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Original Research

Changes in the Organic Carbon Content of Agricultural Soils in the Middle and Lower Reaches of the Yangtze River in China: Based on Data from Long-Term Localization Experiments

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Abstract

The literature of long−term fertilization experiment in the Yangtze River Economic Belt from 1993 to 2023 was collected, and the data of farmland soil organic carbon were extracted and integrated. Using the normalization treatment and the analysis method of relative annual variation, the overall change of soil organic carbon content in farmland in the Yangtze River Economic Belt under long-term different fertilization measures was studied, and the change differences of soil organic carbon content under three tillage modes were compared, so as to judge and analyze the influence of the duration of the experiment on soil organic carbon dynamics. The results showed that under long-term different fertilization measures, the organic carbon content of farmland soil in the Yangtze River Economic Belt in China showed an overall upward trend. NP, NPK, O, and NPKO treatments all increased the organic carbon content of agricultural soils, with the NPKO treatment being the largest. The sole application of inorganic nitrogen fertilizer reduced the organic carbon content of the soil. The rates of change in soil organic carbon content were 0.11g·$(kg{\cdot}a)^{-1}$, 0.31 g·$(kg{\cdot}a)^{-1}$, and 0.30 g·$(kg{\cdot}a)^{-1}$ for dryland, paddy and water−dry rotation farmland, respectively. There is some variation in the rate of change of soil organic carbon content between soil types. The average rate of change of organic carbon was 0.20 g·$(kg{\cdot}a)^{-1}$for red soils, 0.13 g·$(kg{\cdot}a)^{-1}$ for tidal soils and 0.19 g·$(kg{\cdot}a)^{-1}$ for rice soils. The trend of NPKO>O>NPK>NPK>NP>N is basically maintained for the rate of change of soil organic carbon content. N treatment showed a reduction in organic carbon content in all soil types. Considering the carbon fixation of farmland soil, the combined application of organic and inorganic fertilizers is a more suitable fertilization method in this area.

Keywords: Yangtze River's middle and lower reaches, fertilization practices, soil, organic carbon

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Introduction

Soil organic carbon has a significant impact on CO_2 concentrations in the atmosphere, and carbon sequestration in agricultural soils has long been recognized as an important method of reducing CO_2 emissions [1]. According to the UN Intergovernmental Panel on Climate Change (IPCC), good science-based agricultural practices can contribute at least 5.50×10^{15}t of emission reduction potential (in CO_2 equivalent), with soil carbon sequestration accounting for up to 89% of this potential [2]. Since 2015, when China began to implement its chemical fertilizer reduction policy [3], the use of organic fertilizers and the optimization of agricultural management measures has been vigorously promoted in various regions, resulting in a clear trend of carbon enhancement in farmland soils. Some scholars have conducted extensive research on the impact of agricultural management practices on the organic carbon content of farmland soils, and the findings concluded that the scientific and reasonable application of both chemical and organic fertilizers has significantly contributed to the improvement of farmland soil organic carbon content [4-6].

Since ancient times, the middle and lower reaches of the Yangtze River have been one of China's most significant food supply hubs [7]. In the past, this area was referred to as the one where "Suzhou and Lake are ripe for the world to see." The middle and lower reaches of the Yangtze River have developed into China's most significant economic hub thanks to the country's ongoing development [8]. It includes seven Chinese provinces or municipalities: Shanghai, Jiangsu, Zhejiang, Anhui, Hunan, Hubei, and Jiangxi. It is located between 110° and 122° East longitude and 28° and 34° North latitude. Since the majority of the region's annual precipitation falls during the hot summer months due to the influence of the temperate monsoon climate, it is better suited for the development of plantations like those of rice and wheat. There is no doubt that the vast amount of farmland in the middle and lower reaches of the Yangtze River has enormous potential for carbon sequestration and reduction, but current research on the overall impact of agricultural management practices on soil organic carbon dynamics in this strategically important region is not yet complete, making it impossible to gauge the maximum factors for fertilizer application and the maximum magnitude of impact on the organic carbon content of farmland in the region [9]. Even so, the findings of pertinent research conducted in a few provinces and cities in the middle and lower reaches of the Yangtze River nonetheless offer a brief glimpse into the impacts of various cropping strategies and fertilization techniques on the organic carbon content of the region's farmland soils. For instance, it has been demonstrated in Jiangsu that continuous use of organic fertilizers can speed up the mineralization of soil organic carbon and increase the overall content of soil organic carbon [10]. Double-season rice farming in paddy soils has been demonstrated to improve soil carbon sequestration in Zhejiang [11]. On the overall analysis of the middle and lower reaches of the Yangtze River, there is still a dearth of trustworthy information. This study collected data from 59 representative long-term locational fertilizer application test sites distributed in different provinces (cities) of the middle and lower reaches of the Yangtze River to evaluate the overall effects of different fertilizer application measures on the dynamic distribution of soil organic carbon in farmland. We investigated the overall changes in soil organic carbon content of farmland in the middle and lower reaches of the Yangtze River using normalized treatment and rate of change analysis methods, and compared the differences in soil organic carbon content under three cropping patterns, including dryland field, paddy field, and water-dry rotation, to determine and analyze the effects of trial duration on soil organic carbon content. The study's findings can be used to guide fertilizer management for carbon sequestration and emission reduction in farmland in the middle and lower reaches of the Yangtze River, as well as for long-term development.

Method and Material

Study Areas

The study area includes seven provinces (cities) including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, and Hunan, covering an area of about 9.24×10^5 km^2, accounting for 9.62% of China.

Data Sources

From 1993 to 2023, a total of 135 research papers on long-term locational fertilizer trials in China's middle and lower reaches of the Yangtze River were collected and collated, from which data on trial location, soil type, tillage pattern, monitoring time, fertilizer application treatment, and organic carbon (matter) content were extracted. The following criteria were used to select data for collection: The selection criteria for data collection were: (i) the fertilizer measures were inorganic N fertilizer alone (N), inorganic N fertilizer with phosphate (NP), inorganic NPK, organic fertilizer alone (O) and organic inorganic fertilizer with organic (NPKO); (ii) the trial was a long-term locational trial with a period of more than 3a and the text included the year in which the trial started and ended; (iii) the test soil samples were taken from the surface of the tillage layer (0-20cm); (iv) the organic matter or organic carbon content was determined at the beginning and end of the soil test; and (v) the trial was conducted with no application as a control. After screening, 54 papers that met the criteria were ultimately obtained, involving 59 test sites, including 220 treatment samples overall, four different types of soil, 12 dryland fields, 18 paddy fields, and 29 water-dry rotations. The data in the figures were extracted using Get Data software from the text, figures, and tables in the literature. Organic carbon content and soil organic matter content can be converted using a factor of 0.58.

Changes in Organic Carbon Content

Change in Average Annual Content

Average annual organic carbon changes were calculated separately for the no-fertilizer treatment and each fertilizer treatment during the test cycle:

$$AC = \frac{SOC_t - SOC_0}{t}$$

Where AC is the annual variation of organic carbon content in farmland soils; t is the time difference between the start and end of the test observation; and SOC_0 and SOC_t are the test site's beginning and end organic carbon content ($g \cdot kg^{-1}$).

Rate of Change

To determine the rate of change in organic carbon in farmland soils, subtract the change in organic carbon content caused by each fertilizer treatment from the change in organic carbon content caused by no fertilizer treatment:

$$RAC = \frac{(SOC_t - SOC_0)_{TR} - (SOC_t - SOC_0)_{CK}}{t}$$

Where RAC denotes the rate of change in the organic carbon content of farmland soils; TR denotes the fertilizer treatment; and CK denotes the no-fertilizer treatment.

Data Processing

Because the effect of carbon sequestration in agricultural soils may vary depending on tillage method, the data in this study were statistically analyzed and compared by three tillage methods: dry field, paddy field, and water-dry rotation, and the data were processed using DPS 18.1 software and tested for significance (P<0.05).

Results

Overall Distribution of SOC Changes

In this study, of the 162 test treatment samples counted, 131 samples showed an increase in organic carbon content with the continuation of the test, accounting for approximately 80.86%, while the remaining 31 samples showed a decrease, accounting for approximately 19.14% (Table 1). The rate of change of soil organic carbon in farmland of the Yangtze River's middle and lower reaches ranged from -0.51 to 0.52 $g \cdot (kg \cdot a)^{-1}$, with an average rate of change of 0.24 $g \cdot (kg \cdot a)^{-1}$. In the dryland field, the rate of change of soil organic carbon ranged from -0.11 to 0.15 $g \cdot (kg \cdot a)^{-1}$, with an average rate of change of 0.11 $g \cdot (kg \cdot a)^{-1}$. The rate of change of soil organic carbon in paddy fields ranged from -0.15 to 0.43 $g \cdot (kg \cdot a)^{-1}$, with an average rate of change of 0.31 $g \cdot (kg \cdot a)^{-1}$; the rate of change of soil organic carbon in dry and water rotation fields ranged from -0.51 to 0.52 $g \cdot (kg \cdot a)^{-1}$, with an average rate of change of 0.30 $g \cdot (kg \cdot a)^{-1}$. The organic carbon content of farmland soils is increasing in general under all three tillage patterns, with the rate of change of soil organic carbon in paddy field being higher than the other two tillage patterns.

Table 1. Dynamic distribution of soil organic carbon under different tillage patterns.

Tillage patterns	Organic carbon dynamics	Number	Relative change /$g \cdot (kg \cdot a)^{-1}$	Overall change /$g \cdot (kg \cdot a)^{-1}$	Test period/a	Average age/a
Dryland	Addition	42	0.15±0.02ab	0.11±0.02a	21.30	21.57
	Reduction	8	-0.11±0.02ab		22.23	
Paddy	Addition	37	0.43±0.07a	0.31±0.07a	16.52	15.41
	Reduction	9	-0.15±0.04ab		13.62	
Water-dry rotation	Addition	52	0.52±0.20a	0.30±0.18a	10.62	10.79
	Reduction	14	-0.51±0.32b		11.50	
Total	Addition	131	0.37±0.16	0.24±0.11	16.27	16.50
	Reduction	31	-0.27±0.09		17.11	

Note: Different lowercase letters in the same column indicate significant differences (P<0.05)

Table 2. RAC under different fertilization practices.

Tillage patterns		Fertilization practices				
		N	NP	NPK	O	NPKO
Dryland	Numbers	9	7	12	10	12
	RAC	-0.03±0.03c	0.01±0.04c	0.07±0.02bc	0.16±0.03b	0.27±0.05b
Paddy field	Numbers	3	4	15	7	17
	RAC	−0.03±0.08a	0.06±0.15a	0.21±0.12a	0.33±0.09a	0.52±0.11a
Water-dry rotation	Numbers	11	4	21	9	21
	RAC	−0.17±0.05a	0.04±0.02a	0.18±0.04a	0.39±0.07a	0.67±0.55a
Total	Numbers	23	15	48	26	50
	RAC	−0.09±0.03b	0.03±0.04ab	0.16±0.04ab	0.28±0.04ab	0.52±0.23a

Note: The unit of RAC is g·(kg·a)$^{-1}$; Different lowercase letters in the same row indicate significant differences (*P*<0.05)

SOC Changes with Fertilization Practices

Table 2 depicts the characteristics of changes in organic carbon content of farmland soils under different fertilizer applications, with the exception of N fertilizer alone, which had an enhancing effect on farmland soil organic carbon content. The average rate of change in organic carbon for fields with organic fertilizer (O and NPKO) was 0.16 g·(kg·a)$^{-1}$ and 0.27 g·(kg·a)$^{-1}$ for dryland soils, 0.33 g·(kg·a)$^{-1}$ and 0.52 g·(kg·a)$^{-1}$ for paddy soils, and 0.39 g·(kg·a)$^{-1}$, and 0.67 g·(kg·a)$^{-1}$ for water-dry rotation soils, respectively. For agricultural fields with inorganic fertilizers, the rate of change of soil organic carbon ranged from -0.03 to 0.07 g·(kg·a)$^{-1}$ for dryland fields, -0.03 to 0.21 g·(kg·a)$^{-1}$ for paddy fields, and -0.17 to 0.18 g·(kg·a)$^{-1}$ for water-dry rotations. The rate of change of organic carbon in field soils under different fertilization measures was characterized by: NPKO>O >NPK>NP>N. And this was also used to describe the rate of change of total organic carbon in farm soils under the combined three tillage patterns. It can be seen that organic fertilizer and organic-inorganic combination treatments increase the organic carbon content of farmland soil more than inorganic fertilizer alone. The reason is that the organic fertilizer treatment directly increases the input of organic matter into the farmland soil, whereas the NPK treatment indirectly increases the soil organic matter content by achieving better crop growth through a more balanced nutrient input when compared to the N and NP treatments.

SOC Changes with Time

The test periods used in this study ranged from 3 to 41a and were split into three combinations with various durations. The rates of change in farmland soil organic carbon content at the corresponding experimental periods were calculated for each of the three tillage patterns (Fig. 1). Among them is the lack of trial data for more than 29 years for the water-dry rotation model (Fig. 1a). The organic carbon content of the cropland under all three tillage strategies exhibited a rising tendency as the experiment went on, however the rate of change gradually decreased. The rate of change (absolute value) in the organic carbon content of agricultural soils under various fertilizer treatments tended to decline during the course of the experiment, but the disparity in rate of change between fertilizer applications shrank

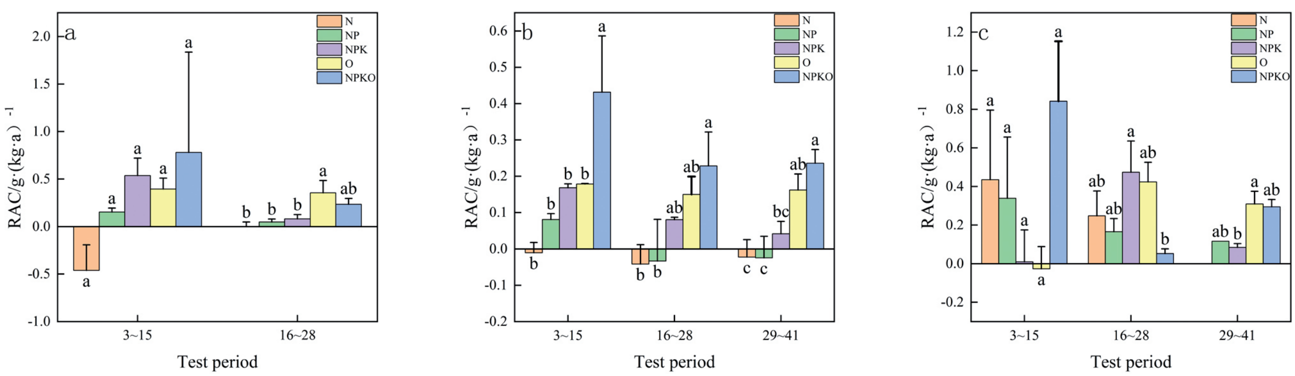

Fig. 1. Variation of RAC with experimental period under different fertilization measures.
Note: Different lowercase letters indicate significant differences (*P*<0.05).

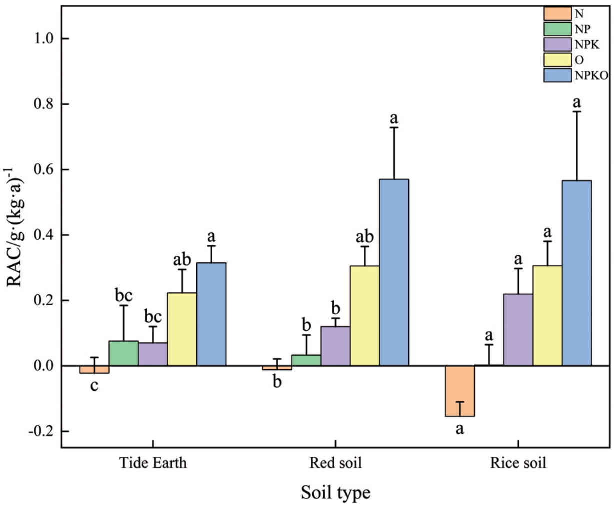

Fig. 2. Influence of farmland soil type on SOC under different fertilization practices. Note: Different lowercase letters indicate significant differences (P<0.05).

noticeably. The magnitude of the difference in the rate of change in organic carbon content (absolute values) between the different fertilization practices in the paddy (Fig. 1c) and dry-water rotations was more pronounced over the 28a experimental period. For dryland soils, the effect of soil carbon sequestration with different fertilizer applications remained relatively significantly different over the 28a duration of the trial.

SOC Changes with Soil Type

Red soil, tidal soil, and rice soil were the three types of soil used in the experiment. Each type's rate of change in soil organic carbon content under various fertilization strategies was counted independently. Fig. 2 displays the findings from a total of 85 groups of rice soil data, 34 groups of tidal soil data, and 43 groups of red soil data. As can be observed, the rate of change in soil organic carbon content varies somewhat depending on the type of soil. For example, the average rate of change in organic carbon for red soils is 0.20 g·(kg·a)$^{-1}$, while the rate for tidal soils is 0.13 g·(kg·a)$^{-1}$ and the rate for rice soils is 0.19 g·(kg·a)$^{-1}$. In both red soil and tidal soil, the pattern of NPKO>O>NPK>NP>N was maintained, with the NPKO fertilization treatment being significantly greater than the chemical fertilization (N, NP and NPK) treatments alone. All three soil types' organic carbon contents decreased as a result of the N fertilizer (N) application alone.

Discussion

Different tillage practices result in different natural environments and crop kinds in agricultural production, and these variations will have an impact on the soil's organic carbon content either directly or indirectly [12-14]. The findings of this study demonstrate that the organic carbon content of farmland soils in the middle and lower reaches of the Yangtze River under the three tillage patterns are all increasing, with the rate of change of soil organic carbon in paddy fields being higher than that of the remaining dry field and water-dry rotational tillage patterns, though the difference between the three patterns did not reach significance. This may be due to the large variation in trial duration between the three tillage patterns in this study, with an average trial duration of 21.57a for dry fields, 15.41a for paddy fields and 10.79a for water-dry rotations. Early findings similarly suggest that paddy fields have greater carbon sequestration capacity compared to dryland fields.

The results of this study showed that the average rate of change in soil organic carbon content of farmland under different fertilization measures (N, NP, NPK, O and NPKO) in the middle and lower reaches of the Yangtze River was 0.24g· (kg·a) $^{-1}$. It shows that, in comparison to no fertilizer application, fertilizer application contributes to the accumulation of organic carbon in farmed soils. This outcome is superior to Wang [15] and others' findings on the organic carbon content of farmland topsoil in China and comparable to Zhu et al.'s findings on rice and wheat rotational farmland in the lower reaches of the Yangtze River [16]. The first study examined the entire nation, whereas this one focused on the middle and lower sections of the Yangtze River in dryland, paddy, and water-dry rotating agriculture. This may account for the discrepancy between the two studies. The rate of change in soil organic carbon content in this study's NPKO fertilizer treatment for farmland in the middle and lower reaches of the Yangtze River was 0.52 g·(kg·a)$^{-1}$, which was comparable to the findings of Zhu et al. regarding the organic carbon content of red soil in the southern region of China [16]. The rate of change in the organic carbon content of farmland soils under the NPK fertilization treatment was typically higher than that of the N and NP treatments when inorganic fertilizers (N, NP, and NPK) were applied to the farmland for a protracted period of time. This was especially noticeable in the dryland soils in this study. This might be because crops receiving the NPK treatment receive more nutrients than those receiving the N and NP treatments, and as a result, have more developed root systems, increasing the amount of residue and root input to the soil [17]. On the other hand, it shouldn't be forgotten that a single application of N fertilizer may stimulate soil respiration, lowering the amount of organic carbon in the soil [18, 19]. The rate of change in soil organic carbon content was faster under the NPKO treatment than the O treatment in the dry field, paddy field, and water-dry rotation farmland. Both the O and NPKO treatments considerably boosted the accumulation of organic carbon in the soil. This is because, even though organic fertilizer can directly add organic material to farmland soil, its fertilizer effect is released more gradually, and the combination of inorganic fertilizer and organic fertilizer is more favorable to the rise in the active organic carbon content of soil aggregates [20-22]. A higher rate of change in the organic carbon content of the farm soils under the O and NPKO treatments in this study than under the application of inorganic fertilizers (N, NP, and NPK) alone was also a result of the application of organic fertilizers (O and NPKO), which as previously mentioned, allow for the direct input of organic material into the soil.

The ability of agricultural soils to store organic carbon is somewhat constrained. An equilibrium condition develops when soil organic carbon reaches a specific level, and as it does so, the amount of soil organic carbon increases slowly at first and then rapidly [39-45]. This notion is supported by the current study's findings on the rate of change in soil organic carbon content over the course of the experiment under three different tillage patterns. Different soil types indicate various physicochemical characteristics, which have a significant impact on crop choice and growth and, consequently, on the soil's capacity to store carbon. The findings of this study demonstrate that red soils have the greatest ability to sequester carbon. The carbon sequestration effects of each soil type remained much the same in terms of fertilizer application: NPKO>O >NPK>NP>N. For red soils, tidal soils, and rice soils in particular, the combination of organic and chemical fertilizers was noticeably more effective than chemical fertilizers alone.

Conclusions

In conclusion, under various long-term fertilizer application measures, the organic carbon content of farming soils in the middle and lower sections of the Yangtze River in China demonstrated an overall increasing tendency. The organic carbon content of farmed soils increased following the application of the NP, NPK, O, and NPKO treatments compared to the N treatment, with the NPKO treatment having the greatest impact. The three types of tillage – dry field, paddy field, and water-dry rotation – had no discernible impact on the change in the amount of soil organic carbon in agriculture. In the middle and lower parts of the Yangtze River, wise fertilizer use can aid in maximizing the capacity of agricultural soils to store carbon. Combining organic and inorganic fertilizers is a better fertilization strategy for this area from the perspective of carbon sequestration in agriculture soils. Under various long-term fertilization techniques, the organic carbon content of farmland soils in the middle and lower reaches of the Yangtze River in China showed an overall increasing trend. Inorganic nitrogen and phosphorus (NP), inorganic nitrogen, phosphorus, and potassium (NPK), organic fertilizer alone (O), and organic and inorganic fertilizer alone (NPKO) treatments all increased the organic carbon content of farmland soils, with NPKO treatment being the largest increase. Whereas soil's organic carbon content was decreased by inorganic nitrogen (N) alone. The rate of change of the soil's organic carbon content varies to some extent depending on the kind of soil, with red soil changing at a faster rate than rice soil and tidal soil. Combining organic and inorganic fertilizers is a better way of fertilization for this area from the perspective of carbon sequestration in agricultural soils.

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Conflict of Interest

The authors declare no conflict of interest.

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