

ORGANIC FERTILIZER INCREASES SOIL ORGANIC CARBON AND CROP YIELD IN FOUR-YEAR TILLAGE AND CROP ROTATIONS ON THE LOESS PLATEAU, CHINA

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Abstract. To define the role of organic or inorganic fertilizers in the stability and sustainability of soil organic carbon (SOC) and crop yield, we examined changes in SOC and crop yield, as well as their correlation, in nine different fertilization treatments (sheep manure [M], sheep manure and urea [MN], sheep manure and diammonium phosphate [MP], sheep manure, urea, and diammonium phosphate [MNP], urea and diammonium phosphate [NP], urea and potassium sulfate [NK], diammonium phosphate and potassium sulfate [PK], diammonium phosphate, urea, and potassium sulfate [NPK], no fertilizer [CK]) from 2015 to 2018 on the Loess Plateau. The organic carbon content was higher in organic fertilizer (M, MNP, MP, MN) than in inorganic fertilizer treatments (NP, NPK, NK, PK) and the control. Crop yield was higher for organic than for inorganic fertilizers, whereas that of the control was always lower than those in the fertilization treatments. The highest crop yield was obtained in MNP. Crop yield and soil organic matter quality score correlated positively, with correlation coefficients ranging from 0.5994 to 0.7151. Our results provide a theoretical basis for organic and inorganic fertilizer application in dry farming areas on the Loess Plateau and aid the long-term healthy development of soil in cultivated areas.

Keywords: *different fertilization treatments, dry land, farmland soils, SOC content, food crops*

Introduction

Increasing the content of organic carbon in soil is not only conducive to the development of agriculture but also plays a vital role in ecosystems globally (Blair et al., 2006). However, the overexploitation of farmland has caused a continuous decrease in the soil organic carbon (SOC) content and soil degradation, ultimately affecting the development of agriculture and challenging the sustainable use of soil (Adams et al., 2020; Akoto-Danso et al., 2019). Soil organic carbon is an important basis for soil fertility (Beza et al., 2016) and regulates physical, chemical, and biological processes in soil, and is a prerequisite for the sustainable utilization of land and high and stable crop yields (Arunrat et al., 2020; Bhatt et al., 2020; Bibi et al., 2019). In addition to being influenced by local climate and soil properties, the SOC content is determined by the fertilization method (Bista et al., 2019; Cai et al., 2016). Fertilization has become a common farmland management measure for improving crop yield, an important factor affecting the conversion rate and accumulation of SOC, and the primary factor in the evolution of soil fertility (Cenini et al., 2016; Van Groenigen et al., 2017). Fertilization mainly affects the organic carbon content and soil dynamics by increasing the bio-yield

of crops and the input of organic residues to the soil, as well as by affecting the number and activity of soil microorganisms and thereby the biodegradation of organic matter (Chen et al., 2015). The effect of fertilization on increasing SOC contents also depends on climatic conditions (Choudhary et al., 2019; Dong et al., 2015). A variety of fertilizers have been widely used in agricultural production to provide sufficient nutrients for plant growth and increase aboveground biomass production (Espinoza et al., 2017). Increased plant biomass, as an important source of SOC, increases the supply of soil carbon sources and the amount of organic carbon in soil (Frossard et al., 2016). Fertilizer application slowly changes the physical and chemical characteristics of the soil, affecting microbial and root activity in the soil and indirectly the SOC reservoir (Gao et al., 2015; Gelaw et al., 2015).

The rapid development of the fertilizer industry has decreased the dependence of agriculture on organic fertilizers, leading to a decreased amount of organic matter in farmland soils and an altered balance of SOC (Gwon et al., 2019). The application of fertilizer, especially when unbalanced, has a negative effect on the SOC content, the accumulation of SOC, as well as the content of SOC components (Han et al., 2020). The application of organic fertilizer has the opposite effect (He et al., 2015a). Organic fertilizer is rich in elements and organic nutrients needed for plant growth, meets the nutrient needs of different long-term crops, improves soil structure as well as physical and chemical properties, directly affects the level of the comprehensive soil fertility index, and renders crop yields stable and sustainable (He et al., 2015b). Increasing the application of organic fertilizer as a substitute for inorganic fertilizers is an effective way to solve problems related to the application of inorganic fertilizers (Horak et al., 2020). To this end, many studies have been carried out to elucidate changes in the SOC content after soil fertilization and the relationship between crop yield and the SOC content (Hwang et al., 2020). Li et al. (2015) and others found that the SOC content was significantly increased after long-term application of organic fertilizer and a combined application of organic and inorganic fertilizer. Liu et al. (2018) reported that long-term application of organic fertilizer was positively linearly correlated with the total organic carbon and nitrogen content of farmland. After entering the soil, organic fertilizer effectively improves soil physical and chemical characteristics in the tillage layer, and successfully regulates the content of soil nitrogen, phosphorus, and potassium, increasing the SOC content (Iqbal et al., 2019; Jalal et al., 2020). The large amount of carbon and nitrogen sources provided by organic fertilizer increase the microbial biomass, thus promoting root–microbial interactions (Kolbe et al., 2015).

The Loess Plateau region is a typical rain-fed agricultural area. For a long time, agricultural production was mainly focused on cultivation of food crops due to prevalent drought conditions and low precipitation, soil erosion and degradation, as well as wind and sand hazards. The SOC content is only approximately 1%, rarely reaching 1.5%. In the past 20 years, with the increase in the farmers' investment in land, the input of inorganic fertilizers has increased, neglecting the use of organic fertilizer, a practice that has resulted in reduced soil quality. Therefore, the effect of fertilization on crop yield and SOC in the Loess Plateau needs to be studied to develop a sustainable agriculture, improve the quality of cultivated land, increase agricultural production and income, and reduce greenhouse gas emissions. Several studies have been conducted to assess the impact of the combined use of inorganic fertilizers and organic materials on crop yield and soil nutrients. However, such research has hardly been conducted in the Loess Plateau region. Therefore, the purpose of this study was to assess the stability and

sustainability of increasing SOC and crop yield using long-term experiments. We show that the use of only organic fertilizer or a combination of inorganic and organic fertilizers increases the SOC content and ultimately increases crop yield.

Materials and methods

Study sites

The field experiment was conducted in 2015 and 2018 at a study site located in the middle of the Loess Plateau (36°51'N, 109°18'E). The site is located 1068 m above sea level (*Fig. 1*); it has a mean annual temperature of 8.8 °C and an annual precipitation level of 500.0 mm in the last 10 years. The recorded annual precipitation was 381.2 mm in 2015 and 492.1 mm in 2016. The recorded annual precipitation was 557.6 mm in 2017 and 536.3 mm in 2018. The precipitation during the growth period (between March and September) was 240.5 mm in 2015, accounting for 63% of the total annual precipitation, 417.9 mm in 2016, accounting for 79.47% of the total annual precipitation, 443.1 mm in 2017, accounting for 79.47% of the total annual precipitation; and 503.1 mm in 2018, accounting for 93.8% of the total annual precipitation 2018 (*Table 1*). The soil type in the study site was loess soil; basic soil physical and chemical properties were measured at the depth of 0–20 cm before fertilization (*Table 2*).



Figure 1. Test field

Table 1. Precipitation in the study area from 2015 to 2018 (mm)

Year	Annual precipitation	Growth period precipitation
2015	381.2 mm	240.5 mm
2016	492.1 mm	417.9 mm
2017	557.6 mm	443.1 mm
2018	536.3 mm	503.1 mm
Average precipitation in the last 10 years	500.0 mm	427.2 mm

Table 2. Basic physical and chemical properties of the soil before fertilization

Soil depth (cm)	Bulk density	SOM	TN	TP	pH
20 cm	1.387	8.053	0.382	0.588	8.42

SOM, soil organic matter. TN, soil total nitrogen. TP, soil total phosphorus, all in ($\text{g}\cdot\text{kg}^{-1}$)

Experimental design

Organic and inorganic fertilizers were used. The nitrogen fertilizers (N) were urea and diammonium phosphate, the phosphate fertilizer (P) was diammonium phosphate, the potassium fertilizer (K) was potassium chloride, and the organic fertilizer (M) was sheep manure. Organic fertilizer treatments were the following: M, MN, MP, and MNP. Inorganic fertilizer treatments were NP, NK, PK, and NPK. In addition, a no-fertilizer treatment was used as the control (CK). The fertilizers were spread evenly on the soil surface before sowing. The nine fertilization practices are shown in *Table 3*.

Table 3. Experimental fertilization levels

Treatment	Illustration
M	Sheep manure (0.75 kg/m^2)
MN	Sheep manure (0.75 kg/m^2) + Urea 0.021 kg/m^2
MP	Sheep manure (0.75 kg/m^2) + Diammonium phosphate (0.017 kg/m^2)
MNP	Sheep manure (0.75 kg/m^2) + Urea (0.021 kg/m^2) + Diammonium phosphate (0.017 kg/m^2)
NP	Urea 0.021 kg/m^2 + Diammonium phosphate (0.017 kg/m^2)
NK	Urea (0.021 kg/m^2) + Potassium sulfate (0.012 kg/m^2)
PK	Diammonium phosphate (0.017 kg/m^2) + Potassium sulfate (0.012 kg/m^2)
NPK	Diammonium phosphate (0.017 kg/m^2) + Urea (0.021 kg/m^2) + Potassium sulfate (0.012 kg/m^2)
CK	No fertilizer

Local heat and moisture conditions dictate that crops are only grown once a year. Millet was planted in 2015, and the millet cultivar was Changsheng 7. Broomcorn millet was planted in 2016, and the broomcorn millet cultivar was BaiRuanmei. Millet was planted in 2017, and the millet cultivar was Changsheng 7. Soybeans were planted in 2018, and the soybean variety planted was Zhonghuang 35. Each of the nine treatments contained 4 plots, yielding a total of 36 plots. Each plot was 3.5 m long and 8.57 m wide (plot area of 30 m^2). The soil fertility and environmental conditions in all plots were uniform. Organic fertilizer, potash fertilizer, and phosphate fertilizer were each applied once, urea fertilizer was applied at a rate of 136 g per plot, and the remaining 500 g of nitrogen fertilizer were applied during the flowering period. The millet was fertilized with urea on April 24th, 2015, and supplementary nitrogen fertilizer was added on July 1st. The broomcorn millet was fertilized with urea on April 26th, 2016, and supplementary nitrogen fertilizer was added on July 16th. The millet was fertilized with urea on April 27th, 2017, and supplementary nitrogen fertilizer was added on July 3rd. Urea fertilizer was added to soybeans on April 28th, 2018, and supplementary nitrogen fertilizer was added on July 26th. The experimental design of the different fertilization experiments is shown in *Table 4*.

Table 4. Experimental design of the different fertilization experiments

Experimental plots								
1 MN	2 M	3 NPK	4 PK	5 NK	6 NP	7 CK	8 MNP	9 MP
10 MP	11 MN	12 PK	13 NK	14 CK	15 NPK	16 NK	17 M	18 MNP
19 MNP	20 MP	21 CK	22 NK	23 NP	24 PK	25 NPK	26 MN	27 M
28 M	29 MNP	30 NP	31 CK	32 NPK	33 NK	34 PK	35 MP	36 MN

M, organic fertilizer; MN, organic fertilizer combined with nitrogen fertilizer; MP, organic fertilizer combined with phosphate fertilizer; MNP, organic fertilizer combined with nitrogen and phosphate fertilizer; NP, nitrogen fertilizer combined with phosphate fertilizer; NK, nitrogen fertilizer combined with potassium fertilizer; PK, phosphorus combined with potassium fertilizer; NPK, nitrogen combined with phosphate and potassium fertilizer; CK, no-fertilizer control. Consecutive integers (1, 2... 27) indicate the plot number

Soil sampling and crop harvesting

Soil sample collection method: taking each plot as a unit, the soil sampling point was more than 1 m away from the boundary of the sample plot. Sampling points were randomly selected with an S shape. Surface debris was then removed and soil samples were collected. All soil samples from the same sampling point were combined and then passed through a 2-mm sieve. Samples were stored and labelled after the relevant sampling information had been recorded. The soil samples were transported to the laboratory, air-dried naturally, plant roots and other impurities removed, and the SOM content measured. SOM was analyzed using the dichromate oxidation method. The 2015 millet was harvested on October 10th. The 2016 broomcorn millet was harvested on October 4th. The 2017 millet was harvested on October 12th. The 2018 soybean crop was harvested on October 4th. In 2017, SOM was measured on October 12th. In 2016, SOM was measured on October 6th. In 2017, SOM was measured on October 13th. In 2018, SOM was measured on October 5th. At the end of the growing season, three quadrats (1 m × 1 m) were harvested in each plot by cutting at the soil surface level; the harvested plants were dried in an oven (75 °C, 24 h), weighed, and the value was converted to plot yield. The final crop yield was obtained by harvesting four replicates of each treatment.

Calculations and statistics

The productivity of the cropping system was determined using the sustainable yield index. The sustainable yield index (SYI) developed by Singh was used for assessment (Zhou et al., 2019):

$$SYI = \bar{Y} - \sigma_{n-1}/Y_{max}$$

where $\bar{Y}$ is the mean yield, σ_{n-1} is the standard deviation, and Y_{max} is the maximum yield data obtained from the treatment in any year.

One-way ANOVA was used to examine the effects of fertilization treatment on SOC, crop yield, and the sustainable yield index (SYI; $P < 0.05$). Before the analysis, we

performed a normality and homogeneity test of the data. Linear regression analysis was used to show the relationship between crop yield and SOC. All statistical analyses were performed using the software package IBM SPSS Statistics (version 26.0). The differences between the treatments were calculated using the least significance difference test at a 0.05 probability level. Figures were prepared using Origin 9.0.

Results

Soil organic carbon

To evaluate the impact of various fertilization treatments on crop yield, we analyzed the effects of MP, MN, PK, NP, CK, NPK, NK, and MMNP fertilization. We studied the effects of long-term application of inorganic fertilizers (N, P), organic fertilizer, and combined application of inorganic and organic fertilizers on SOC dynamics. The variation trend of SOC in different treatments was similar over time. The increase in soil SOC by organic fertilizer treatment, especially in combination with inorganic fertilizer, was significant in comparison to that observed by inorganic fertilizer treatment and no fertilizer application ($P < 0.05$).

Overall, higher SOC contents were recorded after fertilization. In 2015, the SOC content of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was greater by 80%, 78%, 85%, 94%, 18%, 13%, 9%, and 16% compared with the CK treatment, respectively. In 2016, the SOC content of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was higher than that of the CK plots by 77%, 80%, 82%, 83%, 23%, 12%, 5%, and 22%, respectively. In 2017, the SOC content of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was greater by 74%, 90%, 91%, 93%, 17%, 8%, 4%, and 17% compared with the CK treatment, respectively. In 2018, the SOC content of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was higher than that of the CK plots by 74%, 86%, 86%, 101%, 25%, 4%, 1%, and 22%, respectively (Fig. 2).

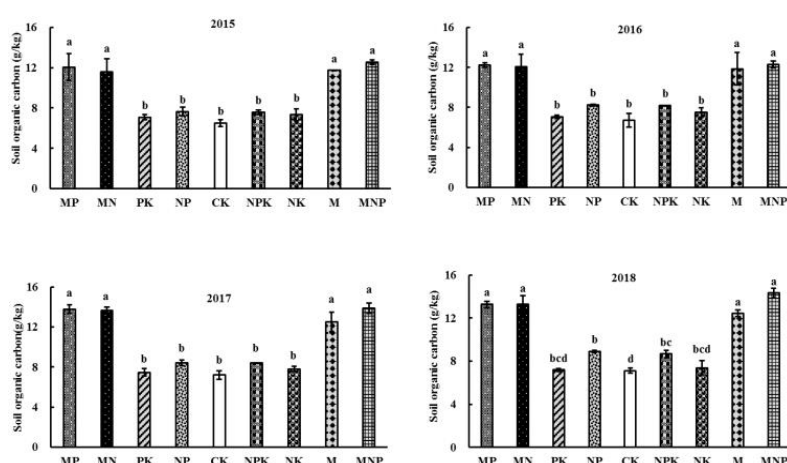


Figure 2. Soil organic carbon content (mean $\pm$ standard error) at different fertilization from 2015 to 2018. Note: Values in the same column and the same year followed by different letters indicate significant differences (Duncan $P < 0.05$). The error bar is the standard deviation. M, organic fertilizer; MN, organic fertilizer combined with nitrogen fertilizer; MP, organic fertilizer combined with phosphate fertilizer; MNP, organic fertilizer combined with nitrogen and phosphate fertilizer; NP, nitrogen fertilizer combined with phosphate fertilizer; NK, nitrogen fertilizer combined with potassium fertilizer; PK, phosphorus combined with potassium fertilizer; NPK, nitrogen combined with phosphate and potassium fertilizer

Crop yield

The average yield for the period 2015–2018 was used to evaluate the long-term effects of different fertilization practices. Organic fertilizer treatments increased crop yield significantly more than inorganic fertilizer and no fertilizer treatments ($P < 0.05$). Overall, higher crop yield was recorded after fertilization. In 2015, the crop yield of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was greater by 22%, 2%, 25%, 81%, 1%, 48%, 42%, and 42% compared with the CK treatment, respectively. In 2016, the crop yield of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was higher than that of the CK plots by 279%, 316%, 198%, 337%, 271%, 28%, 28%, and 177%, respectively. In 2017, the crop yield of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was greater by 266%, 317%, 121%, 320%, 295%, 177%, 101%, and 205% compared with the CK treatment, respectively. In 2018, the crop yield of the M, MN, MP, MNP, NP, NK, PK, and NPK plots was higher than that of the CK plots by 118%, 171%, 189%, 239%, 119%, 120%, 146%, and 165%, respectively (Fig. 3).

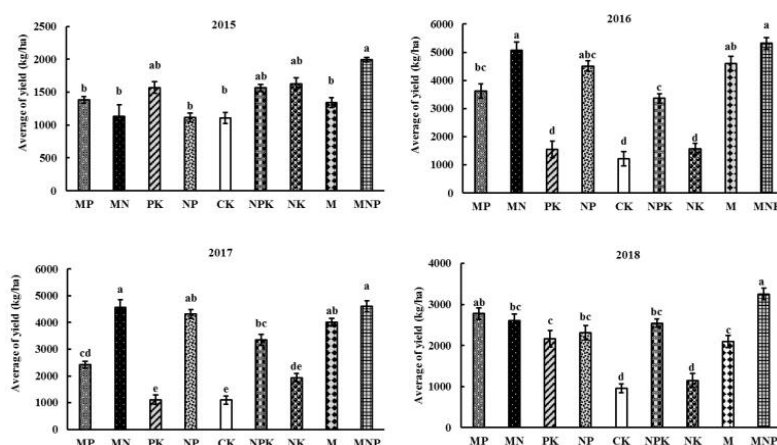


Figure 3. Average yield (mean $\pm$ standard error) at different fertilization treatments in 2015, 2016, 2017, and 2018. Note: Values in the same column and the same year followed by different letters indicate significant differences (Duncan $P < 0.05$). The error bar is the standard deviation. M, organic fertilizer; MN, organic fertilizer combined with nitrogen fertilizer; MP, organic fertilizer combined with phosphate fertilizer; MNP, organic fertilizer combined with nitrogen and phosphate fertilizer; NP, nitrogen fertilizer combined with phosphate fertilizer; NK, nitrogen fertilizer combined with potassium fertilizer; PK, phosphorus combined with potassium fertilizer; NPK, nitrogen combined with phosphate and potassium fertilizer; CK, no-fertilizer control

Correlation among different parameters and SYI

Using Pearson correlation analysis (Fig. 4), we found a significant correlation between crop yield and SOC in 2015, 2016, 2017, and 2018 ($P < 0.05$). The SYI value for the for yield in organic fertilizer treatments was greater than that in the other treatments, indicating that application of organic fertilizer increases crop yield as compared to the other fertilization treatments (Table 5). The SYI value was the highest in the MNP treatment, while the lowest SYI value was in the CK treatment. The SYI values in the other organic fertilizer treatments (MP, MN, M) were similar to that of the MNP treatment. These results indicate that organic fertilizer has the potential to maintain a sustainable crop yield.

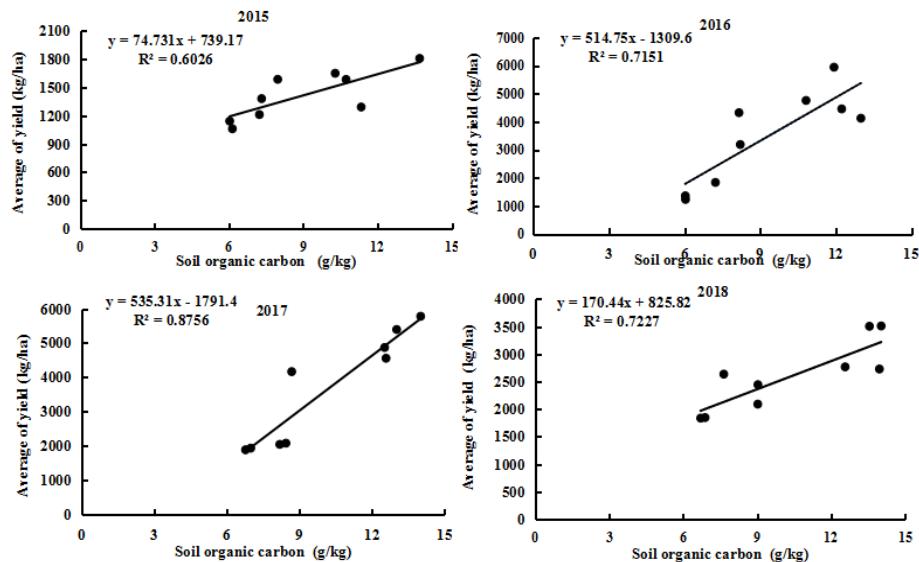


Figure 4. Correlation of SOC and crop yields in 2015, 2016, 2017, and 2018. Note: Values in the same column and the same year followed by different letters indicate significant differences (Duncan $P < 0.05$). M, organic fertilizer; MN, organic fertilizer combined with nitrogen fertilizer; MP, organic fertilizer combined with phosphate fertilizer; MNP, organic fertilizer combined with nitrogen and phosphate fertilizer; NP, nitrogen fertilizer combined with phosphate fertilizer; NK, nitrogen fertilizer combined with potassium fertilizer; PK, phosphorus combined with potassium fertilizer; NPK, nitrogen combined with phosphate and potassium fertilizer; CK, no-fertilizer control

Table 5. Sustainable yield index (SYI) values for the four years of growing influenced by different fertilization treatments

Years	MP	MN	PK	NP	CK	NPK	NK	M	MNP
SYI ₂₀₁₅	0.60ab	0.62a	0.49b	0.48b	0.30c	0.50b	0.50b	0.57ab	0.69a
SYI ₂₀₁₆	0.57ab	0.61a	0.47b	0.47b	0.31c	0.48b	0.49b	0.54ab	0.67a
SYI ₂₀₁₇	0.58ab	0.61a	0.46b	0.45b	0.29c	0.51b	0.48b	0.55ab	0.68a
SYI ₂₀₁₈	0.59ab	0.60a	0.51b	0.49b	0.30c	0.48b	0.48b	0.58ab	0.70a

Values in the same column and the same year followed by different letters indicate significant differences (Duncan $P < 0.05$)

Discussion

Organic fertilizers significantly increased the SOC content and crop yield compared with non-organic fertilizers and no fertilizer application. Different fertilization models significantly increased the SOC content. Their application increased crop growth, which in turn increased the amount of crop residues. As crop residues are decomposed, they are converted into organic carbon, thereby increasing the SOC content (Zhao et al., 2019; Jalal et al., 2020). The applied inorganic fertilizers were not as effective as the organic fertilizers in increasing the SOC content, mainly because inorganic fertilizer application increased the activity of soil microorganisms and thus the consumption of SOC (Zanatta et al., 2019). The total organic carbon reservoir in the soil originated from decomposition in the soil (Yu et al., 2020; Yang et al., 2019). Consequently, SOC

accumulation was greater than its consumption. The application of inorganic fertilizer increased the SOC content, although the increase was lower than in the soil amended with organic fertilizers. These results were consistent with those of other studies (Yusuf et al., 2015).

The organic carbon content of the soil amended with organic fertilizer was greater than that of the soil treated with inorganic fertilizers and the control. The SOC accumulation rate in the NPK, NK, and PK treatments during the four years of crop rotation was small because of the relatively small rate of organic carbon formation, which is mainly due to plant residues, root residues, and root secretions. There was no input of exogenous organic carbon. In the present study, the crop yield in the CK treatment was significantly lower than that in the treatments with fertilizers, confirming that fertilization affected the crop yield. The highest crop yield obtained in the MNP treatment is attributed to N and P, which were directly supplemented to the soil, while mineral fertilizer regulates the release intensity and rate of inorganic nutrients in the soil. The crop thus has a continuous access to nutrients, the nutrient demands are met at all stages of plant growth, and consequently crop yield is improved (Yan et al., 2020; Yadav et al., 2020). Besides the application of organic fertilizers, decomposition in soil is another process that produces organic acids, promotes soil nutrient cycling, improves soil efficiency, and increases crop yield, which has been reported in various other studies (Xu et al., 2015, 2020; Wild et al., 2017).

We observed a positive correlation ($P < 0.05$) among SOC, crop, and crop yield in all growing seasons. The results indicated that crop yield increased with increasing SOC. There was a significant difference in crop yield and the SYI under different long-term fertilization protocols. The highest SYI was obtained after application of organic fertilizer, it was lower in treatments with inorganic fertilizers, and the lowest in the control. Mineral nutrients provided by inorganic fertilizers were immediately released into the soil and absorbed and utilized by the crops (Wang et al., 2015, 2020); therefore, soil fertility was short-lived and the SYI was low. Only a tiny fraction of mineral nutrients was immediately released from organic manure, and most of the nutrients were released slowly; the process was longer and thus could meet the nutrient demand of the crops throughout the whole season (Villamil et al., 2015). This reduces the reliance on chemical fertilizers, maintains the stability and sustainability of crop production, and preserves a high SYI.

Conclusions

Long-term fertilization can significantly improve the SOC content. The SOC content in treatments with organic fertilizers was higher than that in treatments with inorganic fertilizers and in the control. Application of organic fertilizer accelerated the accumulation of SOC, nitrogen, and other nutrients as compared to the application of inorganic fertilizer or no fertilizer application. Long-term fertilization also significantly improved crop yield. The highest crop yield was obtained with MNP fertilization, indicating that organic fertilizer combined with N and P fertilizer can effectively improve crop yields by directly supplementing soil nutrients while regulating the release of nutrients to meet the needs of the crops. The crop yield dependence on fertilizer is thus reduced. The combination of organic and inorganic fertilizers in the soil of the dry farming area on the Loess Plateau can promote the long-term healthy development of soil in this cultivated area.

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Conflict of interests. The authors declare no conflict of interests.

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