L_i$, SOC$_i$, $\rho_{bh}$, and $F_i$ are the thickness (cm), SOC concentration (kg g$^{-1}$), bulk density (g cm$^{-3}$), and the proportion (%) of coarse (>2 mm) fragments in the $i$th layer, respectively. The occurrence of coarse particles in the loess soils of the study region was rare, so $F_i$ was considered to be negligible. We could determine SOC to a depth of 40 cm more reliably by using the data obtained for the two layers, 0–20 cm and 20–40 cm, which included the measured soil bulk densities. To estimate SOC in the 0–100 cm and 100–200 cm soil layers, a mean soil bulk density value for loess soils (1.25 g cm$^{-3}$) was used (Wang et al., 2010a).

2.3. Estimation of SOC stocks

2.3.1. Geostatistics

To estimate SOC stocks, data on both the SOC (kg C m$^{-2}$) and the area (m$^2$) of the study region are required. Geostatistics (Webster, 1985) can be used to convert an SOC dataset from discrete points to a spatially continuous surface with optimal interpolation. Based on regionalized variable theory (Matheron, 1963), geostatistics uses semivariograms (Yost et al., 1982) to quantify spatial autocorrelations and provide input parameters for spatial interpolation, i.e., kriging (Krige, 1951). An empirically derived semivariogram can be expressed as:

$$\gamma(h) = \frac{1}{2 N(h)} \sum_{i=1}^{N(h)} (Z(x_i + h) - Z(x_i))^2$$

where $\gamma(h)$, the semivariogram estimator, is half the expected squared difference between paired data separated by a distance $h$ (Webster and Oliver, 2000). $Z(x_i + h)$ and $Z(x_i)$ are observations at positions $x_i + h$ and $x_i$, respectively, and $N(h)$ denotes the number of data pairs.

Standard theoretical models (spherical, Gaussian, exponential, linear, and circular) were then fitted to the empirical semivariogram derived from the measured data. The best fitted model, with the smallest residual sum of squares and the largest coefficient of determination, was used to provide input parameters for kriging interpolation. Essentially, the predictions obtained in this manner are like weighted moving means:

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i)$$

where $Z^*(x_0)$ is the predicted value at position $x_0$, $Z(x_i)$ is the known value at sampling site $x_i$, and $n$ is the number of sites within the neighborhood searched for the interpolation. The weight, $\lambda_i$, is decided by spatial autocorrelation according to the semivariogram (Burgess and Webster, 1980), under the conditions of unbiased error and minimized estimation variance. Here, original datasets were log-transformed and an ordinary point kriging method was used for interpolation, without trend removal. The predicted map quality of the SOC was tested by cross validation with replacement (Isaaks and Srivastava, 1989). The geostatistical analysis was conducted using GS + software (version 7.0).

2.3.2. Derivation of an accumulation process using GIS

After spatial interpolation, a SOC surface was created to cover the entire area of the Loess Plateau region. This surface was exported as a raster layer with a defined resolution (3000 m × 3000 m) in which every grid square was assigned both a SOC value and an area value. The next step was to use an accumulation process as follows:

$$\text{SOC}_a = \sum_{i=1}^{n} \text{SOC}_i \times \text{Area}_{grid} \times 10^{-12}$$

where SOC$_a$ is the total amount of soil organic carbon stock (Pg C; 10$^{15}$ g C) at depth $h$ in the study region, $n$ is the total grid number of the raster, $i$ is the $i$th grid square, SOC$_h$ is soil organic carbon density (kg C m$^{-2}$) for the $i$th grid square calculated to depth $h$, and Area$_{grid}$ is the area (m$^2$) of each grid square, set by the defined resolution. These calculations were performed using the GIS software package Arcmap Desktop (version 9.1) with the Spatial Analyst module.

2.4. Pertinent environmental factors and classification

To assess the relationships between SOC and pertinent environmental factors at the regional scale, the following variables were examined: precipitation, temperature, elevation, land use, slope gradient and clay plus silt content (<20 μm) (Hassink, 1996).

Precipitation and temperature datasets were derived as annual means of meteorological records (1951–2001) from 68 weather stations distributed throughout the region, and kriging interpolation was employed to create a continuous data surface of mean annual precipitation and mean annual temperature. Then the spatial coordinates of the sampling points were used to extract meteorological parameters for each sampling point from that data surface.

According to standard classification criteria for arid and semi-arid areas, the sampling sites (and associated datasets) were divided into three groups with annual precipitation of: <250, 500–250 and >500 mm (Table 1). The annual temperature and elevation datasets were also divided into three groups: <5, 10–5, and >10 °C and <1000, 1000–1500 and >1500 m (ISTCASLP, 1990, 1991). Land use was classified into three major groups: cropland, forestland and grassland. According to their distribution histograms, slope gradients and clay plus silt contents were divided into five (0’, 10’, 20’, 30’, and >30’) and three groups (<10%, 10–20%, and >20%) and three groups (<70%, 70–85%, and >85%), respectively (Table 1).

2.5. Statistical analysis

The mean and standard deviation values were used to represent SOC in different soil layers. The Kolmogorov–Smirnov (K–S) test was used to determine whether the data were normally distributed. In our study, precipitation, temperature and elevation values were normally distributed; SOC values were log-normally distributed; and land use, slope gradient and clay plus silt content were neither normally nor log-normally distributed. The Runs and Levene tests were used to confirm sample independence and homogeneity of variance. One-way analysis of variance (ANOVA) was used to analyze the effect of each environmental factor on SOC within the groups defined in Section 2.4. Subsequently, Duncan’s Multiple Range test was used to identify statistically significant differences ($p < 0.05$) among the mean values of SOC within each group of each
environmental factor. By using this method, effects of precipitation, temperature, elevation, slope, and clay plus silt content were detected within each land use type; and effects of land use type were detected within each of the groups defined by precipitation, temperature, elevation, slope and clay plus silt content. Statistical analysis was carried out using SPSS 13.0.

3. Results and discussion

3.1. The SOC pool

3.1.1. SOC De (Continued)

Table 1

<table>
<thead>
<tr>
<th>Class</th>
<th>Precipitation (mm)</th>
<th>Temperature (°C)</th>
<th>Land use</th>
<th>Elevation (m)</th>
<th>Slope (°)</th>
<th>CSC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;250 (n = 34)</td>
<td>&lt;5 (n = 37)</td>
<td>Cropland (n = 153)</td>
<td>&lt;1000 (n = 120)</td>
<td>0 (n = 297)</td>
<td>&lt;70 (n = 107)</td>
</tr>
<tr>
<td>2</td>
<td>250–500 (n = 210)</td>
<td>5–10 (n = 235)</td>
<td>Forestland (n = 128)</td>
<td>1000–1500 (n = 192)</td>
<td>0–10 (n = 22)</td>
<td>70–85 (n = 135)</td>
</tr>
<tr>
<td>3</td>
<td>&gt;500 (n = 138)</td>
<td>&gt;10 (n = 110)</td>
<td>Grassland (n = 101)</td>
<td>&gt;1500 (n = 70)</td>
<td>10–20 (n = 27)</td>
<td>&gt;85 (n = 140)</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20–30 (n = 20)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;30 (n = 16)</td>
<td></td>
</tr>
</tbody>
</table>

CSC: clay plus silt content (<20 μm); n = number of samples.

3.2. Effects of environmental factors on SOC

Soil organic carbon is influenced by a large number of related factors and the regulating processes are highly complex and vary spatially in both vertical and horizontal directions. Compared to the deeper soil layers, upper soil layers interact more directly with, and are more sensitive to, climate, vegetation and human activities. In this study, we focused on the relationships between SOC in the 0–40 cm soil layers and six pertinent environmental factors, i.e. precipitation, temperature, elevation, slope, clay plus silt contents (<20 μm) and land use.
Table 2
Soil organic carbon density (SOCD) (kg C m\textsuperscript{−2}) in different soil layers under different land uses.

<table>
<thead>
<tr>
<th>SOC pool</th>
<th>All samples</th>
<th>Cropland</th>
<th>Grassland</th>
<th>Forestland</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n\textsuperscript{a}</td>
<td>Mean\textsuperscript{b}</td>
<td>n</td>
<td>Mean</td>
</tr>
<tr>
<td>SOCD\textsubscript{20}</td>
<td>382</td>
<td>2.64 ± 1.77</td>
<td>153</td>
<td>3.03 ± 1.87a</td>
</tr>
<tr>
<td>SOCD\textsubscript{40}</td>
<td>382</td>
<td>4.57 ± 2.88</td>
<td>153</td>
<td>5.36 ± 3.20a</td>
</tr>
<tr>
<td>SOCD\textsubscript{100}</td>
<td>382</td>
<td>7.70 ± 4.36</td>
<td>153</td>
<td>8.82 ± 4.44a</td>
</tr>
<tr>
<td>SOCD\textsubscript{200}</td>
<td>382</td>
<td>12.45 ± 6.57</td>
<td>153</td>
<td>14.54 ± 5.18a</td>
</tr>
</tbody>
</table>

Different lowercase letters within rows indicate significant differences among land use types according to Duncan’s Multiple Range Test (P<0.05).

\textsuperscript{a} n is the number of samples.
\textsuperscript{b} Mean ± standard deviation.

Table 3
Geostatistical parameters for soil organic carbon density (SOCD) (kg C m\textsuperscript{−2}) in the 0–40 cm and 0–100 cm soil layers.

<table>
<thead>
<tr>
<th>SOC pool</th>
<th>Model</th>
<th>r\textsuperscript{2}</th>
<th>Nugget (C\textsubscript{0})</th>
<th>Sill (C\textsubscript{0} + C\textsubscript{1})</th>
<th>Proportion (C\textsubscript{1}/C\textsubscript{0} + C\textsubscript{1})</th>
<th>Range (km)</th>
<th>Anisotropy ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCD\textsubscript{40}</td>
<td>Spherical</td>
<td>0.947</td>
<td>0.032</td>
<td>0.071</td>
<td>0.451</td>
<td>339</td>
<td>2.22</td>
</tr>
<tr>
<td>SOCD\textsubscript{100}</td>
<td>Spherical</td>
<td>0.925</td>
<td>0.034</td>
<td>0.067</td>
<td>0.507</td>
<td>363</td>
<td>1.92</td>
</tr>
</tbody>
</table>

\textsuperscript{a} SOCD\textsubscript{40}, SOCD\textsubscript{100} refers to SOCD in the 0–40 cm and 0–100 cm soil layers, respectively; r\textsuperscript{2} is the coefficient of determination.

3.2.1. Effects of precipitation and temperature
It is generally accepted that climatic factors, especially precipitation and temperature, are the most important determinants of SOC contents (Homann et al., 1995; Alvarez and Lavado, 1998), due to their effects on the quantity and quality of organic residue soil inputs and on the rates of soil organic matter mineralization and litter decomposition (Quideau et al., 2001; Hevias et al., 2003).

Fig. 3a shows the effects of precipitation on SOCD. Generally, SOC was significantly higher in areas where the precipitation was greater than 500 mm than where it was less than 500 mm (p < 0.05). Precipitation would be expected to influence SOC since higher precipitation is generally associated with higher rates of vegetation growth, and thus, with higher rates of organic carbon input and SOC accumulation. However, there was no effect of increased precipitation on SOCD when amounts were less than 500 mm, since no significant differences in SOCD were detected between arid (<250 mm) and semiarid (250–500 mm) areas. Increasing susceptibility to soil erosion could reduce the positive effect of increased precipitation on SOCD in these areas, by decreasing SOC accumulation through removal of surface litter and particles attached to organic carbon (Lal, 2004b). The semiarid areas are more susceptible to soil erosion by water than the arid areas due to the greater amount of rainfall; storms are also more intense and of longer duration. The semiarid areas are more likely to be cultivated than the arid areas, so that recently tilled bare soils are exposed to the erosive power of rainfall. In contrast, the surfaces of uncultivated arid soils are often protected to a degree by biological surface crusts.

Fig. 2. Spatial distribution of soil organic carbon density (kg C m\textsuperscript{−2}) in 0–40 cm layers of soils in the Loess Plateau region.
(Kenapen et al., 2007). Finally, as indicated by the sampling site data, the semiarid areas have steeper slopes than the arid area. Other studies have shown that the most severe soil erosion in the Loess Plateau region occurs in the semiarid area, in the middle reaches of the Yellow River (Tang, 1991; Xin et al., 2009). Another factor affecting SOCD was temperature, which decreased with increasing precipitation from the southeast to the northwest in our study region (Yang and Shao, 2000). Lower temperatures could result in reduced SOC breakdown, thereby increasing SOC accumulation and weakening the positive effect of precipitation (Townsend et al., 1995; Trumbore et al., 1996).

Fig. 3a also shows different effects of precipitation on SOCD under different land use types. Under cropland, precipitation did not significantly affect SOCD \( (p < 0.05) \). However, cultivation processes on the Loess Plateau, such as land leveling and terracing, fertilization, tillage and crop residue management, tended to increase SOC accumulation in all areas while irrigation mitigated shortages in precipitation. Under forestland, SOCD was significantly higher in areas with precipitation either less <250 mm or >500 mm, compared to that between 250–500 mm \( (p < 0.05) \). The high SOCD under relatively low and high precipitations could be attributed to low decomposition of litter under those precipitation regimes (Seneviratne et al., 1998). For grassland, SOCD significantly increased with increases in precipitation. Different responses of land use to precipitation could be attributed to the nature of the different plant species and diverse complex interactions between them and climatic conditions, soil water conditions, microorganisms and human activities.

Similarly, Fig. 3b shows both an overall effect of temperature on SOCD and the various effects of temperature on SOCD under different land use types. When land use type is not considered, SOCD was significantly lower in areas where temperature was intermediate (5–10 °C) than in both relatively cooler (<5 °C) and warmer (>10 °C) areas, between which there was no significant difference in mean SOCD values \( (p < 0.05) \). Mean annual precipitation was higher (547 mm) in the areas with temperatures less than 10 °C compared with 396 mm in areas with temperatures between 5 and 10 °C. The combination of warmer temperatures and wetter conditions could lead to better biomass productivity and greater SOC accumulation. Relatively higher SOCD in areas with temperatures greater than 5 °C could be attributed to the slower microbial and chemical breakdown of SOC due to the lower temperatures, as well as the drier conditions. The absence of significant differences between areas with temperatures less than 5 °C or greater than 10 °C may coincidentally result from differing interaction effects of precipitation and temperature on SOCD. An additional factor to consider is that areas with intermediate temperatures were mainly located in the central Loess Plateau, which is subject to severe soil erosion (Tang, 1991).

Effects of temperature on SOCD also differed among the various land use types. Under cropland and grassland, temperature had no significant effect on SOCD \( (p < 0.05) \). In these cases, it suggests other factors have greater effects on SOCD than temperature alone, or that the integrated effects of climate, topography and human activities dampened the independent effect of temperature. Under forestland, SOCD was significantly higher in areas with lower (<5 °C) and higher (>10 °C) temperatures than in those areas with intermediate temperatures (5–10 °C) \( (p < 0.05) \). This pattern was consistent with the overall effect of temperature on SOCD as mentioned above, which suggests that the presence or absence of forests in these regions defined by temperature is a dominant factor in determining SOCD.
3.2.2. Effects of elevation

As shown in Fig. 3c, when land use type is not considered, mean SOCD values were significantly lower in areas with intermediate elevations (1000–1500 m) than in areas with relatively higher (>1500 m) or lower (<1000 m) elevations, and there was no significant difference in the mean SOCD values for these two latter elevation classes (p < 0.05). Under cropland and forestland in the same elevation class, the mean SOCD was statistically the same (p < 0.05). This was also true for grassland except at the lower elevations (<1000 m) where mean SOCD values were significantly lower than under the other two land types. Furthermore, under grassland there were no significant differences between the mean SOCD values in areas at elevations below 1500 m but SOCD was significantly higher at elevations above 1500 m (p < 0.05).

The effect of elevation was complex and was probably indirect. For example, there is an association between elevation and climatic parameters such as precipitation and temperature (Trumbore et al., 1996; Garten et al., 1999). This is demonstrated in Fig. 4, which shows that both precipitation and temperature tend to decline with increases in elevation in the Loess Plateau region according to our data. Lower temperatures could reduce SOC turnover rates, leading to increases in SOC levels; Leifeld et al. (2005) suggested that such increases may be in the order of 0.75–2.1 mg g⁻¹ per 100 m increase in elevation in Swiss agricultural soils. However, at lower elevations the wetter and warmer conditions could increase biomass productivity, leading to increased organic carbon inputs. Elevation is also associated with geomorphology that could influence soil erosion and geological deposition processes (Tan et al., 2004; Dai and Huang, 2006), consequently affecting topsoil SOC values. In the Loess Plateau region the most severe erosion occurs from the slopes in an area where the elevations are between 1000 and 1500 m (Tang, 1991; Xin et al., 2009). The same areas have relatively moderate precipitation that fall in intense storms. Soil erosion leads to the removal of SOC and other nutrients, together with soil particles, in runoff waters that enter the river system and are taken out of the region by the Yellow River (Shi and Shao, 2000) in amounts estimated to be 16.4 × 10⁶ t year⁻¹ (SSCCWRA, 1989). Such soil losses also reduce the region’s SOC stocks. Alternatively, valleys and basins with elevations less than 1000 m are the main deposition areas for eroded material. These erosion and deposition processes likely account, at least in part, for the observed differences in SOCD values at the lower (<1000 m) and intermediate (1000–1500 m) elevations.

3.2.3. Effects of slope gradient

Fig. 5 shows the mean SOCD values for the five classes of slope gradients (Table 1). There was no significant difference in SOCD values for slope classes 0° and for slopes greater than 0° (p < 0.05). An ANOVA of the effects of slope on SOCD showed no significant differences among the four classes with slope greater than 0° (p < 0.05).

3.2.4. Effects of clay plus silt content (<20 μm)

Fig. 3d shows the mean SOCD values in areas with different clay plus silt content (CSC), which ANOVA indicated had a significant impact on SOCD (p < 0.05). When land use was not considered, the mean SOCD value was significantly higher in areas with CSC > 70% than in those with CSC < 70% (p < 0.05); there were no significant differences between the SOCD values of the two areas with CSC > 85% and 70–85% (p < 0.05). The same patterns were found under cropland and forestland. However, under grassland mean SOCD values consistently and significantly increased with increasing CSC (p < 0.05).

Other studies have reported that SOCD was significantly related to the CSC of soils (e.g., Hassink, 1996). In our study, fine particles (<20 μm) dominated the sampled soils, which had a mean CSC of 73.6%. This was attributed to the fine parent material of loess soils in the Loess Plateau region (Zhao et al., 1999). The positive effects of higher CSC on SOCD are likely due to the ability of clay and silt particles to adsorb organic matter and to protect it, to varying degrees, from microbial decomposition (Zhao et al., 2006a). Moreover, soil mechanical composition could also indirectly affect SOCD by impacting soil aggregation, hydrology, aeration and temperature (Saxon and Rawls, 2006; Shao et al., 2006).

3.2.5. Effects of land use

Natural factors and human activities have strong interactive effects. Climate, topography and soil characteristics influence human decisions regarding land use while, in turn, human activ-
ities and the choice of land use can change the natural factors, such as soil physical, chemical and biological properties.

Our results indicated that land use had significantly impacted SOCD ($p < 0.05$). As shown in Fig. 6, the mean SOCD values for the three land-use-based groups were significantly different ($p < 0.05$), being highest for cropland, intermediate for forestland and lowest for grassland. When the effect of these three land use types were compared within the groups of precipitation, temperature, elevation and CSC (Fig. 3), cropland had consistently and significantly higher SOCD values than forestland and grassland ($p < 0.05$).

This result was not expected, since it was opposite to the findings of other studies on the Loess Plateau, which found that cropland soils had lower SOC contents compared to those under forestland and grassland (Wang et al., 2001; Li et al., 2005; Chen et al., 2007). It has also been reported that SOC could be depleted by conversion of natural vegetation to cropland due to reduced organic matter inputs and tillage effects that increased decomposition rates (Post and Kwon, 2000). However, most of these studies were conducted on a small scale, investigating individual plots, slopes or catchments that had relatively homogeneous environments. In our large-scale study, the entire Loess Plateau region was considered and climate, topography and soil conditions varied greatly.

Flat areas with favorable soil and water conditions, such as valleys and basins, are favored for use as croplands. Due to the natural conditions of such places, SOC content would be relatively higher in these areas even without human influence. Management practices often involve addition of organic and inorganic fertilizers, which further help to maintain and increase SOC (Glendining et al., 1996; Liu et al., 2006). It has been reported that, in the Loess Plateau region, the inputs of organic and inorganic fertilizers amounted to about $86.7 \times 10^7$ kg/year and $111.3 \times 10^7$ kg/year, respectively, during the 1980s (ISTCASLP, 1999), with further increases in more recent years. Moreover, irrigation and soil erosion control measures in the cropland areas also had positive effects on SOC accumulation (Lal, 2004a,b). In contrast, forestland and grassland were mainly located on the slopes of hilly areas, where the soils were sandier in the northern part of the study region. Vegetation growth and SOC accumulation would be limited by inferior soil and water conditions, severe soil erosion and lack of appropriate management in these areas.

Another factor is that many of the forestland and grassland areas have been established relatively recently (within the last 10 to 60 years) in order to combat soil erosion and degradation under the Chinese government’s “Grain-for-Green” program. It is possible that SOC levels in the soils of the less mature forests and grasslands are in the process of accumulating to higher levels than would occur in cropland in the same locations. Our results only present a large-scale overview of the current SOCD in different land use types across the Loess Plateau region; they do not indicate that cropland could sequesterate more organic carbon than forestland and grassland. It is probable that the potential for further carbon sequestration is high under all land use types. It is possible that additional appropriate management practices, such as fertilization, soil erosion control and artificial fencing for forestland and grassland, and the use of mulches, conservation tillage, and applications of organic and green manure for cropland would enhance SOC sequestration in the Loess Plateau region.

4. Conclusion

In this study, we examined SOC stocks and the effects of environmental factors on SOCD across the entire Loess Plateau region of China. The study and results can be summarized as follows:

- The methodology was based on intensive field sampling and geostatistical analysis, accounting for spatial autocorrelation and variability. This allowed large-scale, updated, SOC stocks to be estimated, without relying on various limited and outdated soil survey datasets and maps of classes. A spatial distribution map of SOCD across the entire Loess Plateau region was produced.
- The SOCD was estimated not only for the upper soil layers but also for deeper layers, to a maximum depth of 200 cm. Compared to other investigated regions in China, the Loess Plateau region was found to have relatively low levels of SOC.
- The 0–20 and 0–100 cm layers of China’s Loess Plateau region currently store about 0.36% and 0.31%, respectively, of the global SOC stocks in these layers, and 8.21% and 5.32% of the total SOC stocks in these layers in China.
- From a regional perspective, precipitation, temperature, elevation, land use, and the clay plus silt content (<20 μm) of the soil all had significant effects on SOCD ($p < 0.05$). Generally, SOCD was highest in soils on mountains (with relatively high elevations and low temperatures) and valleys (with low elevations and high precipitation). Higher fine soil particle contents were associated with higher SOC values. In addition, SOCD was higher under cropland than under forestland or grassland at the regional scale of the entire Loess Plateau.
- Adding data from more sites and/or small-scale studies to this framework could increase the accuracy of the SOC estimations.

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