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The estimation of soil organic carbon distribution and storage in a small catchment area of the Loess Plateau

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ABSTRACT

The distribution and storage of soil organic carbon serve as basic data for the study of soil productivity, soil hydrological properties, and the balance among carbon-based greenhouse gases. In this study, the organic carbon storage and density distribution characteristics of the soil in the Zhifanggou catchment on the Loess Plateau were studied based on field investigations, laboratory measurement, and geostatistics analysis. A total of 1,282 soil samples were collected from 215 sites in addition to 10 profiles from the catchment. The landuse within the catchment was divided into 4 types: farmland, grassland, shrubland, and woodland. The following results were obtained. 1. In the Zhifanggou catchment, the average organic carbon content of the soil at a depth of 0–100 cm is between 2.81 and 3.50 $g \cdot kg^{-1}$. The soil organic carbon content (SOCC) for different landuse types follows the trend shrubland > woodland > grassland > farmland, whereas the soil bulk density follows. The relationship between soil organic carbon content and bulk density follows a power law function. 2. The soil organic carbon density (SOCD) at a depth of 0–100 cm is 1.24–8.34 kg m^{-2}. The coefficient of variation is 0.40, indicating a moderate variation in the average carbon density of 2.63 kg m^{-2}. The soil organic carbon density for different landuse types follows the trend shrubland > woodland > grassland > farmland. In the entire catchment, the proportion of average soil organic carbon density at a depth of 0–20 cm is 50.24%, which decreases with soil depth. The spatial distribution of the soil organic carbon density is closely related to the landuse types and topography. 3. The total soil organic carbon storage (SOCS) at a depth of 0–100 cm in the Zhifanggou catchment is 21.84×10^6 kg. The relationship between soil depth and total organic carbon storage is linear.

1. Introduction

Soil organic carbon distribution and storage are the basic measures used to study soil productivity, soil hydrological properties, and the balance among carbon-based greenhouse gases (Kern, 1994). According to the previous research, the global soil carbon pool at a soil depth of 100 cm (13.95×10^{14}–22×10^{14} kg) (Batjes, 1996; Eswaren et al., 1993; Post et al., 1982) is 2–3 times the size of the terrestrial vegetation carbon pool (5×10^{14}–6×10^{14} kg) and is more than twice the global atmospheric carbon pool (7.5×10^{14} kg) (Smith, 2004). Therefore, small changes in the soil carbon pool will greatly impact the concentration of atmospheric CO_2 and affect global change. This relationship has become one of the core areas of international research on global climate change.

In recent years, many countries and local governments have assessed the carbon sink capacity in their regions. The most important task is to accurately estimate the characteristics of soil organic carbon density and storage, including at global level (Batjes, 1996; Eswaren et al., 1993) and in some European countries (Batjes, 2002; Krogh, et al., 2003), the United States (Batjes, 2000), India (Bhattacharyya et al., 2000), Brazil (Bernoux et al., 2002), and other countries.

In China, the estimated soil organic carbon storage for terrestrial ecosystems is 50–186 Pg (Fang, 1996; Pan, 1999; Wang et al., 2000). Many regions have conducted research on a small scale. However, most studies have focused on moist or semi-humid areas, such as the eastern, the northern, the southeastern, and the southwestern China (Li et al., 2001; Li et al., 2002; Zhang et al., 2008; Zhao et al., 1997, 2006). There are relatively fewer research studies on arid and semi-arid regions. However, these areas are considered to be the main potential carbon pools.

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The Loess Plateau is located in the arid and semi-arid region of northwestern China. The soil erosion on this plateau is the most serious in China and perhaps the world, and its ecological environment is among the most easily disturbed. Since the 1990s, large-scale management practices or ecological restoration practices, including the construction of basic farmland, “Grain-for-Green,” Closed forest and so on, have been carried out on the Loess Plateau. These efforts have generally been executed in units below the scale of small catchments. Therefore, the study of the soil organic carbon density and storage characteristics for different landuse patterns at the entire catchment scale of catchments typical of the Loess Plateau is important in evaluating the entire carbon storage of the Loess Plateau and will help improve the accuracy of large-scale estimates.

In this study, the combination of field investigations, laboratory analyses, and geostatistics was utilized, and the Zhifanggou catchment, a typical small catchment of the Loess Plateau, was selected as the subject of study. This study had 3 main objectives: 1. to study the soil organic carbon content, bulk density profile distribution, and the relationship between the two; 2. to assess the soil organic carbon density distribution of the small catchment; and 3. to evaluate the soil organic carbon storage of the Zhifanggou catchment.

2. Materials and methods

2.1. Study area

The Zhifanggou catchment is a representative small catchment on the Loess Plateau, which is located at Ansai County, Shaanxi Province, China (longitude 108° 51′ 44″–109° 26′ 18″, latitude 36° 30′ 45″–37° 19′ 31″, 1,010–1,1431 m altitude, 8.27 km^2) (Fig. 1). The geomorphology of this catchment is extremely broken and has the characteristics of a valley. The annual temperature is changed from 7.7 to 10.6 °C (min. −23.6 °C and max. 36.8 °C). The main soil type is cultivated loessial soils, the loess-derived soils texture is uniform, and the soil is mainly composed of sand, silt and clay, contents are 65, 24, and 11%, respectively. The average annual precipitation is 541.2 mm. Seventy-five percent of the annual rainfall in this region is concentrated in July–September. The rainfall is intense and highly erosive. The main landuse and vegetation species include shrubland (*Caragana korshinskii*), woodland (*Populous simonii Carr*., Fruit trees), grassland (*Medicago sativa* L., *Artemisia gmelinii*, *Stipa bungeana*, *Artemisia scoparia*), and farmland (*Triticum aestivum*, *Zea mays*, *Glycine max*) (Fig. 2).

2.2. Sampling method

Soil samples were collected using the grid method. All designed sample sites were arranged on a 1:10,000 scale topographic map. The grid interval was 200×200 m, and a portable GPS was used to locate each sample site. Each site was divided into 6 layers at depths of 0–100 cm: 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm. All samples were collected with a hand auger with 5 cm in diameter. A total of 1,282 soil samples were collected from 215 soil sampling sites (Fig. 3). After air-drying, the soil samples were passed through a 0.25 mm sieve for laboratory analysis. The soil organic carbon content was determined using the dichromate oxidation (external heat applied) method (Nelson and Sommer, 1975).

In addition, a total of 10 profiles at a depth of 100 cm were dug for different landuse types. Undisturbed soil cores were collected and saved in sealed metal boxes. After drying at 105 °C, the average bulk density of each soil layer was determined. The specific operating procedures are described in Han et al. (2010). The sampling layers were consistent with the sampling sites. All of the sampling was finished in the November 2010.

2.3. The calculation of soil organic carbon

The soil organic carbon density (kg m^{-2}) for a certain soil depth was calculated using the following equation (Zhang et al., 2008):

$$\mathrm{SOCD}_h=\sum_{i=1}^{n}\frac{T_i\times \mathrm{soc}_i\times\rho_i\times(1-G_i/100)}{100} \quad (1)$$

whereSOCD_h = the total amount of soil organic carbon density between the soil surface and depth h per unit area (kg m^{-2});T_i = the soil layer thickness of i^{th} layer (cm);soc_i = the soil organic carbon content of i^{th} layer (g kg^{-1});ρ_i = the soil bulk density of i^{th} layer (g cm^{-3});n = the number of layers; in this study, $n=6$;G_i = the proportion (%) of coarse (>2 mm) fragments in the i^{th} layer.

Because coarse particles larger than 2 mm are very rare in loess soils, G_i can be ignored for the purposes of the present study.

The organic carbon density per unit area for each layer was calculated according to the following equation:

$$R_i=\frac{\mathrm{SOCD}_i}{\mathrm{SOCD}_h}\times 100\% \quad (2)$$

whereSOCD_i = the total soil organic carbon density at depth i in the catchment (kg m^{-2}).

According to the organic carbon density, latitude, and longitude of the 215 profile sample sites, Kriging interpolation was executed using ArcGIS Geostatistical Analyst to produce gridded organic carbon density spatial distribution maps of the entire catchment, for which each grid was given a soil organic carbon density value and an area value.

The total soil organic carbon storage of the catchment was calculated as follows (Liu et al., 2011):

$$\mathrm{SOCS}_h=\sum_{i=1}^{n}\mathrm{SOCD}_h\times \mathrm{Area}_{\mathrm{grid}} \quad (3)$$

whereSOCS_h = the total amount of soil organic carbon stock at depth h in the catchment (kg);$\mathrm{Area}_{\mathrm{grid}}$ = the grid area (m^2);n = number of grids.The spatial analysis module of ArcGIS9.3 was used specifically for calculation, and Sigmaplot10, Excel 2007, was used for data analysis.

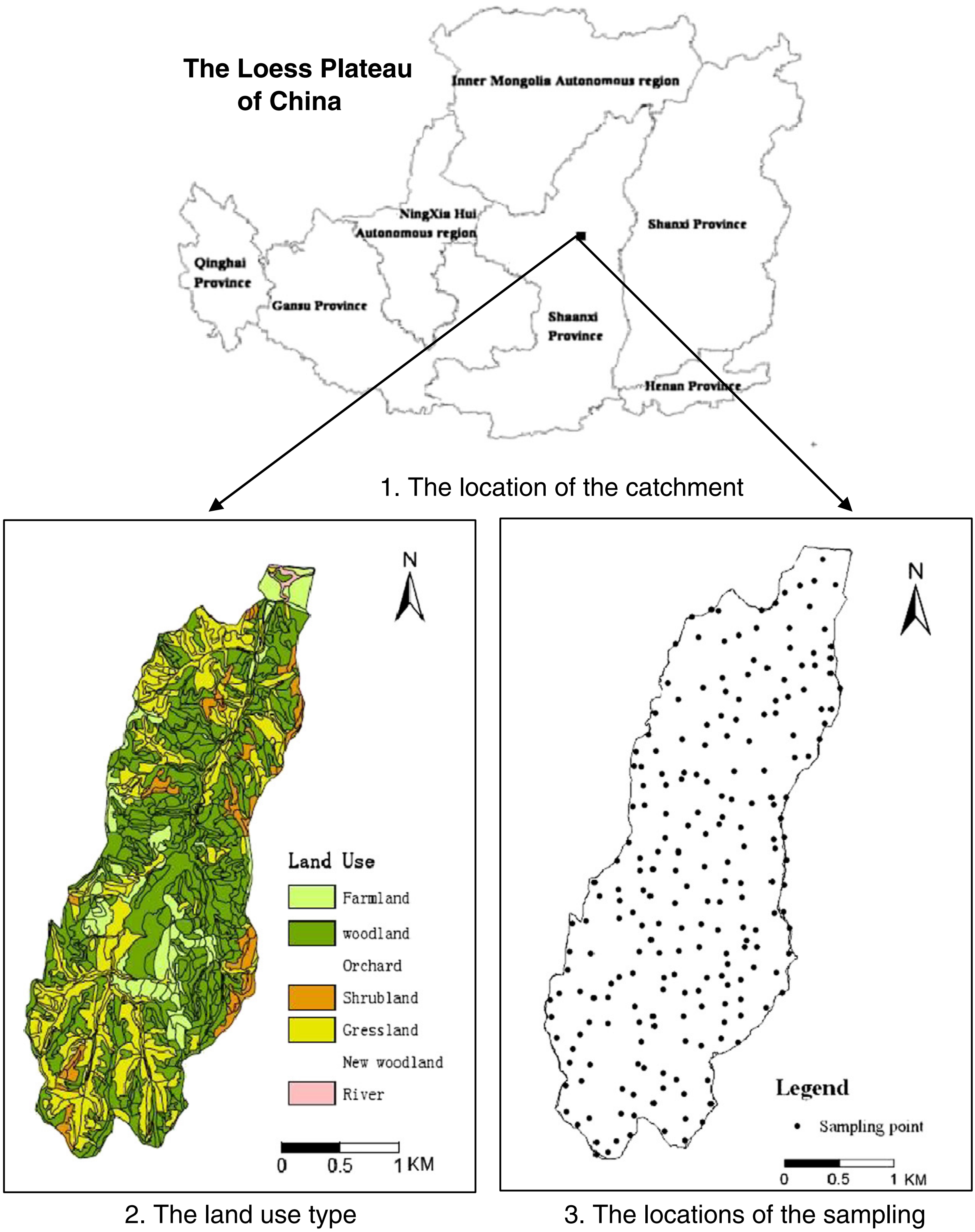
3. Results and discussion

3.1. The soil organic carbon content and analysis

The soil organic carbon input, output, spatial location, and relative soil properties and processes determine the soil organic carbon content. For different landuse types, the soil organic carbon content varies significantly. In the study area, the average organic carbon content of soil at a depth of 0–100 cm for the 4 landuse types is in the range of 2.81–3.50 g kg^{-1}. The content of soil organic carbon in the shrubland is the highest, followed by woodland, grassland, and farmland. The farmland has 24% lower soil organic carbon content than shrubland. In addition, the organic carbon distribution in the soil profiles is different (Fig. 4). Research of all landuse types shows that with the increase of soil depth, soil organic carbon content is decreasing. In the same soil layer, the soil organic carbon content changed with different landuse type and root system distribution. However, the variation is small at depths below 60 cm, where soil organic carbon content is primarily determined by the root system distribution. Similar findings have been reported in previous studies (Han et al., 2010).

3.2. The soil bulk density and analysis

The soil bulk density characterizes the compaction of the soil and its water permeability, which is an important index used to assess a soil's organic carbon content (Howard et al., 1995). Fig. 5 shows the



Figs. 1-3. (1.) The location of the catchment, (2) The land use type, (3) The locations of the sampling sites.

difference in soil bulk density among different landuse types. The soil bulk density for grasslands reached its maximum of 1.32 g cm^{-3} at a depth of 40 cm and remained unchanged with increasing depth; the soil bulk density for the farmland profile reached its maximum value of 1.40 g cm^{-3} at 60 cm. For the other two landuse types, the soil bulk density followed an "S" shape with increasing profile depth. The woodland soil showed different trends from the other three landuse types a depth of 0–20 cm. At a depth of 100 cm, the soil bulk densities of the woodlands, grasslands, and shrubland were relatively similar, at approximately 1.32 g·cm^{-3}, whereas the bulk density for shrubland was relatively lower, at 1.24 g·cm^{-3}. The average soil bulk density was different among different landuse types, following the trend

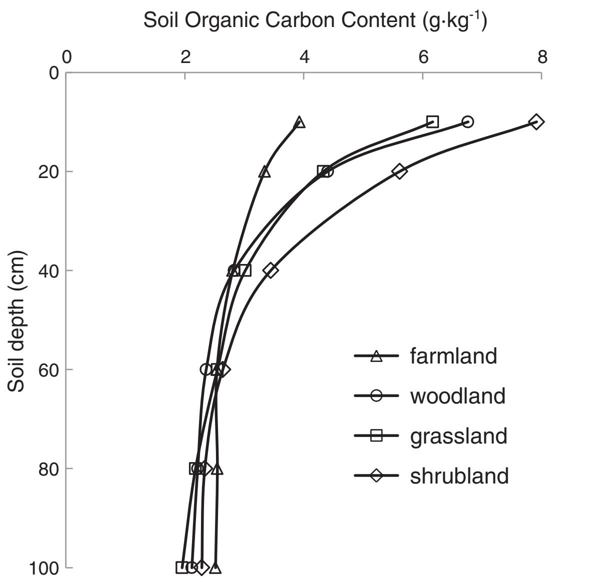


Fig. 4. The soil organic carbon content in the 100-cm soil layer for different land use types.

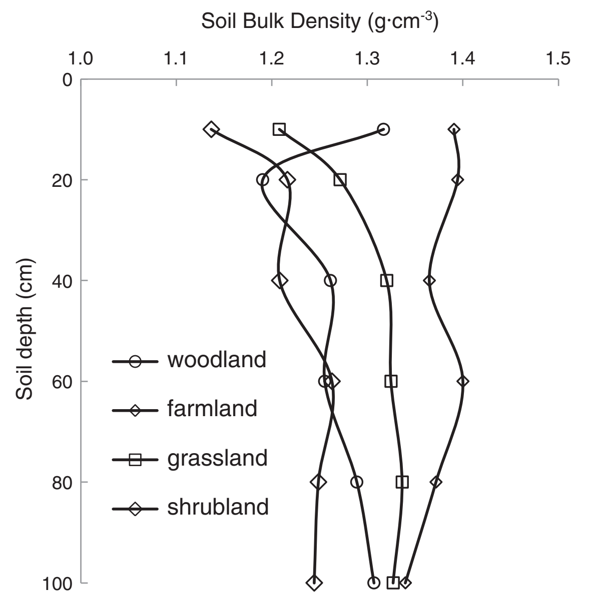


Fig. 5. The mean soil bulk density in the 100-cm soil layer for different land use types.

farmland > grassland > woodland > shrubland. These results indicate that landuse type can affect the soil bulk density, as well as the soil texture, in different ways (Xu, et al., 2008).

In previous studies, it was shown that the relationship between a soil's bulk density and organic carbon content can be expressed as a power law function. In the catchment investigated in the present study, with the organic carbon content represented by (x) and the soil bulk density as (y), the following power law function was obtained: $y = 1.35x^{-0.03}$ ($R^2 = 0.915$, $p < 0.001$).

3.3. Soil organic carbon density and analysis

Eq. (1) was used to calculate the organic carbon density of 1282 soil samples. The range of organic carbon density at a depth of 0–100 cm throughout this study area is 1.24–8.34 kg m^{-2}, with a coefficient of variation of 0.40, and the average carbon density for the catchment is 2.63 kg m^{-2}(Table 1). This average carbon density is far below the average carbon density of 9.6 kg m^{-2} for a depth of 0–100 cm in China estimated by Yu et al. (2005), and it is also lower than the average carbon density of 7.7 kg m^{-2} for the Loess Plateau in China estimated by Liu et al. (2011). This finding suggests that the average organic carbon density of the ZhiFanggou catchment is lower than that of China in general and that of the Loess Plateau. This finding is related to the soil types and rainfall in the study area and to human disturbance, among other factors. Within the catchment, the average soil carbon density at a depth of 0–100 cm for four landuse types, i.e., grassland, woodland, shrubland, and farmland, were 2.58 kg m^{-2}, 2.63 kg m^{-2}, 2.91 kg m^{-2}, and 2.44 kg m^{-2}, respectively; the coefficients of variation were 0.39, 0.44, 0.36, and 0.39, respectively, which are values that are considered to be moderate.

Table 1 and Eq. 2 were used to calculate the organic carbon density (Fig. 6) at depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm for the four landuse types. The organic carbon density at a depth of 0–10 cm followed the order woodland (33.8%) > shrubland (30.9%) > grassland (28.9%) > farmland (22.4%). The organic carbon density at depth of 10–20 cm followed the order shrubland (23.48%) > grassland (21.32%) > woodland (19.93%) > farmland (19.13%). At a depth of 20–40 cm, farmland exhibited the greatest percent density, accounting for 15.71%. The SOCD for the other three landuse types was between 15.43% and 13.57%. At depths of 40–60 cm, farmland exhibited the largest percent density, accounting for 14.59%. The SOCD for the three other landuse types were between 13.07% and 11.26%. At depths of 60–80 cm, farmland exhibited the largest percent density, accounting for 14.33%. The soil organic carbon density percentage for the three other landuse types were between 11.28% and 10.03%. At depths of 80–100 cm, the soil organic carbon density followed he order farmland (13.83%) > woodland (10.53%) > grassland (10.04%) > shrubland (9.78%). It can be clearly observed that for the four landuse types, the organic carbon density and storage at a depth of 0–20 cm follows the order shrubland (54.41%) > woodland (53.77%) > grassland (50.18%) > farmland (41.54%). In the whole catchment, the average organic carbon density for each layer (0–10, 10–20, 20–40, 40–60, 60–80, 80–100 cm) accounts for 29.18%, 21.06%, 14.73% 12.52%, 11.54% and 10.97%, respectively, of the total organic carbon density. The proportion at 0–20 cm is 50.24%, at greater soil depths, the percent organic carbon density decreases markedly, reaching its minimum at the bottom layer. This finding shows that the vertical distribution of the organic carbon density in the profile is mainly affected by landuse type. In addition, the vertical distribution of roots directly affects the organic carbon content in the soil profile at all levels; moreover, with increasing soil depth, decomposition activities become weak, which means that the deeper plant debris is located in the soil, the more slowly decomposition proceeds (Zhou et al., 2005).

Based on semi-variance structure analysis and model fitting, Kriging interpolation gave a continuous surface of organic carbon density covering the catchment (Fig. 7). Figs. 2 and 7 show that in the study area, the overall organic carbon density is distributed in layers, with the spatial distribution of the density following a ladder-like pattern and patch mosaic distribution, which is closely related to the landuse types and topography of the area. The high-density areas are most closely associated with shrubland and woodland, and the low-density areas are most closely associated with grassland and farmland. The gully is a high-density area in organic carbon density. However, as a result of its higher elevation, the periphery of the catchment shows a lower organic carbon density. This pattern reflects the impact of landuse types and topography on the organic carbon density of the catchment. In terms of spatial distribution, the organic carbon density in the eastern part of the Zhifanggou catchment is slightly higher than that of the surrounding areas, and that on the east side of the gully is higher than that on west side.

Table 1
The difference of SOCD (kg m^{-2}) in the different land use types.

	All samples			Grassland			Woodland			Shrubland			Farmland		
	n	Mean	C V	*n*	Mean	C V	*n*	Mean	C V	*n*	Mean	C V	*n*	Mean	C V
SOCD0-10	215	0.80 ± 0.49	0.62	77	0.75 ± 0.42b	0.57	77	0.89 ± 0.60ab	0.68	33	0.90 ± 0.48a	0.54	28	0.55 ± 0.22c	0.40
SOCD10-20	215	0.55 ± 0.26	0.47	77	0.55 ± 0.28ab	0.51	77	0.52 ± 0.23b	0.44	33	0.68 ± 0.28a	0.42	28	0.46 ± 0.22b	0.48
SOCD20-40	215	0.38 ± 0.18	0.47	77	0.40 ± 0.20a	0.50	77	0.36 ± 0.13b	0.38	33	0.42 ± 0.20b	0.48	28	0.38 ± 0.22b	0.59
SOCD40-60	215	0.32 ± 0.14	0.45	77	0.34 ± 0.16a	0.47	77	0.30 ± 0.13a	0.42	33	0.33 ± 0.13b	0.38	28	0.36 ± 0.17b	0.49
SOCD60-80	213	0.30 ± 0.15	0.51	77	0.29 ± 0.17a	0.60	77	0.29 ± 0.12b	0.44	33	0.29 ± 0.14b	0.49	26	0.35 ± 0.18b	0.50
SOCD80-100	209	0.28 ± 0.14	0.51	77	0.26 ± 0.11a	0.43	77	0.28 ± 0.14a	0.50	31	0.28 ± 0.13a	0.47	24	0.34 ± 0.21a	0.64
SOCD0-100	1282	2.63 ± 1.06	0.40	462	2.58 ± 1.00	0.39	462	2.63 ± 1.17	0.44	196	2.91 ± 1.06	0.36	162	2.44 ± 0.95	0.39

Different lowercase letters within rows indicate significant differences among landuse types.
Mean ± standard deviation. CV, coefficient of variation.
n is the number of samples.

3.4. Soil organic carbon storage

Using map of organic carbon density spatial distribution (Fig. 7), created using the Geostatistical tool package of ArcGIS and Eq. (3), it is easy to determine the soil organic carbon storage for the studied catchment. Based on the area of the whole catchment, 8.272×10^6 m^2, the total organic carbon storage at a depth of 0–100 cm was calculated to be 21.84×10^6 kg. For this catchment, a function can be used to express the relationship between the total organic carbon storage and depth. This function is $y = 3.014x + 4.409$ ($R^2 = 0.984$, $p < 0.001$), where soil depth is represented by (x) and total organic carbon storage is represented by (y). In the Zhifanggou catchment, the soil area with an organic carbon density of less than the average 2.63 kg m^{-2} at a depth of 1 m is approximately 5.425 km^2, which accounts for 65.58% of the total area. This illustrates that in this catchment, the soil organic carbon content for most of the soil is low, and the total soil storage is relatively small.

4. Conclusion

1. For different landuse types, the physical and chemical properties of the soil differ as a result of differences in parent material, climatic conditions, soil microorganisms, root distribution, and human activities. Within the Zhifanggou catchment, the average soil organic carbon content of four landuse types at a depth of 0–100 cm is between 2.81 and 3.50 g kg^{-1} and follows the trend shrubland > woodland > grasslands > farmland. The bulk density of the soil follows the opposite trend. The relationship between the soil organic carbon content (x) and the bulk density (y) is $y = 1.35x^{--0.03}$ ($R^2 = 0.915$, $p < 0.001$).
2. Throughout the study area, the range of soil organic carbon density at a depth of 0–100 cm is 1.24–8.34 kg$\cdot$m^{---2}, and the coefficient of variation is 0.40, which indicates a moderate variation from the average carbon density of 2.63 kg m^{-2}. The organic carbon density for different landuse types follows the trend shrubland > woodland > grassland > farmland. Throughout the catchment, the fraction of the total organic carbon density at a depth of 0–20 cm is 50.24%, and decreases with increasing soil depth
3. In the Zhifanggou catchment, the organic carbon density distribution shows a ladder-like pattern and patch mosaic distribution, which is closely related to the landuse types and topography of the area. The organic carbon density in the eastern part of the catchment is slightly higher than that in the other regions. The organic carbon density on the east side is higher than that on the west side. The

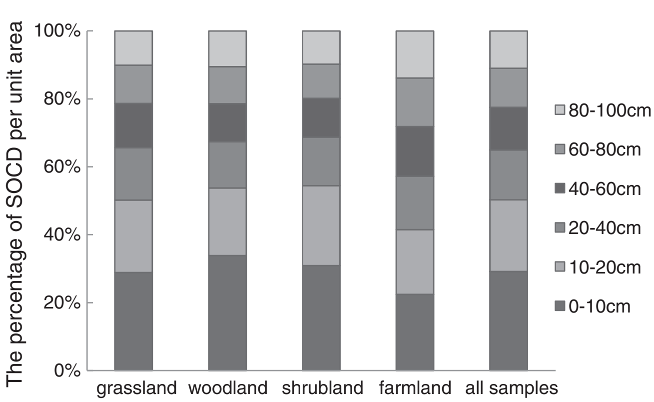


Fig. 6. The soil organic carbon density for different landuse types at different depth.

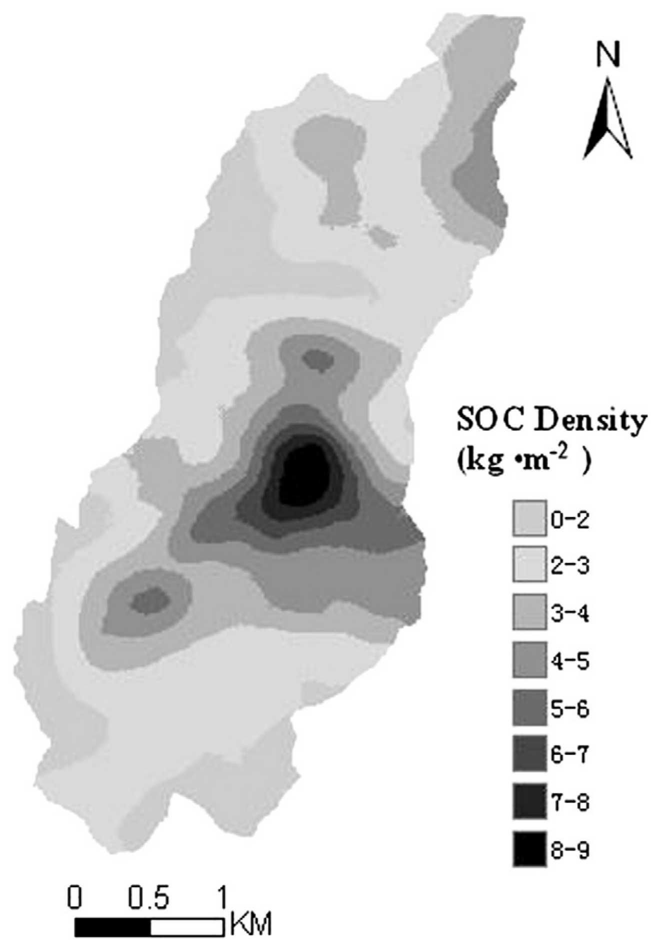


Fig. 7. The spatial distribution of the soil organic carbon density (0–100 cm) in the catchment.

gully is one of the highest-density areas. However, the periphery of the catchment has a lower organic carbon density due to its higher elevation.

4. The total organic carbon storage of the Zhifanggou catchment at a depth of 0–100 cm is 21.84×10^6 kg. The relationship between soil depth (x) and total organic carbon storage (y) can be expressed by the function $y=3.014x+4.409$ ($R^2=0.984$, $p<0.001$). The soil area with a lower organic carbon density than the average value accounts for approximately 65.58% of the total catchment area, which indicates that in this catchment, the organic carbon content for most soil is low, and the total soil storage is relatively small.

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