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Spatial-Temporal Variability of Soil Organic Carbon Density and Its Related Factors in Fengqiu County of Yellow River Basin, China: A Model and GIS Technique Approach

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Abstract: The accurate estimation of the soil organic carbon (SOC) sequestration rate is very important for studying farmland soil fertility and environmental effects. In this research, a typical fluvor-aquic soil area, Fengqiu county, located in the Yellow River basin of the Huang-Huai-Hai Plain of China, was chosen as a study area. The physicochemical properties of 70 soil samples collected from the surface layer (at a depth of 0–20 cm) in 2011 were analyzed, and related data about the sampling sites were also collected from the Second State Soil Survey of China (SSSSC), conducted in 1981. The results revealed that the SOC density (SOCD) in Fengqiu county increased greatly on a spatio-temporal scale. The average SOCD increased from 15.66 to 26.09 Mg ha^{-1}, and the SOCD sequestration rate was more than 0.20 Mg C ha^{-1} year^{-1} in most regions. Few areas showed lost carbon in the past 30 years (1981–2011). In addition, the study suggested that all the areas present strong carbon sequestration potential in the coming decades from 2011, and the carbon sequestration potential was mainly between 32–40 Mg ha^{-1}. Finally, the SOCD sequestration rate was not only affected by natural factors, such as soil type and pH, but also positively correlated with artificial soil management measures, such as fertilization and straw returning. Therefore, we concluded that the farmland in Fengqiu county showed significant carbon sequestration characteristics in the past 30 years (1981–2011). Considering that soil has a great potential for carbon sequestration in the future, the trend of carbon sequestration in farmland soil might continue for a period of time. Furthermore, the results of this study emphasized that strengthening soil scientific management may play a positive role in improving soil carbon sequestration.

Keywords: carbon sequestration rate; cropland; fluvor-aquic soil; influence factors; organic carbon stock

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1. Introduction

In the context of global warming, the terrestrial ecosystem, with its massive carbon storage capacity, could have a significant impact on global carbon sequestration [1]. According to previous research data, the global soil carbon pool is approximately 2500 Gt, which includes about 1550 Gt of organic carbon and 950 Gt of inorganic carbon. The carbon pool in soil is 3.3 times the size of the atmospheric pool (760 Gt) and 4.5 times that of the biotic pool (560 GT) [2]. Global terrestrial ecosystems fixed carbon at a rate of 1 Pg year^{-1} to 4 Pg year^{-1} during the 1980s and 1990s, offsetting 10% to 60% of fossil fuel emissions [3–5]. The accurate calculation of the dynamics of SOC is also important for a mechanistic understanding of the SOC cycle and for assessing the feedbacks between SOC and climate change [6,7].

The Yellow River is the third longest river in Asia, after the Yangtze River and Yenisei River, and the sixth-longest river system in the world at an estimated length of 5464 km. The Yellow River basin has an east–west extent of about 1900 km and a north–south extent of about 1100 km. Its total drainage area is about 752,546 km^2, and fluvo-aquic soil is one of the most important soil types in this area [8,9]. The Yellow River is China's important grain production region, and cropland was continuously exploited for yield. Agricultural measures (e.g., tillage and fertilization) have a profound impact on soil organic carbon (SOC). Farming is treated as the main human land use activity, and the effect of tillage on soil carbon storage and its variation tendency has been widely noticed by researchers worldwide [10,11]. In recent years, research on the dynamic changes of soil carbon storage, carbon fixation and carbon cycling in farmland has become a hot topic in the global response to climate warming. The dynamic change of soil carbon is not only affected by natural factors but is also influenced by agricultural cultivation management measures, such as fertilizer application and retuning straw [12].

Over the last hundred years, the Yellow River basin has experienced intense soil erosion due to the combined impact of natural processes and human activity. Over the period, 134.2 $\pm$ 24.7 Gt of soils and 1.07 $\pm$ 0.15 Gt of SOC have been eroded from hillslopes based on a soil erosion rate of 1.7–2.5 Gt $year^{-1}$ [13]. Compared with natural soil, the carbon storage of cropland, which is under serious human disturbance but could be adjusted in a short time, has shown more activity in the global carbon storage [14,15]. Previous studies have shown that increased SOC was closely related to amendments with crop residues and organic manure, synthetic fertilizer applications and soil properties [16–21]. Soil physical and chemical properties are the primary influence factors of SOC storage, such as pH, aeration and soil structure [22–24]. Meanwhile, farming activities are generally considered to be the most influential factor in soil organic carbon. Frequent ploughing destroyed the natural structure of soil, which resulted in the SOC being exposed instead of protected by soil aggregate, and the utilization rate of oxygen was improved by the microorganism. At last, the decomposition of SOC was accelerated via mineralization, but fertilization is the most important factor affecting the soil organic carbon library among agricultural management measures. The long-term application of chemical fertilizer changed the soil structure, fertilizer capacity and microbial activity and affected the decomposition rate of SOC, but the application of organic fertilizer could supply the organic carbon source and improve the physical properties of the soil, which could keep the dynamic balance of SOC [14]. Thus, it can be seen that the changes in SOC storage not only changed the fertility but also influenced the carbon cycle in regional and global areas. The former determined the productivity of the crop and its stability digestively, and the latter was closely related to the concentrations of greenhouse gases in atmospheric and global warming [16]. Therefore, it is of great significance to study the characteristics of SOC variation and its influencing factors.

The farmland soil carbon pool plays an important role in the global carbon cycle, and the cropland SOC content varies with climate, topography, soil properties and artificial cultivation [14,16]. Exploring the characteristics of SOC spatial variability on a regional scale is of great significance to comprehend the carbon cycle process and the mechanism of the land ecosystem [25]. Furthermore, farmland SOC sequestration has a certain effect on food security on account of the close relationship between the soil carbon pool and grain yield.

Over the last decades, large numbers of scientific projects have been approved to research the variability of SOC in croplands around the world. Li et al. [26] predicted that agricultural lands in the U.S. were gaining SOC at a rate of 72.4 Tg C $year^{-1}$ and that agricultural lands in China were losing SOC at a rate of 73.8 Tg C $year^{-1}$ via a biogeochemical model, DNDC (denitrification–decomposition model), based on the 1990 data of the climate, soil properties, crop types, acreage and crop management at a county scale. Huang and Sun [16] revealed that the concentration of SOC increased in 53% to 59% of the national croplands, decreased in 30% to 31% and stabilized in 4% to 6%, respectively, from an analysis of the literature databases from 1980 to 2006. Some other related studies indicated that SOC declined in some croplands of southwestern China and suggested that agricultural soil in China had lost 30% to 50% or more of the original SOC pool due to degradation [27,28].

Previous researchers have made great efforts to reveal SOC changes at the regional scale, but the results were conflicted, such as significant increases in SOC having occurred in eastern and northern China and SOC having decreased in northeastern China [16]. Moreover, influencing factors also varied by region because of spatial heterogeneities. Thus, the confirmation of the variation of SOC and the key influencing factors for SOC is important for controlling carbon emissions and enhancing cropland fertility in typical agricultural areas of China. The Yellow River basin is an important grain-producing region in central China. Thus, studying the spatial-temporal variability of soil organic carbon density and its related factors would have a positive impact on improving soil fertility.

In the study, Fengqiu county, an agricultural county adjacent to the Yellow River, was selected as the research area. We hypothesized that the change of SOC in this region would be closely related to the soil natural factors (e.g., soil texture, climate, topography, etc.), and agricultural activities would be another key factor that disturbed SOC. In order to reveal the spatial-temporal variability of SOC and its related factors in farmland, the main objectives of this study were as follows: (1) exploring the spatial-temporal variability of SOC density in the past 30 years (1981–2011), (2) quantifying the effects of natural and anthropogenic factors on SOC and (3) evaluating the potential change of SOC in the future at a county scale.

2. Materials and Methods

2.1. Description of the Study Area

Fengqiu county (34°53′–35°14′ N, 114°14′–114°46′ E) is located on the north shore of the Yellow River of central China, with an area of 1220.50 km^2, (Figure 1). It belongs to a warm temperate continental monsoon climate, and the average annual temperature is 13.9 °C, while the multi-year average precipitation is 615 mm. Half of the precipitation occurs from June to August. The crop rotation production system in the region accommodates two crops per year as a result of its comfortable water and temperature conditions. Agricultural land, construction land and unutilized land were the major land use types, and agricultural land occupied 73.74% of the total area [29].

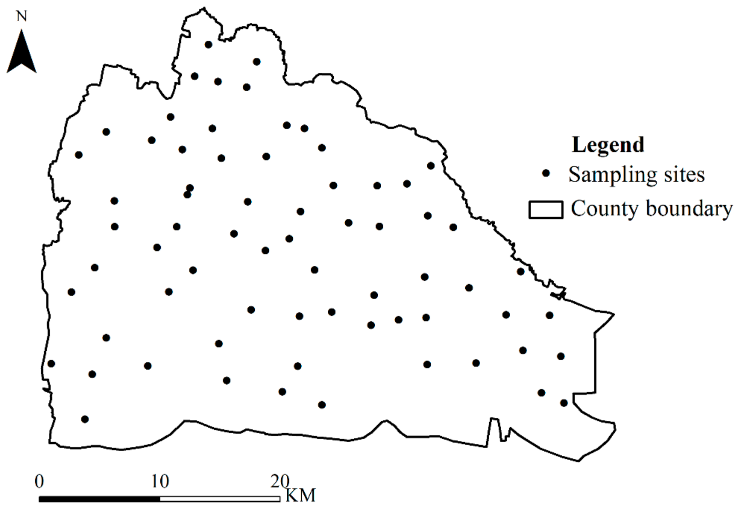

Figure 1. Distribution map of sampling sites in Fengqiu county.

2.2. Sampling Sites Selection and Data Collection

A total of 70 soil sampling sites, which covered all soil types of Fengqiu county, were evenly distributed in farmland in the county (Figure 1). The collected soil samples were used to determine SOC and other physicochemical properties of cropland in 2011. SOC data were obtained from the Second State Soil Survey of China (SSSSC), which was conducted by local soil survey offices in 1981 [30]. A total of 1312 samples were analyzed to determine the SOC content, soil granulometric fraction, pH and bulk density, which were published in a series of monographs of Fengqiu county [29]. Recent soil information was collected from the county in 2011. The distribution of sampling sites was consistent with those in the SSSSC. The geographical coordinates and the elevation of the sampling points were determined by a satellite global positioning system (handheld GPS). The collected soil samples and other geographic information were prepared for further analysis.

2.3. Soil Sampling and Analysis

The locations of the 2011 cropland sampling sites are shown in Figure 1. We collected five topsoil samples from the four corners and the center in a 10 m × 10 m square at each site, using a 5 cm-diameter stainless steel soil sampler, and the samples were carefully mixed by hand to form a composite. Undisturbed soils, which were used to measure soil bulk density, were sampled using a cutting ring at the same positions as those described above. All soil samples were transported directly to the laboratory and stored at 4 °C before analysis.

Moist soil samples were gently broken apart along natural break points and passed through an 8 mm wire filter. The plant and organic debris in the sieved soil was carefully removed with forceps. After thorough mixing, half of the sieved subsamples were used for soil particle-size analysis. Another subsample was air dried and used to determine SOC concentration and pH. SOC content was determined using the potassium dichromate heating method [31], and pH was measured by potentiometry with a pH meter [31]. Soil particle size was obtained using the pipette analysis method with three physical fractions of clay (particle size < 0.002 mm), silt (fine and coarse particles; 0.02 mm to 0.002 mm) and sand (fine and coarse particles; 2 mm to 0.02 mm) [32]. In addition, soil bulk density was determined using the cutting ring method [32].

The SOC density (SOCD) of a single layer was calculated with the following equation [33]:

$$\mathrm{SOCD} = \mathrm{SOC} \times \rho \times H \times (1 - \delta_{2mm}/100) \times 10^{-1} \quad (1)$$

where SOCD is given in Mg ha^{-1}, SOC is the soil organic carbon concentration (g kg^{-1}), ρ is the soil bulk density (g cm^{-3}), H is the thickness (cm) of the soil layer (20 cm in this study) and δ_{2mm} is the volume fraction (%) of > 2 mm particles in the soil (assumed to be zero, as the value is negligible in most top soils).

The SOC stock in different soil types covering different areas was calculated as:

$$\mathrm{SOCP} = \sum_{i=1}^{n} (S_i \times \mathrm{SOCD}_i) \quad (2)$$

where SOCP represents the SOC pool in the region (Mg), S_i is the area of soil type i (ha) and SOCDi is the SOCD of soil type i (Mg ha^{-1}).

$$\mathrm{SOCD\ rate} = (\mathrm{SOCD}_{2011} - \mathrm{SOCD}_{1981})/30 \quad (3)$$

where the SOCD rate represents the change rate of SOCD from 1981 to 2011 (Mg ha^{-1} year^{-1}), SOCD$_{2011}$ represents the SOCD in 2011 (Mg ha^{-1}), SOCD$_{1981}$ represents the SOCD in 1981 (Mg ha^{-1}) and 30 represents the 30 years from 1981 to 2011.

With this understanding of the SOC level at saturation, SOC saturation was calculated by the following estimate model established by Qin et al. [34] and based on the datasets from sites worldwide. The statistical model performed well in 19 long-term experiments [34]. The linear equations are shown as:

$$\mathrm{SOCS} = 140.5 \times e^{-0.021\times\mathrm{MT}} - 98.8 \times e^{-0.42\times\mathrm{MP}} - 39.6 \times e^{-0.10\times\mathrm{CL}} - 4.1 \times \mathrm{pH} - 27.7 \quad (4)$$

$$\Delta SOCD = SOCS - SOCD_{2011} \quad (5)$$

where SOCS is the SOC level at saturation (Mg ha^{-1}), MT is the mean annual temperature (°C), MP is the annual total water input that is the sum of the mean annual precipitation and irrigation (100 mm), CL and pH represent the soil clay (<0.002 mm) fraction (%) and pH value, respectively, and ΔSOCD is the future SOC sequestration potential.

2.4. Statistical Analysis

Correlation analysis was used to examine the relationships between the SOCD rate and related factors (including soil type, topography, fertility and artificial measures). Correlation analysis was performed by a bivariate Pearson's unilateral significance test. Statistical analysis was performed with the SPSS 22.0 software package for Windows (SPSS Inc., New York, NY, USA).

3. Results and Discussion

3.1. Description of SOCD Statistics in 1981 and 2011

The measured parameters for SOCD in 1981 and 2011 were higher than those in 1981, except for the minimum, which could be linked to the heterogeneity of agriculture practices, such as synthetic fertilizer augmentation, the optimal combinations of nutrients and the development of no-tillage and reduced-tillage practices. Compared to the changing amplitude of SOCD from 1981 to 2011 in mean, there were more remarkable differences in the mean values for SOCD between 2011 and 1981 (Table 1). These analyses indicate that SOCD presented a significant change from 1981 to 2011. Therefore, it might be necessary to use SOCD to evaluate soil carbon spatial-temporal variability and related factors rather than SOC in the paper.

Table 1. Statistics for SOCD and soil carbon content in 1981 and 2011.

Item	Range	Min	Max	S.D.	C.V.	Median	Mean
$SOCD_{1981}$ (Mg ha^{-1})	17.40	8.93	26.33	4.98	3.80	15.20	15.66
$SOCD_{2011}$ (Mg ha^{-1})	45.80	8.49	54.29	9.42	4.32	24.74	26.09

3.2. Variability of SOCD from 1981 to 2011

The distribution maps of SOCD were obtained using an inverse distance weighted interpolation algorithm method via ArcMap software [35] (Figure 2). Compared to 1981, the study area presented a remarkable growth of SOCD, especially in the middle and western regions. The SOCD content was mainly between 10–20 Mg ha^{-1} in 1981 (Figure 2A); however, SOCD was more than 35 Mg ha^{-1} in some micro-regions and was not less than 25 Mg ha^{-1} in an area that makes up half the total county (Figure 2B). Thus, it can be seen that SOCD presented an increasing trend in the cropland of Fengqiu county. Similarly, the SOCD growth distribution map of Fengqiu county from 1981 to 2011 presented strong carbon sequestration (Figure 3A), which reflected the pure growth of carbon in the unit area. Almost all the cropland shows carbon fixation according to this interpolation result. The SOCD growth rate distribution map made the SOCD change tendency in the cropland clear, on the other hand (Figure 3B). The central area presented a higher SOCD change rate compared to the surrounding area. The SOCD growth rate was more than 0.20 Mg C ha^{-1} $year^{-1}$ in most regions, and few areas showed lost carbon in Fengqiu.

Possible reasons for the spatial variations in SOCD might include farming practices, such as fertilization, soil amelioration measures and other related human actives. During the past 49 years (1961–2009), there was about a 37-fold increase in N fertilization and a 91-fold increase in P fertilization in China, and the FAOSTAT Database shows that cereal grain yields had increased 3.5-fold from 1.2 to 5.4 Mg ha^{-1}, while the total grain production increased 3.4-fold from 110 to 483 million tons (MT) [36]. The recent large-scale application of integrated nutrient management for cropping systems has increased crop yields and reduced environmental risk in China [37]. Fengqiu was no exception; the application of manure or manure mixed with mineral fertilizer significantly increased organic carbon through a long-term experiment on fluvo-aquic soil under a maize–wheat rotation system in Fengqiu County [38]. According to the long-term effects of various tillage managements on aggregation and organic carbon accumulation at the State Experimental Station of Agro-Ecosystem in Fengqiu, no tillage and intermittent tillage combined with straw management could markedly accelerate organic carbon accumulation in macro-aggregates and increase carbon sequestration in fluvo-aquic soil [39]. Some recent studies also suggested that the regular addition of fertilizer and organic residues into soil could enhance the availability of nutrients in the soil, such as dissolved organic C, microbial biomass C and $KMnO_4$ oxidisable C [40–42]. Those improved SOC compositions have positive effects on SOC accumulation by improving soil quality [43–45]. On the other hand, some researchers have reported that large amounts of fertilizers and organic matter have been added to the soil in the study area since 1981 [46–48]. Thus, agro-management may be one of the key factors of the variability of SOC from 1981 to 2011.

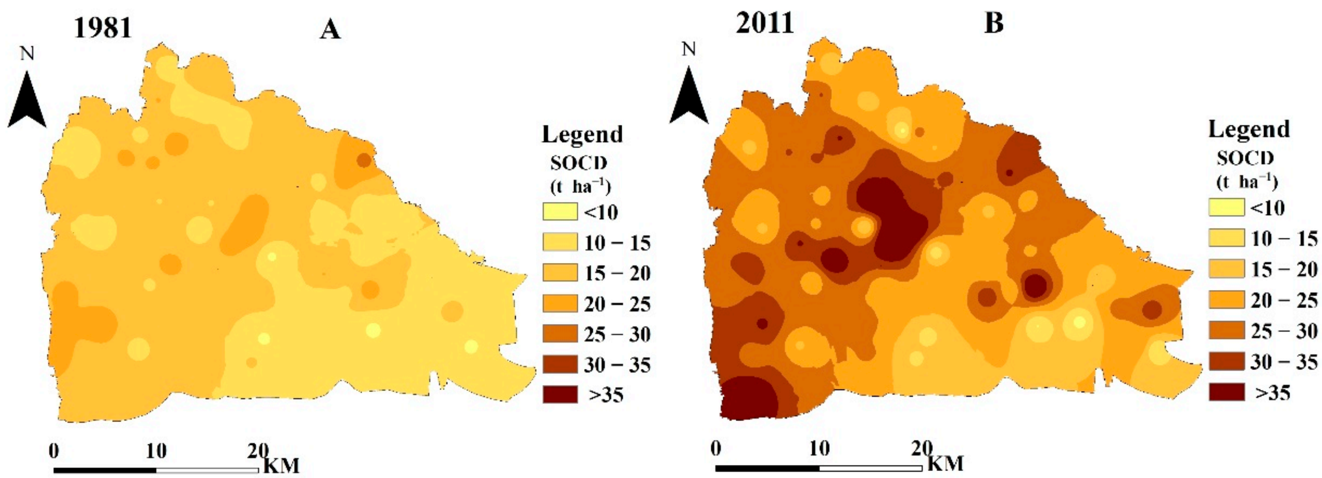

Figure 2. SOCD distribution maps of Fengqiu county in 1981 (**A**) and 2011 (**B**).

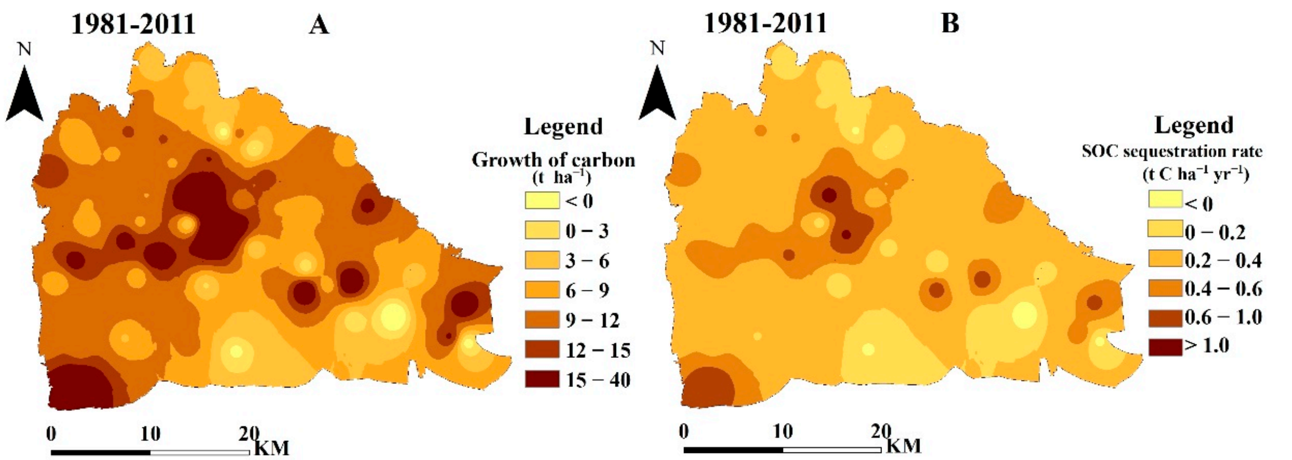

Figure 3. Distribution maps of SOCD growth (**A**) and change rate (**B**) of Fengqiu county from 1981 to 2011.

3.3. Spatial-Temporal Variability of SOC Stock and Carbon Sequestration Potential

Procter et al. [49] noted that soil type influences microbial activity and soil carbon storage. Soil respiration data have suggested that the soil type effects the microbial activity that occurs in the field; the soil type may improve predictions of how soils will store carbon in a future high-CO_2 world. The SOCD in the study area varied widely for all soil types based on the statistical analysis (Table 2). In 1981, the combined soil had the highest SOC stock value; salined flavo-aquic soil, fixed aeolian sandy soil, sandy soil and silting soil presented relatively lower values, while the SOCD of semifixed aeolian sandy soil was the lowest. However, in 2011, the variability of the SOC stock values was same as the former. The growth rates of the carbon stock were between 10.78% and 76.25% in different soil types. Fluriogenic soil presented the highest growth rate value, followed by fixed aeolian sandy soil. Combined soil, anthropogenic-alluvial soil and silting soil presented relatively lower values.

Table 2. The amount and change of SOC stock in different soil types.

Group	Subgroup	Genus	Area (ha)	SOC Stock (t)			Growth Rate of Carbon Stock (%)	Carbon Sequestration Potential (Mg ha^{-1})
				Year 1981	Year 2011	Saturation Value		
Aeolian sandy soil	Aeolian sandy soil	Fixed aeolian sandy soil	1196.00	19,270.10	33,284.24	41,035.26	72.72	6.48
		Semifixed aeolian sandy soil	260.00	2323.07	2573.48	7119.58	10.78	17.49
Fluvo-aquic soil	Fluvo-aquic soil	Cinnamon-combined soil	3336.67	57,965.42	78,736.85	129,417.92	35.83	15.19
	Yellow fluvo-aquic soil	Anthropogenic-alluvial soil	4662.67	70,279.96	112,098.90	184,395.62	59.50	15.51
	Yellow fluvo-aquic soil	Combined soil	46,817.34	757,287.74	1,275,688.45	1,829,766.68	68.45	11.83
	Yellow fluvo-aquic soil	Sandy soil	6907.33	116,200.20	141,799.10	222,493.29	22.03	11.68
	Yellow fluvo-aquic soil	Silting soil	9134.67	161,702.23	248,191.40	360,832.81	53.49	12.33
	Salined flavo-aquic soil	Salined flavo-aquic soil	14,170.00	208,999.07	368,370.67	542,950.02	76.25	12.32

Based on the SOC saturation estimate model (Equations (4) and (5)), SOC sequestration potential, which refers to the holding capacity under local circumstances, was vital to work out relevant measures regarding CO_2 reduction. Using the SOC in 2011 as a reference, the saturation value of the SOC stock per soil type in Fengqiu was estimated (Table 2). Combined soil presented the highest saturation value of SOC stock, followed by salined flavo-aquic soil silting soil, sandy soil, anthropogenic-alluvial soil, cinnamon-combined soil, fixed aeolian sandy soil and semifixed aeolian sandy soil, respectively. Furthermore, using the SOC stock in 2011 as a reference, carbon sequestration potential values were calculated. The carbon sequestration potential denoted the difference between the saturation value of carbon stock in the future and the SOC stock value in 2011. Thus, the carbon sequestration potential values represented the possible maximal net increment of organic carbon stock in topsoil. The evaluated results showed that semifixed aeolian sandy soil presented the highest carbon sequestration potential value, followed by cinnamon-combined soil and anthropogenic-alluvial soil. Combined soil, sandy soil, silting soil and salined flavo-aquic soil presented relatively lower values, while fixed aeolian sandy soil was the lowest. What is more, the carbon sequestration potential distribution map of Fengqiu county showed that all areas present strong carbon sequestration potential in the coming decades from 2011, and the carbon sequestration potential was mainly between 32–40 Mg ha^{-1} (Figure 4).

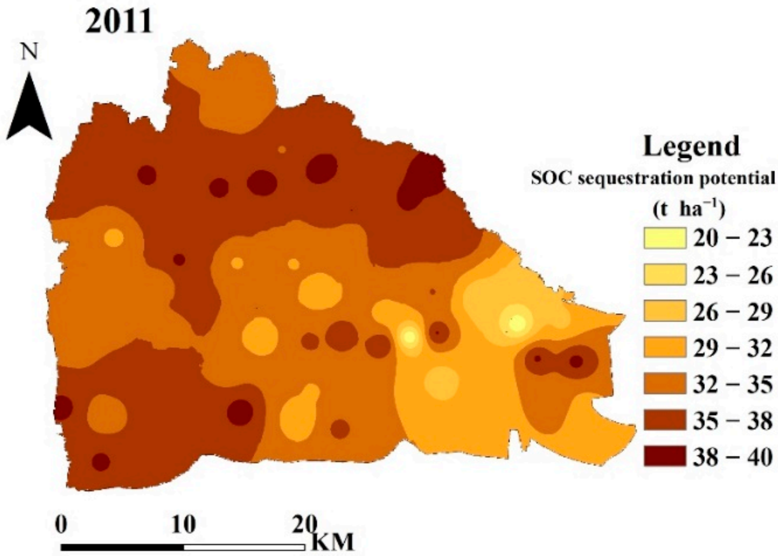

Figure 4. Carbon sequestration potential distribution map of Fengqiu county from 2011.

3.4. Effect of Related Factors on SOC Sequestration Rate

According to the research area and available data, the soil type (e.g., subgroup, texture), topography (e.g., groundwater table, elevation), fertility (e.g., pH, total nitrogen, total phosphorus, total potassium) and artificial measures (e.g., returning straw, fertilization) were selected as related factors. Based on the correlation analysis between the SOCD rate and related factors, the results show that the soil type, fertilizer and artificial measures were closely related to the SOCD rate at a significance level ($p < 0.05$), but the correlation between the topography and SOCD rate was not significant. Furthermore, pH, total nitrogen and total phosphorus showed a highly significant correlation with the SOCD rate at a significance level ($p < 0.01$) (Table 3).

Table 3. Correlation analysis between the SOCD rate and related factors.

Type of Factors	Impact Factors	Correlation Coefficient	Significance Level
Soil type	Subgroup	0.21	*
	Texture	0.10	—
Topography	Groundwater table (m)	0.13	—
	Elevation (m)	−0.06	—
Fertility	pH	−0.51	**
	Total nitrogen (g kg^{-1})	0.61	**
	Total phosphorus (g kg^{-1})	0.48	**
	Total potassium (g kg^{-1})	0.11	—
Artificial measures	Returning straw	0.39	*
	Fertilization	0.27	*

** Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level.

In conclusion, the change in SOCD was closely related to soil nutrition supply, especially nitrogen and phosphorus. Artificial measures could not be neglected because returning straw and fertilization could input organics, which affect the SOC content in topsoil directly. Crop residue retention is important for sequestering SOC, controlling soil erosion and improving soil quality [50].

The aboveground and underground biomass of plants can be enhanced through fertilizer application. Fertilization could increase maize root growth and nutrient content and improve soil fertility and carbon sequestration through root residue into soil [51]. Pan et al. [52] also found that well-managed, combined organic/inorganic fertilization could both enhance C storage in soils and reduce emissions from N fertilizer use while contributing to a high crop productivity in agriculture through a long-term fertilization trial. The abundant effective nitrogen in fertilizer is beneficial to the conversion of exogenous organisms into humus, which improves soil organic carbon storage indirectly [53]. The correlation analysis also confirmed that soil nitrogen and phosphorus, but not potassium, had a significant correlation with the SOCD rate (Table 3). It could be inferred that there is a close relationship between the soil nitrogen and phosphorus content and the SOC budget.

Different soil types presented different hydrothermal properties, which were necessary conditions for organic carbon decomposition, cycle and transformation [54].

4. Conclusions

The results revealed that the SOC sequestration rate was more than 0.20 Mg C ha^{-1} year^{-1} in most regions, and few areas showed lost carbon in the 30 years (1981–2011). Increasing trends in the soil organic carbon density (SOCD) and the soil organic carbon pool (SOCP) were obvious from 1981 to 2011, and the study area presents a great carbon sequestration potential for the future. The estimated data also showed that all areas present strong carbon sequestration potential in the coming decades from 2011, and the carbon sequestration potential was mainly between 32 and 40 Mg ha^{-1}. Furthermore, the applications of additional organic-inorganic materials, such as straw and chemical fertilizer, contributed to improving the soil carbon sequestration capacity and fertility.

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