Soil Organic Carbon Change and Carbon Sequestration Potential Estimation in Farmland of the Songnen Plain: Postprint

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Abstract

Based on data from the second national soil survey (1979-1985) and 2015 field sampling, the soil type method was used to calculate the topsoil organic carbon density and soil carbon pool storage of farmland in the Songnen Plain and its counties over the past 35 years; the spatial distribution and variation characteristics of farmland soil organic carbon density in the Songnen Plain were analyzed; and the saturation value method was employed to fit the changing trends of farmland soil organic carbon content in the Songnen Plain and its counties and cities, thereby estimating the carbon sequestration potential of its farmland soils. The results indicated that: (1) The average topsoil organic carbon density of farmland in the Songnen Plain in 2015 was 1.61 kg/m^2, with approximately 81.59% of farmland soils exhibiting a decreasing trend in organic carbon density over the past 35 years, concentrated in the northern, eastern, and southeastern regions of the Songnen Plain, with the most significant decreases observed in eastern Fuyu County, central Yi' an County, western Zhaodong County, western Fuyu County, and other areas; (2) The total topsoil organic carbon pool storage of farmland in the Songnen Plain in 2015 was 233.63 Tg, representing a decrease of 32.62 Tg compared to the second national soil survey; (3) The total carbon sequestration potential of topsoil in the Songnen Plain' s farmland in 2015 was -32.7 TgC, demonstrating a "carbon source" trend, and the average carbon sequestration potential per unit area of farmland soil was -1.793×10 ^{3} Tg/km^2.

Full Text

Preamble

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Temporal and Spatial Variations of Organic Carbon and Evaluation of Carbon Sequestration Potential in the Agricultural Topsoil of the Songnen Plain

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Abstract

Soil organic carbon (SOC) density and storage in the agricultural topsoil of the Songnen Plain were evaluated using the soil-type method based on data from the Second National Soil Survey (1979–1985) and field observations from 2015. The spatial distribution of SOC density was analyzed using ArcGIS, and a fitting analysis of SOC storage trends across districts and counties of the Songnen Plain over the past 35 years was conducted using the saturation value method to estimate the carbon sequestration potential of agricultural soils. The main results are as follows: (1) The average agricultural topsoil organic carbon density in 2015 was 1.61 kg/m². Approximately 81.59% of the agricultural topsoil area in the Songnen Plain showed a decreasing trend in SOC density over the last 35 years, with SOC mainly distributed in the north, east, and southeast of the plain. The most significant decreases occurred in eastern Fuyu County, central Yi' an County, western Zhaodong County, and western Fuyu County. (2) The total organic carbon storage in agricultural topsoil was 233.63 Tg in 2015, representing a decrease of about 32.62 Tg compared to the second national soil survey. (3) The organic carbon sequestration potential of agricultural topsoil in the Songnen Plain was approximately -32.7 TgC, indicating a carbon source area, with an average value per unit area of -1.793 × 10³ kg C/km².

Keywords: agricultural topsoil organic carbon; carbon sequestration potential; Songnen Plain

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Introduction

Soil represents the largest and slowest-turnover carbon pool in terrestrial ecosystems, with the soil organic carbon pool being its primary component. Existing as organic matter in the Earth' s surface soil, the soil organic carbon pool is approximately twice the size of the atmospheric carbon pool (1500 GtC) and plays a crucial role in the global carbon cycle. Increases in soil carbon storage can mitigate the rise in atmospheric CO concentrations caused by human activities, as even minor changes significantly affect the magnitude and distribution of carbon sinks and sources. Farmland ecosystems, as the most active component of the global carbon pool, experience rapid changes in both the quality and quantity of soil carbon under human cultivation and irrigation. These changes not only alter soil fertility and crop yields but also impact regional and global terrestrial ecosystems and climate change due to their dual potential as atmospheric carbon sources and sinks. The IPCC Fourth Assessment Report indicates that the global agricultural sector has a natural mitigation potential of up to 7300 (-1100 to 16900) GtCO -eq annually, demonstrating that agricultural development’ s contribution to climate change primarily stems from the greenhouse gas mitigation capacity of soil organic carbon sequestration.

China, as a major global agricultural nation, has attracted widespread attention regarding the impact of its farmland soil on atmospheric CO concentrations. Research on farmland soil organic carbon balance, change patterns, and regulatory measures has become a hotspot in global climate change studies. However, estimates of soil carbon pools still show significant variation, making the enrichment and standardization of regional-scale soil carbon storage data an effective approach to improving national carbon pool estimation accuracy.

The Songnen Plain, located in one of the world’ s three major black soil regions in Northeast China, features distinctive agricultural soil resources with high organic matter content and fertility, representing an important agricultural production zone. It is also one of the regions most significantly disturbed by human activities over the past century, with the largest farmland expansion and most rapid agricultural development, making it highly significant for research. Studies on the balance and changes of farmland soil organic carbon storage in the Songnen Plain provide reference for revealing regional-scale farmland soil carbon source-sink characteristics, understanding greenhouse effect mitigation under human intervention, and improving soil quality and food security.

Previous research indicates that farmland soil carbon storage in Northeast China shows a declining trend, with notable decreases in Heilongjiang and Liaoning provinces. Li Zhongpei noted that the black soil organic carbon pool in the Songnen Plain is in a deficit state. Ming et al. found that most black soil organic carbon content has reached a relatively stable equilibrium under current production levels. Zhang Chunhua et al. and Ren Chunying et al. analyzed farmland topsoil organic carbon storage and sequestration potential in southern Songnen Plain using data from the Second National Soil Survey and 2010 measurements, finding increasing trends in SOC density and storage with a sequestration potential of 8.17 TgC. Liu Guodong et al. estimated the carbon sequestration potential of topsoil in central-western Songnen Plain as -0.917 TgC. These results demonstrate that while Northeast China’ s farmland soil organic carbon pool is generally deficient, regional variations in cycling and balance status are evident.

Existing partitioned assessments of the Songnen Plain show inconsistent results due to different data sources and study areas, leading to low comparability. Most current results are from over a decade ago, requiring improvement in breadth and timeliness. This study utilizes 2015 field sampling data and the Second National Soil Survey data to analyze farmland topsoil organic carbon density, storage, and changes across the Songnen Plain and its counties over the past 35 years. By analyzing the relationship between organic carbon variation and initial values, we estimate farmland soil carbon sequestration potential, aiming to improve and unify regional soil organic carbon storage data and provide a typical case study for understanding soil carbon cycle impacts on climate change under human intervention.

1. Study Area Overview

The Songnen Plain, formed by alluvial deposits from the Songhua and Nen Rivers, is one of the three major plains in Northeast China, alongside the Sanjiang and Liaohe Plains. Located in southwestern Heilongjiang and northwestern Jilin provinces (42°30 N–51°20 N, 121°40 E–128°30 E), it lies in a mid-latitude region with a temperate continental semi-humid to semi-arid monsoon climate. Influenced by alternating winter and summer monsoons, the region experiences four distinct seasons with cold, dry winters. The annual average temperature increases gradually from north to south. The plain features gentle topography with meadow soil, chernozem, and paddy soil as main soil types. The primary land use is cropping and livestock farming, with corn as the main crop and limited rice cultivation, following a single-crop-per-year system.

2. Data Sources

2.1 Soil Sample Collection and Measurement

The 2015 soil property data used in this study were obtained through field data collection across 35 administrative counties in the Songnen Plain cultivation area. Sampling followed the National Cultivated Land Geographic Survey and Quality Technical Regulations. To minimize fertilizer effects, samples were uniformly collected before plowing. Each county established 5–7 sampling sites, with 1–2 surface soil profiles (0–10 cm) excavated at each site after clearing surface litter and humus. Central point coordinates were recorded, and 500 g of mixed soil samples were collected in bags. Samples were air-dried, sieved, and analyzed. Soil organic carbon was measured using the potassium dichromate oxidation-external heating method, and soil bulk density was determined using the ring knife method.

2.2 Soil Survey Data

The Second National Soil Survey data for the Songnen Plain were provided by the Institute of Soil Science, Chinese Academy of Sciences. This dataset utilized China’ s 1:1,000,000 soil database, generating spatial distributions of soil properties at different layers (0–10, 10–20, 20–30, 30–70 cm) based on 94,000 soil profiles and 7,292 typical profiles. The survey period was defined as 1979–1985, with soil organic matter (SOM) data used for this study.

2.3 Soil Type Maps

Soil type data were derived from the Harmonized World Soil Database (HWSD) constructed by the Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA), with Chinese data sourced from the 1:1,000,000 soil data from the Second National Land Survey. The soil classification system primarily used the FAO-90 system. Within the Songnen Plain region, soil distribution covered 211,592.22 km², accounting for 99.7% of the plain' s total soil area, including 10 soil groups and 21 subgroups.

2.4 Land Use Type Maps

Land use data for 1980 and 2015 were selected as temporal endpoints to align with soil physicochemical property acquisition periods. Data sources included Landsat-TM/ETM images downloaded from USGS Global Visualization Viewer (30 m resolution). Following the Land Use Status Survey Technical Regulations, land use types were classified into six categories: farmland, forest, grassland, wetland, urban land, and unused land, establishing a land use database.

3. Methods

3.1 Soil Organic Carbon Density Calculation

Soil organic carbon density (SOC density) refers to the mass of soil organic carbon per unit area within a certain depth, representing an important indicator of soil quality and terrestrial ecosystem contributions to global change. SOC density is determined by organic carbon content, bulk density, and gravel content (>2 mm). For China's agricultural soils, long-term cultivation has reduced gravel content in the plow layer, and in the flat Songnen Plain, gravel content can be considered negligible. The calculation formula for SOC density per square meter within a soil layer is:

$$C_d = 0.58 \times SOM \times B \times 0.1$$

where C_d is soil organic carbon density (kg/m^2), 0.58 is the Bemmelen coefficient converting organic matter to organic carbon, SOM is organic matter content (g/kg), B is soil bulk density (g/cm^3), and 0.1 is the conversion coefficient.

3.2 Soil Organic Carbon Storage Estimation

Soil organic carbon storage is an evaluation index representing soil carbon sequestration potential. Current research typically employs methods such as life zone, forest type, vegetation type, climate parameter, regression, and soil type approaches. This study used the soil type method to estimate topsoil organic carbon storage in the Songnen Plain:

$$C_s = \sum_{i=1}^{n} S_i \times C_{di}$$

where C_s is soil organic carbon storage (g), S_i is the area of the i-th soil subgroup (m^2), C_{di} is the organic carbon density of the i-th soil subgroup (g/m^2), and n is the number of soil subgroups.

3.3 Farmland Soil Carbon Sequestration Potential Estimation

This study employed the saturation value method to estimate farmland topsoil carbon sequestration potential in the Songnen Plain. This method treats the difference between the organic carbon content level when soil type organic carbon change reaches zero and each measured value as the soil organic carbon increase potential at that point:

$$SOC_p = SOC_s - SOC_o$$

where SOC_p is soil carbon sequestration potential, SOC_s is soil saturated carbon storage, and SOC_o is the 2015 soil organic carbon storage. The saturation level depends on climate, topography, and parent material conditions under which soil carbon storage stabilizes. The saturation level was determined by finding the soil carbon density value where the change in soil carbon content equals zero, serving as the soil carbon pool saturation level.

3.4 Data Statistics and Spatial Analysis

ArcGIS 10.2 was used for spatial data processing and analysis, including spatial overlay of farmland topsoil organic carbon density. SPSS 20.0 was employed for correlation analysis between sampling point SOC density, area, and meteorological elements.

4. Results

4.1 Farmland Soil Organic Carbon Density and Distribution Characteristics

From 1980 to 2015, the average soil organic carbon density in the Songnen Plain showed a decreasing trend. In 1980, SOC density ranged from 1.06–2.44 kg/m^2 with a coefficient of variation of 0.27; in 2015, it ranged from 1.34-1.95 kg/m^2 with a coefficient of variation of 0.12, indicating reduced variation and stabilization of soil properties. Among different soil types, black soil and chernozem consistently showed the highest organic carbon densities due to their formation environment in the cold temperate zone with distinct seasons, where abundant vegetation produced thick humus layers. From 1980 to 2015, all soil types except solonchak and fluvisols showed decreasing trends, with the largest decline in anthropogenic soils (31.63%), followed by black soil (27.01%) and alfisols (26.34%). Solonchak and fluvisols increased by 39.64% and 58.49%, respectively.

shows organic carbon densities for different soil types in 1980 and 2015.

Spatially, farmland topsoil organic carbon density decreased from northeast to southwest. In 1980, 72.71% of farmland had SOC density of 1.70–3.68 kg/m², concentrated in central and western regions. In 2015, 39.01% had SOC density of 1.19–1.70 kg/m², mainly in northern and eastern areas, while 19.36% had density <0.78 kg/m² in southwestern regions. Decreasing areas accounted for 81.59% of total farmland, concentrated in northern, eastern, and southeastern regions, with the most significant declines in eastern Fuyu County, central Yi'an County, western Zhaodong County, and western Fuyu County. [Figure 4: see original paper] shows the spatial distribution and absolute changes in farmland topsoil organic carbon density.

4.2 Farmland Soil Organic Carbon Storage and Changes

From 1980 to 2015, total farmland topsoil organic carbon storage in the Songnen Plain decreased from 266.25 Tg to 233.63 Tg, a reduction of 32.62 Tg (12.25%). Among 10 soil groups, anthropogenic soils and solonchak showed the largest storage decreases (25.33% and 7.03%, respectively), while the remaining six types increased storage, consistent with SOC density trends.

At the county level, only Wudalianchi and Zhenlai showed increased storage, while all other counties decreased. Tongyu County had the largest increase (2.07 TgC), followed by Wudalianchi (1.21 TgC). Correlation analysis using SPSS showed a significant correlation (r=0.895, p<0.001) between farmland area change and organic carbon storage change, indicating that farmland expansion leads to increased storage, though the effect depends on the magnitude of change. and show area percentages and organic carbon storage by soil type and county.

4.3 Farmland Soil Carbon Pool Saturation Status

Using 1980 SOC density as initial data and fitting its relationship with change amounts, the saturation level represents the stable carbon density achievable under current climate, land use, and management practices. The fitted curve shows that when initial SOC density is 1.52 kg/m², the change amount is zero. Below this value, SOC tends to increase; above it, SOC tends to decrease. As SOC density increases, the rate of increase gradually slows, reaching saturation at 1.52 kg/m².

At the county level, 11 counties showed highly significant correlations between initial SOC density and change amount, including Jiutai, Zhaodong, and Kedong. Kedong County had the highest saturation level (2.49 kg/m^2), while Changling had the lowest (0.47 kg/m^2). shows saturation levels for each county.

4.4 Farmland Soil Carbon Sequestration Potential

Based on saturation values, if climate, land use, and agricultural management remain unchanged, the Songnen Plain' s farmland soil carbon sequestration potential is -32.7 TgC, indicating that over the past 35 years, the region' s farmland soil would release 32.7 TgC to the atmosphere, requiring an annual carbon input of 0.93 TgC/a to reach stable equilibrium. This demonstrates a carbon source status.

Except for Longjiang, Qian Gorlos, and Suiling counties with positive potentials, all other counties showed negative potentials. Zhaoyuan, Zhaodong, and Zhaozhou had the largest carbon emission potentials, requiring agricultural management adjustments to reduce emissions. The average per-unit-area sequestration potential was -1.793×10^3 kg C/km^2. shows county-level results.

Comparison with previous studies shows consistency with Liu Guodong et al.' s findings of declining SOC storage in central-western Songnen Plain, but differs from Zhang Chunhua et al. and Ren Chunying et al., likely due to different data sources and time periods. provides comparative results.

5. Discussion

5.1 Causes of Farmland Soil Organic Carbon Changes

Changes in SOC storage and sequestration potential depend on SOC density variations, which are closely related to climate change and human activities. Global warming accelerates SOC decomposition, while human activities such as reclamation directly alter SOC content. From 1980 to 2015, temperature increased at 0.94°C/10a while precipitation decreased at 5.87 mm/10a. SOC density change showed weak negative correlation with temperature ($r=-0.098$) and weak positive correlation with precipitation ($r=0.134$, $p<0.001$), indicating combined climatic effects.

Human activities increasingly influence SOC density. Land use conversion analysis using ArcGIS 10.2 showed that conversion of forest, wetland, and unused land to farmland all decreased average SOC density. Wetland conversion caused the largest decline (37.05%), followed by forest (25.73%) and grassland (22.38%). shows SOC density changes by land use type.

5.2 Conclusions

(1) From the Second National Soil Survey to 2015, average farmland topsoil organic carbon density in the Songnen Plain decreased from 1.80 to 1.61 kg/m^2, with the reduction concentrated in northern, eastern, and southeastern regions. Total storage decreased by 32.62 Tg, primarily related to

declining SOC density in black soil and chernozem.

(2) At the county level, only Qian Gorlos, Wudalianchi, and Zhenlai showed increased storage, with Tongyu having the largest increase and Nongan the largest decrease.

(3) The carbon sequestration potential of farmland topsoil was -32.7 TgC, with most counties showing negative potentials, indicating a carbon source status under current management. This aligns with Xi Xiaohuan et al.' s findings of declining SOC storage in Northeast China and Li Zhongpei et al.' s conclusion that the black soil carbon pool remains in deficit.

The study reveals uncertainties due to the long interval between data periods and lack of long-term experimental data. Further quantification of climate and human disturbance factors, as well as specific management measures like fertilizer application and straw return, requires additional research.

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Note: Figure translations are in progress. See original paper for figures.