SYNERGISTIC EFFECT OF FERTILIZATION ON INTERANNUAL VARIATION OF SOIL CARBON AND NITROGEN CONTENTS AND SOYBEAN YIELD IN SEMIARID SOIL

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Abstract. The effects of long-term fertilization on soil organic carbon (SOC), total nitrogen (TN), and soybean yield stability were studied in semiarid areas of China for optimizing soil fertilization and obtaining stable and efficient soybean yield. SOC, TN, and soybean yields in different soil layers were measured after performing nine fertilization treatments for 5 consecutive years. The results showed that CK treatment (1,264.2 kg·hm^{-2}) was significantly lower than other treatments. Under the combination of organic and inorganic treatments, the interannual variation of soybean yield under treatment with organic fertilizer combined with nitrogen and phosphate fertilizer was smaller, while the stability and sustainability indices were higher. The organic carbon and TN contents in surface soil (0–20 cm) showed an increasing trend with different fertilization. There was a significant positive linear correlation between SOC and TN contents in topsoil (0–20 cm) ($P < 0.01$; correlation coefficient = 0.947**). The yield of soybean increased with the increase of SOC and TN contents in topsoil (0–20 cm), with a significant positive correlation between them ($P < 0.05$). The yield of soybean increased with the increase of SOC and TN contents in surface soil (20–40 cm), although no significant positive correlation between SOC and TN contents was observed.
Keywords: *semiarid district, fertilization, sustainable yield index, organic fertilizer, chemical fertilizer*

Introduction

Carbon and nitrogen are the basic elements that constitute the macromolecular matter of an organism (Betson et al., 2007; Kim, 2015). Changes in carbon and nitrogen input in the ecosystem can affect carbon accumulation, distribution, and cycling process in the soil-plant system (Hu et al., 2018). With the continuous global attention to greenhouse gas emission reduction, the importance of soil carbon and nitrogen cycle research has become increasingly prominent (Gu et al., 2020). Soil organic carbon (SOC) and total nitrogen (TN), as important parts of soil nutrients, not only are the main sources of essential nutrients, but also important components of soil carbon and nitrogen library; the extent of these reserves affecting the stability and sustainability of ecosystems can affect the global ecological system in terms of atmospheric carbon dioxide concentration and carbon and nitrogen cycle (Inubushi et al., 2020). SOC stores the largest SOC pool in the surface terrestrial ecosystem. Small changes in SOC and nitrogen stocks will have a profound impact on atmospheric greenhouse gas concentrations and global carbon and nitrogen cycle (Jovovic et al., 2021). Therefore, the study of the effects of fertilization on high and stable crop yield and soil carbon and nitrogen and their synergistic effects is important for food security and addressing

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climate change (Kennedy and Schillinger, 2006). Soil nitrogen is the most important limiting factor in agricultural production (Adjuik et al., 2020). Crop yield can be enhanced using nitrogen fertilizers (Adhikari et al., 2015). At present, China's average nitrogen application rate is more than 200 kg·hm^{-2}, far higher than the global average (Chen et al., 2021). The nitrogen loss of fertilizer is a major challenge in agricultural non-point source pollution causing the eutrophication of water bodies, accumulation of groundwater nitrate, and generation of greenhouse gas (Chu et al., 2015).

Soil carbon and nitrogen storage is affected by human activities such as land use, tillage, and fertilization, among which the effect of fertilization on soil carbon and nitrogen storage has been one hot research topic (Doran et al., 1998). SOC and TN are the most important indicators of soil fertility, among which SOC is essential for soil nutrient transformation, and its storage reflects the ability of soil to trap carbon, while the content of SOC directly affects the maintenance and improvement of soil fertility (El-Sherbeny et al., 2022). SOC is an important factor for the sustainable development of crop production; organic carbon reduction is the main factor limiting crop yield as it regulates soil's physical, chemical, and biological process (Bauer and von Wiren, 2020). Maintaining higher levels of SOC (in terms of quality and quantity), as well as sustainable use of land and crops is a prerequisite for high and stable yield (Cao et al., 2022).

Fertilizer is one of the most basic factors affecting crop yield (Feng et al., 2021). However, excessive use of fertilizer will not only reduce the quality of crops, but also have a serious impact on soil, environment, and water resources (Gashu et al., 2020). Therefore, appropriate fertilization is important for increasing agricultural production (Gowda et al., 2022). The effect of chemical and organic fertilizers on crop yield and soil fertility has been a topic of debate (Velechovsky et al., 2021). Long-term localized fertilization experiments have the characteristics of long duration and repeatability of climate, which can systematically reveal the evolution law of soil fertility and change in crop yield and provide a theoretical basis for the evaluation of the rationality of fertilization system (Wang et al., 2022). A large number of studies have been conducted on the effects of organic and chemical fertilizers on crop yield and soil nutrients (Zhang et al., 2021). Long-term application of organic fertilizers could significantly increase the content of SOC and available nutrients, with a better effect than chemical fertilizers (Zhao et al., 2021). Under the condition of using the same amount of nutrients, the yield increase effect of organic fertilizers was not as good as that of chemical fertilizers in the current season, but from the perspective of long-term yield increasing effect, the yield increasing effect of organic fertilizers was not inferior to, and even exceeded, that of chemical fertilizers (Zhu et al., 2021). Studies have shown that long-term fertilization, with nitrogen combined with phosphate and potassium fertilizer (NPK), or with organic combined with inorganic fertilizers can increase the SOC total content; the effect of organic fertilizers and NPK can also improve the soil nutrient content (Hu et al., 2018). Organic fertilizers have a better effect on soil fertility than chemical fertilizers, and organic manure treatment with a high fertilizer rate can improve the soil nutrient profile since the biological organic fertilizer in the soil has a higher net residual, increases the TN content in soil (Semenov et al., 2020). In terms of increasing production, previous research has shown that under the condition of the same amount of nutrients, the effect of organic fertilizers on increasing production is not as good as that of chemical fertilizers (Shao et al., 2021). Therefore, the effects of organic and chemical fertilizers

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on soil fertility evolution and crop yield can be assessed through long-term fertilization studies (Shen et al., 2021).

The total arable land area of the Loess Plateau is 16.91 million hm^2. Agricultural production is mainly based on planting industry, especially food crops. Due to drought, soil erosion, and wind and sand damage, soil quality has significantly degraded and the organic carbon content has decreased. Especially over the past 20 years, with the increase of farmers' investment in land, farmers pay more attention to the input of chemical fertilizer and ignore the input of organic fertilizer, which creates several challenges for soil quality. Therefore, understanding the relationship between fertilization, crop yield, and soil carbon and nitrogen is of great significance for sustainable development of agriculture, improvement of cultivated land quality, increase of agricultural production, and reduction of greenhouse gases in the Loess Plateau.

Materials and methods

Study sites

The field experiment was conducted from 2014 to 2018 at a study site located in the middle of the Loess Plateau (36°51′N, 109°18′E) (*Fig. 1*). The site is located 1,068 m above sea level and 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 423.6 mm in 2014,381.2 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 (*Table 1*) (Shen et al., 2021). The soil type at 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*).

Table 1. *Meteorological data for each year*

Years	Annual precipitation
2014	423.6 mm
2015	381.2 mm
2016	492.1 mm
2017	557.6 mm
2018	536.3 mm

Table 2. *Basic physical and chemical properties of the soil of the 0–20-cm soil layers*

Soil depth (cm)	Organic carbon	TN	TP	TK	pH
20	8.27	0.38	0.59	17.55	8.3

SOC, soil organic carbon; TN, soil total nitrogen; TP, soil total phosphorus; TK, soil total potassium; all in ($g\cdot kg^{-1}$)

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 winter 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-

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fertilizer treatment was used as the control (CK). The fertilizers were spread evenly on the soil surface before sowing. Nine fertilization practices are shown in *Table 3*.

Figure 1. *The locations of study sites in Ansai County, Shannxi Province, China*

Table 3. *Experimental fertilization and 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. The experiment of planting soybean started in 2014 and ended in 2018. The soybean variety planted in ‘Zhonghuang 35’ was planted by the double row equidistant planting method, with a sowing amount of 3.5 kg·hm^{-2}. Overall, 450 soybean seedlings were planted in each district, 10 rows in each district, 45 plants in each row, row spacing of 35 cm with plant spacing of 19 cm. The soybean sowing rate in kernel was 45 kg ha^{-1}. The split plot design was adopted in the experiment, which was a rectangular plot with a total area of 2,000 m^2 divided into 4 block groups, each of which consisted of 9 plots (with a total of 36 plots, *Table 4*). The plots were rectangular (3.5 × 8.57 m). Nine different fertilization treatments were used in the experiment, and each treatment was repeated four times. The nutrient content of the manure was 24.36 g·kg^{-1} organic carbon, 11.24 g·kg^{-1} TN, 17.43 g·kg^{-1} total phosphorus, and g·kg^{-1}. The nitrogen fertilizer applied was urea, with 46% nitrogen content, at 212 kg·hm^{-2}. The phosphorus fertilizer applied was superphosphate, with 44% P_2O_5, at 170 kg·hm^{-2}. The potassium fertilizer applied was potassium sulfate, with 50% P_2SO_4, at 120 kg·hm^{-2} per plot.

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Before sowing crops in spring, fertilizers were evenly applied to the surface of the soil and plowed to the upper 20 cm of soil. Organic, phosphorus, and potassium fertilizers were applied as base fertilizers at one time, 20% of nitrogen fertilizer was applied as base fertilizer at one time, and the remaining 80% of nitrogen fertilizer was applied at the soybean jointing stage. *Table 5* lists the specific field test time.

Table 4. *Experimental design of the different fertilization experiment in Ansai*

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

Table 5. *The specific field test time*

Years	**Fertilize**	**Sow**	**Topdressing fertilizer**	**Crop harvesting**	**Soil sample collection**
2014	April 15	April 17	July 2	October 5	October 11
2015	May 5	May 7	July 9	October 8	October 15
2016	May 6	May 7	July13	October 13	October 18
2017	April 15	April 17	July 10	October 8	October 14
2018	April 24	April 28	July 26	October 11	October 16

Soil sampling and crop harvesting

Soil samples were collected 1 week after crop harvest from 36 plots using manual soil drill (undisturbed soil drill, inner diameter 2.64 cm, Model YZ-1, Yakai Technology Company, Cangzhou, China). Soil was collected from 36 plots, and the distribution of sampling points was in the shape of “S.” Seven sample points were collected from each plot with sampling depth of 0–20 cm and 20–40 cm, respectively and were mixed into one sample at the same depth. Some of the samples were dried and weighed at 105 °C, and the soil bulk density was calculated according to the drying soil weight, the inner diameter of the soil drill and the sampling depth. The remaining samples were air-dried, ground, and passed through a 100-mesh sieve for the determination of SOC and TN with an elemental analyzer (Flash EA 1112, Thermofinnigan, Italy).

After the crops were mature, six rows in the middle of each plot were taken for sampling, one group in every two rows, and a total of three sampling groups were

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distributed diagonally. The measured length of two rows of soybeans in each group was 3 m, and the measured end point in the former group was vertically separated from the measured starting point in the latter group by 3 m. The soybean in the sampling area was harvested artificially, and all sampled soybean seeds were first degreed at 105 °C, dried to a constant weight at 70–80 °C to obtain the water content of the seeds, which then was normalized to 14%. The soybean yield in each plot under different fertilization treatments was calculated. After the crop was harvested, straw was collected from the field and transported to the laboratory.

Calculations and statistics

SOC and TN reserves in the 0–20-cm and 20–40-cm soil layers were selected to study soil fertility after fertilization. The calculation method of SOC and TN storage is as follows:

$$SOC_{stock} = \mathrm{H_i} \times \mathrm{BD_i} \times D_i / 10 \quad \text{(Eq.1)}$$

$$TN_{stock} = \mathrm{P_i} \times \mathrm{BD_i} \times D_i / 10 \quad \text{(Eq.2)}$$

where Hi ($g \cdot kg^{-1}$) is the SOC content in different soil layers, Pi ($g \cdot kg^{-1}$) is the soil total N content of the layer of soil ($g \cdot kg^{-1}$), BD_i ($g \cdot cm^{-3}$) is the soil bulk density in different soil layers, and Di is the depth of the soil layer (cm)

Higher stability is commonly presented by lower variability with low *SI*. The *SI* is calculated as:

$$SI = \frac{Y_{std}}{Y_m} \times 100\% \quad \text{(Eq.3)}$$

where Y_{std} is the standard deviation of the grain yield (average of four experimental sites) of a particular treatment during the simulation period, and Y_m is the mean yield (average of four experimental sites) for the treatment over the same predicted period. The productivity of the cropping system was determined using the sustainable yield index (*SYI*). The *SYI* developed by Singh was used for assessment:

$$I_{SYI} = (\overline{Y} - \sigma_{n-1})/Y_{max} \quad \text{(Eq.4)}$$

where $\overline{Y}$ 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.

The contribution rate of fertilizer to crop yield was calculated as follows = (yield of a fertilization treatment quantity-yield of no fertilization treatment)/yield of a fertilization treatment × 100%.

Results

Effects of long-term fertilization on yield variation, stability and sustainability of soybean, and contribution rate of fertilizer

Under long-term fertilization, the crop yield varied greatly from year to year and showed an overall upward trend. CK treatment had the lowest average crop yield, which was 1,264.2 $kg \cdot hm^{-2}$, while the 5-year mean yields of MP, MN, PK, NP, NPK, NK, M

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and MNP treatments were 4174, 3,626, 3,247, 3,137, 3,561, 1,965, 3,550, and 4,218 kg·hm^{-2}, respectively. MNP treatment had the most significant increase in crop yield, followed by MP treatment. Compared with the soybean yield of 2014, the yield with CK treatment in 2018 decreased by 14.69% on average, while the yield with fertilizer treatment increased by 55–233% on average.

Compared with CK treatment, different fertilization treatments significantly improved soybean yield. Taking CK as the control, in 2014, the yield with MP, MN, PK, NP, NPK, NK, M, and MNP treatments increased by 163%, 131%, 113%, 94%, 142%, 17%, 137% and 174%, respectively; in 2015, the yield with MP, MN, PK, NP, NPK, NK, M, and MNP treatments increased by 237%, 185%, 153%, 154%, 186%, 62%, 182%, and 227%, respectively. In 2016, the yield with MP, MN, PK, NP, NPK, NK, M, and MNP treatments increased by 245%, 200%, 162%, 159%, 189%, 65%, 193%. and 249%, respectively, using CK as the control. In 2017, the yield with MP, MN, PK, NP, NPK, NK, M, and MNP treatments increased by 254%, 201%, 179%, 175%, 196%, 65%, 197%, and 259%, respectively, using CK as the control. In 2018, the yield with MP, MN, PK, NP, NPK, NK, M, and MNP treatments increased by 261%, 225%, 183%, 167%, 201%, 73%, 202%, and 269%, respectively, using CK as the control (*Fig. 2*).

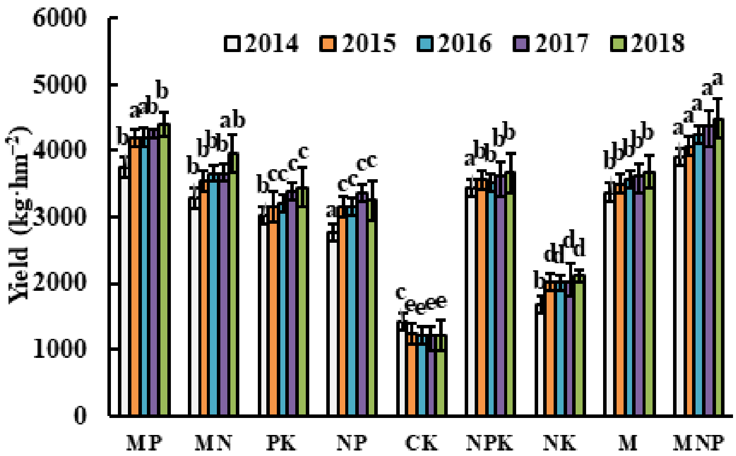

Figure 2. *Soybean yield under different fertilization treatments from 2014 to 2018. The bars with the same letter for the same year indicate no significant differences. Error bars are standard errors of the means. Lowercase letters represent significant differences within groups at P < 0.05*

The stability index (*SI*) was used to evaluate the yield stability of each treatment. The smaller the SI value, the higher the stability, and vice versa (*Fig. 3a*). The order of the *SI* value of different treatments was CK > NP > PK > NK > M > NPK > MN > MP > MNP; compared with chemical fertilizer treatment, organic fertilizer treatment increased the SOC content rapidly, and the yield increasing effect was significantly higher than that of chemical fertilizers, which made the soybean yield obtain high stability. The *SYI* is a parameter to determine whether the system can be sustained. The higher the *SYI* value, the better the system sustainability is. The *SYI* value of MNP treatment was the highest, while that of CK treatment was the lowest. The order of yield sustainability is MNP > MP = MN > M > NPK > NP > PK > NK > CK; the sustainability of organic fertilizer treatment was higher than that of chemical fertilizer treatment and no fertilizer treatment. The relationship between coordinated high yield,

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stable yield, and sustainability of crops under different fertilization treatments was analyzed, and four quadrants were divided by the average yield *SI* and sustainability index of crops under different fertilization treatments (*Fig. 3b*). The results showed that MNP-treated crops could maintain high yield stability and sustainability while obtaining high yield. CK- and NK-treated crops showed low yields and low yield stability and sustainability.

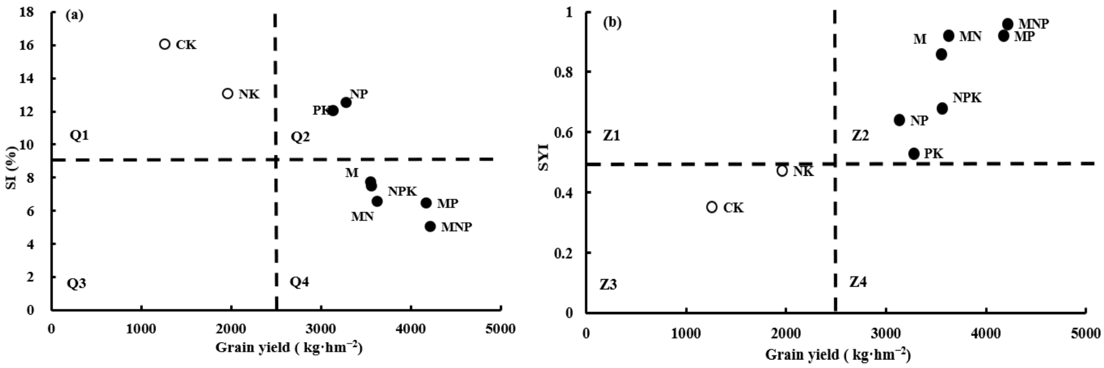

Figure 3. *Response relationship between soybean yield and stability (SI) index and sustainability yield index (SYI) under different fertilization treatments*

The yield of PK and NP treatments was higher, although the yield stability and sustainability were lower. The yield with MP, M, and MN treatments was higher and stable. Compared with no fertilization and chemical fertilizer application, NPK improved crop yield and ensured higher yield sustainability and stability. The contribution rate of fertilizer to crop yield fluctuated between different years, and on the whole, first increasing then remaining stable with fertilization years (*Fig. 4*).

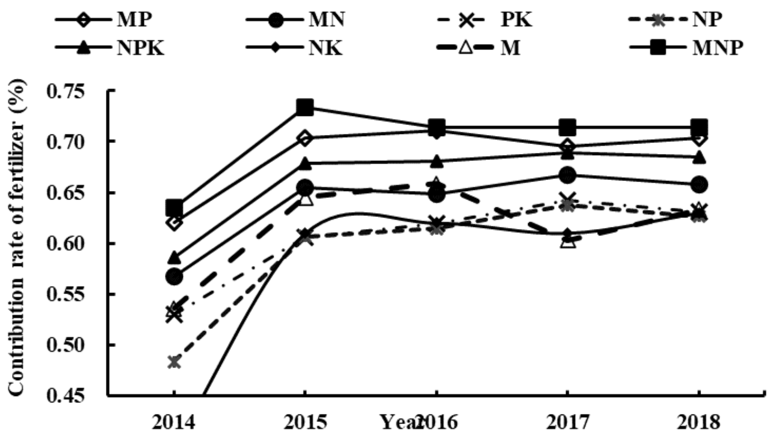

Figure 4. *Variations of the contribution rate of fertilizers with experimental years*

In the first year, the contribution rate of fertilizer fluctuated greatly, which may be caused by the instability of the yield in the early stage of the experiment. In the subsequent 4 years, the contribution rate of fertilizer fluctuated slightly and tended to be stable, at approximately 50%. The inflection points of each treatment equation appeared after 2014, that is, the dependence of soybean grain yield on fertilizer gradually

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increased with years. Different fertilization treatments had different contribution rates to crop yield. The average contribution rates were as follows: MNP (70%) > MP (69%) > NPK (66%) > MN (64%) > M (62%) > PK (61%) > NP (59%) > NK (57%).

Long-term change of SOC content under different fertilization methods

Compared with the SOC content under CK treatment, the change trends of surface SOC content (0–20 cm) under different fertilization treatments were different (*Fig. 5a*). After years of cultivation for CK treatment, the organic carbon content of surface soil (0–20 cm) increased from 4.97 $g \cdot kg^{-1}$ in 2014 to 7.11 $g \cdot kg^{-1}$ in 2018, with an annual average of 5.62 $g \cdot kg^{-1}$. The organic carbon content with M, MN, MP, and MNP treatments showed an overall increasing trend. The annual average values with M, MN, MP, and MNP treatments were 11.03 $g \cdot kg^{-1}$, 10.74 $g \cdot kg^{-1}$, 10.79 $g \cdot kg^{-1}$, and 11.11 $g \cdot kg^{-1}$, respectively. After 2018, the organic carbon content with M, MN, MP, and MNP treatments was more than 14 $g \cdot kg^{-1}$. However, with PK and NK treatments, the increasing trend was not obvious, and the average value was approximately 6 $g \cdot kg^{-1}$ for several years.

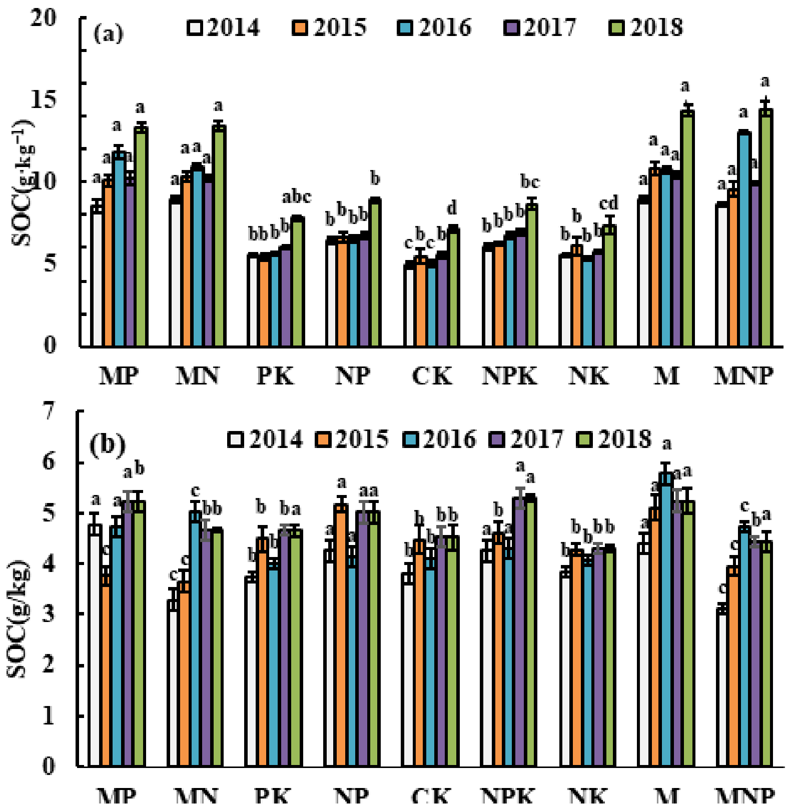

Figure 5. *Stoichiometric characteristics of soil SOC contents with different fertilization. Bars with the same letter for the same year indicate no significant differences. Error bars are standard errors of the means. Lowercase letters represent significant differences within groups at P < 0.05*

The trend of SOC content in the lower layer of soil (20–40 cm) under different fertilization treatments showed that the annual fluctuation was small, and so was the difference of SOC content in different fertilization treatments. The range under CK

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treatment over many years was 3.81–4.52 g·kg^{-1}, with an average value of 4.32 g·kg^{-1}. Under chemical fertilizer treatment, the content of organic carbon in the lower layer was 67.76–72.40% of that in the surface layer, while under organic fertilizer treatment, the content of organic carbon in the lower layer was 38.51–48.15% of that in the surface layer (*Fig. 5b*).

Changes of soil TN content under different long-term fertilization methods

Compared with that under CK treatment, the variation trend of TN content in surface soil (0–20 cm) under different fertilization treatments was different (*Fig. 6a*). The Soil TN content under all organic fertilizer treatments was greater than that under chemical fertilizer treatment and no fertilization. After years of cultivation with CK treatment, the TN content in the topsoil (0–20 cm) remained at approximately 0.37 g·kg^{-1}, with little inter-annual change. The average values with M, MN, MP, and MNP treatments were 0.68 g·kg^{-1}, 0.68 g·kg^{-1}, and 0.69 g·kg^{-1}, respectively. After 2018, the soil TN content under organic fertilizer treatment exceeded 0.80 g·kg^{-1}. However, for the treatment involving chemical fertilizer NK, the increasing trend was not obvious, and the average value of the treatment remained at approximately 0.44 g·kg^{-1}.

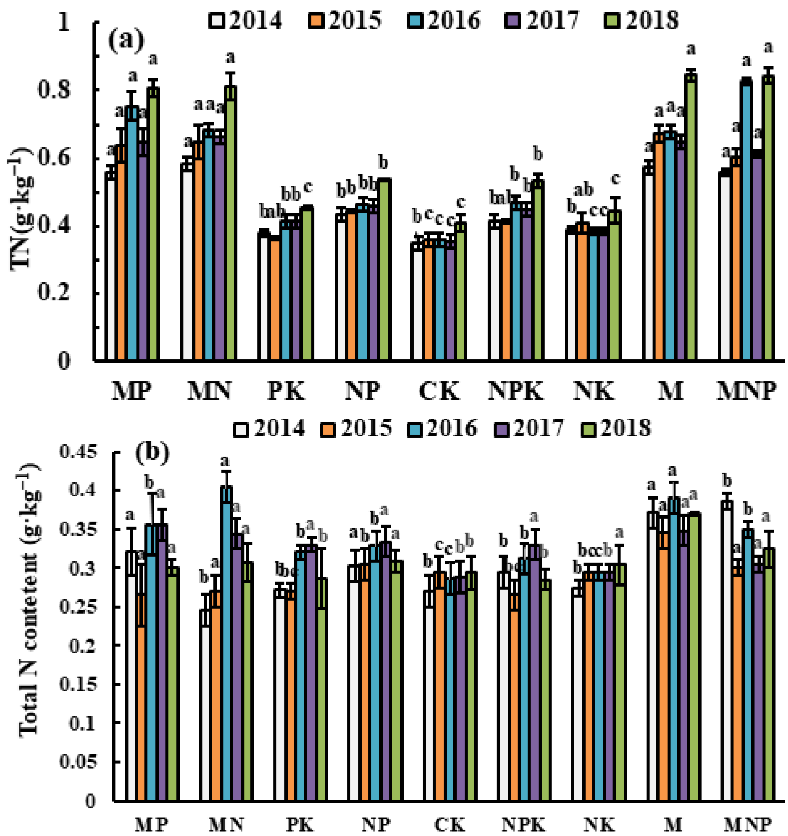

Figure 6. *Stoichiometric characteristics of soil TN contents with different fertilization. Bars with the same letter for the same year indicate no significant differences. Error bars are standard errors of the means. Lowercase letters indicate significant differences within groups at P < 0.05*

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The trend of TN content in the lower layer of soil (20–40 cm) under different fertilization treatments showed that the annual fluctuation was small, and so was the difference of TN content in different fertilization treatments. The range under CK treatment over many years was 0.27–0.29 g·kg^{-1}, with an average value of 0.28 g·kg^{-1}. Under chemical fertilizer treatment, the TN content in the lower layer was 65.12–73.13% of that in the surface layer, while under organic fertilizer treatment, the TN content in the lower layer was 43.96–59.20% of that in the surface layer (*Fig. 6b*).

Correlation analysis of SOC and TN content and C:N ratio

There was a significant positive linear correlation between SOC and TN content in topsoil (0–20 cm) ($P < 0.05$; correlation coefficient = 0.947**) (*Fig. 7a*). The soil TN content increased by 0.055 g·kg^{-1} for every 1 g·kg^{-1} increase in the SOC content. The SOC content was high, and so was the soil TN content; hence, the C:N ratio tends to be stable, which is important to soil characteristics and crop growth. According to the average value of the C:N ratio over many years, compared with no fertilization, fertilization significantly changed the C:N ratio of soil from 15.30 to 16.08. Compared with that with CK treatment, the C:N ratio with MP, MN, M, and MNP treatments increased by 1–5%, while the C:N ratio with PK, NP, NPK, and NK treatments decreased by 1–2%. Applying organic fertilizer increased the content of SOC; hence, the C:N ratio with organic fertilizer treatment was greater than that with chemical fertilizer and no fertilizer application (*Fig. 8a*).

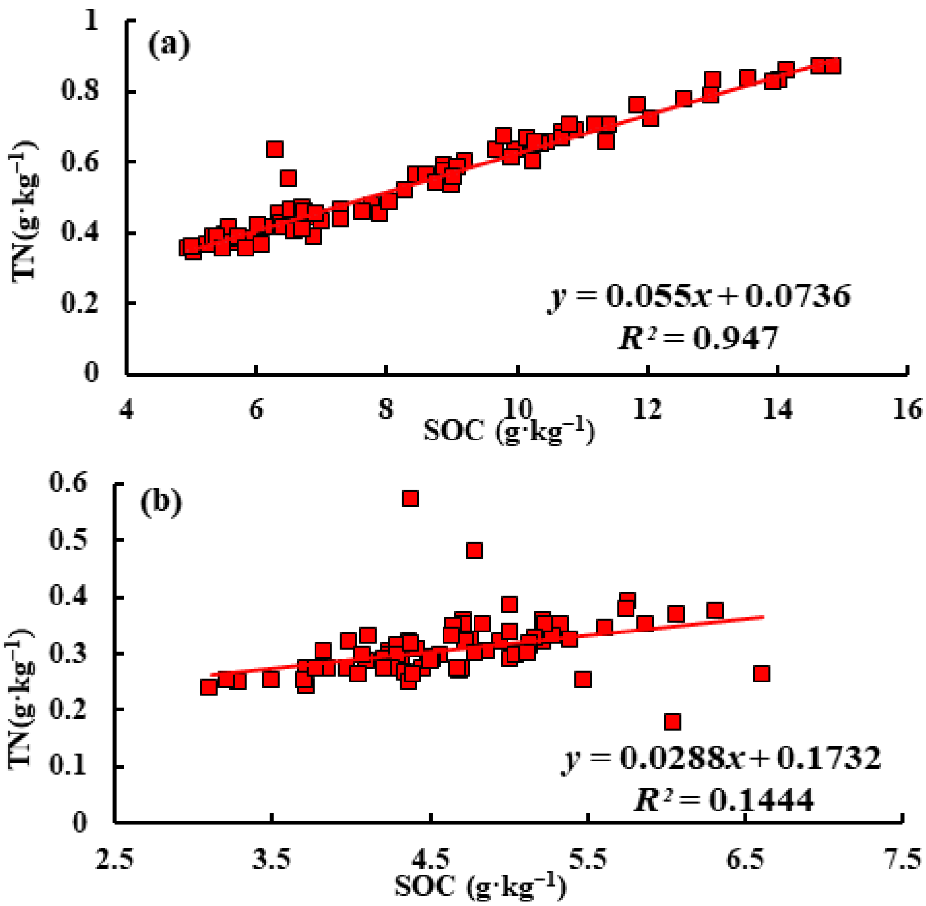

Figure 7. *Correlation between SOC and TN content in different soil layers*

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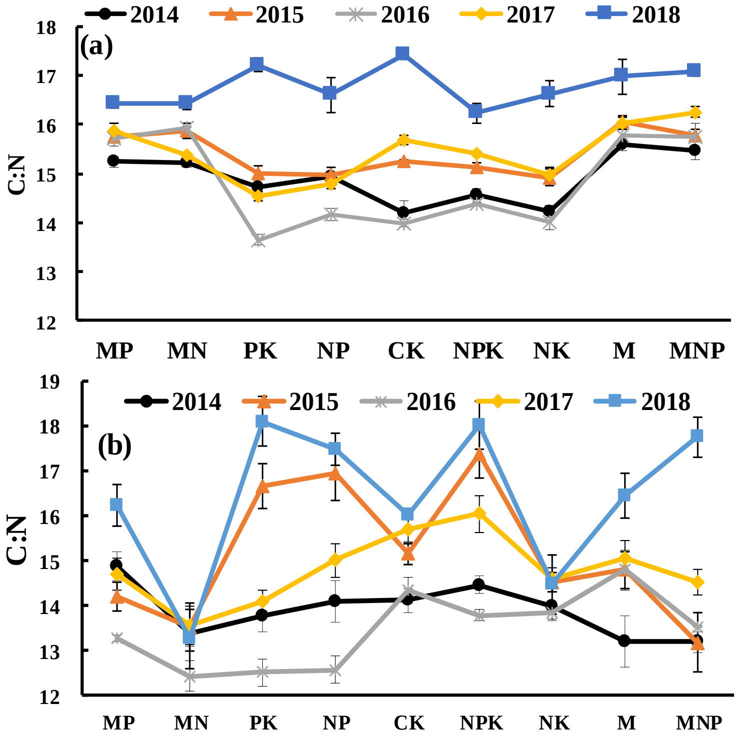
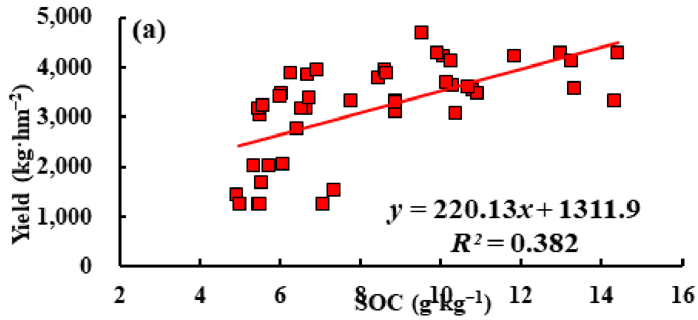


Figure 8. *Stoichiometric characteristics of C:N in different soil levels*

There was no significant linear correlation between SOC and soil TN content in the subsurface soil (20–40 cm) ($P > 0.05$; correlation coefficient = 0.144) (*Fig. 7b*). Compared with no fertilization, fertilization did not significantly change the soil C:N ratio; the soil C:N ratio ranged from 15.93 to 13.22. Compared with that with CK treatment, the C:N ratio with NP and NPK treatments increased by 1–6%; the C:N ratio with MP, Mn, NK, M, and MNP treatments decreased by 3–12%, while that with PK treatment remained constant (*Fig. 8b*).

Relationship between soil carbon and nitrogen content and crop yield

Soil TN and organic carbon contents were the main factors affecting soil productivity and soybean yield. Soybean yield increased with the increase of SOC (*Fig. 9a*) and soil TN (*Fig. 9b*) contents in surface soil (0–20 cm), both of which were significantly positively correlated ($P < 0.05$) (*Fig. 9a*). SOC (*Fig. 9c*) and soil TN (*Fig. 9d*) contents of surface soil (20–40 cm) increased, and so did the soybean yield; however, there was no significant positive correlation between the two ($P > 0.1$).



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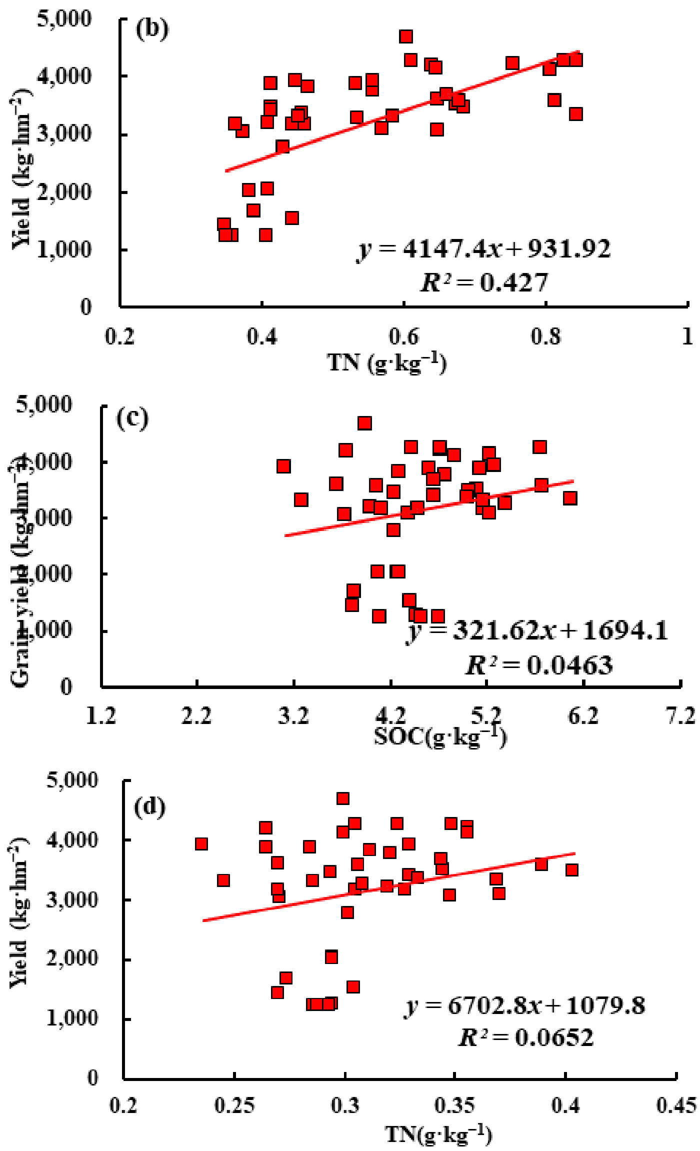

Figure 9. *Correlation between SOC, TN, and crop yield*

Discussion

Effects of fertilization on crop yield

In this study, we observed a long-term fertilization condition between crop yield interannual change (*Fig. 3*) and the lowest average yield with CK treatment under different fertilization modes (1,264.5 kg·hm^{-2}) compared with the soybean production in 2014; CK production fell by 14.69% in 2018, the average yield under different fertilization modes to MNP processing production was 4,218 kg·hm^{-2}, compared with the soybean production in 2014, and the CK production rose by 14.97% in 2018. In addition, the yield of soybean increased by 55–233% under all fertilization treatments; the yield increased most obviously by MNP treatment due to the significant increase of yield effect after MNP applied organic fertilizer. This provides nitrogen and phosphorus nutrition elements along with other trace elements that can be supplied in a timely manner. While processing MNP, organic fertilizer could improve the physical and

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chemical properties of soil, thus it can be used to provide good ecological environment and soil fertility, and improve resistance to natural disasters and unfavorable factors affecting crop yield, thereby increasing crop yields (van der Ent et al., 2020). At 1 year, M treatment soybean yield was significantly lower than that of NPK; the two fertilizer treatments of soybean yield gap in the 2018 M treatment was slightly higher than that of NPK, since the applied fertilizer can increase the soil available nutrient content. Organic fertilizer, which has longer lasting effect, can improve the capacity of the soil nutrients, which enhances the soil nutrient content of M, thereby meeting the growth demand of crops, resulting in a yield similar to or greater than that obtained from using chemical fertilizers (Lin et al., 2015).The output of MNP processing under interannual amplitude showed a high *SI*, which indicates that it is conducive to maintaining the stability of soybean processing, production and sustainability (Gatamaneni Loganathan et al., 2020). Fertilizer application can improve the sustainability of soybean yield; organic fertilizer treatment is superior to chemical fertilizer treatment, while MNP treatment showed the best sustainability, which may be related to the long-term combined application of mechanical fertilizer on soil productivity (Hati et al., 2021). Fertilization of soil can provide the nutrients needed to soybean, alleviate large fluctuations of soybean yield caused by adverse environmental factors, improve soybean yield, and effectively maintain the sustainability of crop production system (Lv et al., 2021). The yield with M treatment was affected due to insufficient fertilizer distribution in the early stage and small amount of nutrients in the mechanized fertilizer mineralization (Kaur et al., 2021). Although chemical fertilizer treatment can provide nutrients to soybean, it is relatively poor in improving soil physical quality due to the lack of organic fertilizer. Therefore, long-term use will lead to large annual fluctuation of yield, which is less stable and sustainable than MNP treatment (Latkovic et al., 2020).

Effects of different fertilization on SOC, TN, and C/N in different topsoil layers

After 5 years of a long-term positioning experiment, SOC and nitrogen dynamic changes were found to be closely related and were not only reflected in the annual change of SOC and TN content, but also in the soil carbon pool and nitrogen pool reserves, which showed consistent performance. With the increase of fertilization years, the contents of SOC and TN in different fertilization treatments showed a trend of significant increase.

Organic fertilizer treatment significantly increased soil SOC and TN content with the fixed number of cultivation year. The annual average SOC and TN contents were significantly higher than those with chemical fertilizer and CK treatments due to the dynamic change in SOC content, which depends on the system input and output level of carbon. Organic fertilizer processing of root secretion, root crop, crop straw, and organic manure is the main source of SOC input, and not only directly of SOC input, but it can also improve soil nutrient conditions and enhance soil enzymatic and microbial activities. Organic fertilizers are transformed into organic carbon and nitrogen after microbial action and enter the soil surface, thereby increasing the source of SOC (Li et al., 2021). Organic fertilizers also increase the stability of soil aggregates, which in turn promote the absorption and accumulation of SOC and nitrogen through physical protection and chemical combination (Sun et al., 2021).There was no input of exogenous organic matter in the treatment of chemical fertilizer, and the SOC primarily originated from a small amount of stubble, small, and medium-sized soil animals and soil microbial activities; hence, the soil organic matter content did not increase with the increase of fertilization years. In *Figure 4b*, in all of the organic manure treatments in

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the 0–20-cm soil layer, the soil TN content changed with the number of years of planting and significantly improved, while the change in the TN content with chemical fertilizer treatment was not obvious. The application of organic fertilizer plays an important role in nitrogen fixation, since it can reduce the loss of nitrogen from the soil, increase SOC stock, and improve the ability to retain nitrogen in soil. Nitrogen in fertilizer processing for inorganic state is more prone to volatile and nitrate leaching, besides being absorbed by crops. Chemical fertilizers can mitigate soil TN content better than CK, since they increase crop yields, thereby enhancing the growth of branches and leaves and root residues, and increase SOC content (Liu et al., 2020a).

In the surface layer of soil (20–40 cm), the organic carbon content under chemical fertilizer treatment was 67.76–72.40% of that in the 0–20-cm layer and 38.51–48.15% of that in the surface layer under organic fertilizer treatment. Under chemical fertilizer treatment, the TN content was 65.12–73.13% of the 0–20-cm layer, while under organic fertilizer treatment, the TN content was 43.96–59.20% of the 0–20-cm layer. The changes of SOC and TN contents with all of the fertilization treatments showed a decreasing trend, which made the SOC and TN contents appear to be high in the surface layer and low in the subsurface layer of the profile. This can be explained as follows: First, fertilization is mainly concentrated in the surface layer; hence, it takes time for the carbon and nitrogen elements in the fertilizer to penetrate the soil. Second, in the first year of fertilization, there was an “excitation effect” of nitrogen consumption in the decomposition process of fertilizer, and nitrogen would be limited in supply to plant growth because of which straw decomposition occurs due to competition between the two; therefore, a decreasing trend appears (Liu et al., 2020b).

With fertilizer decomposition conversion and lower migration into the soil, SOC and TN contents are supplemented. The generation of stratification phenomenon is mainly attributed to soil surface receiving a large number of farmland fertilizer while being influenced by rainfall (and snow), which causes significant differences in the soil surface and lower organic carbon and TN contents (Masto et al., 2012).

SOC and soil TN contents in surface soil (0–20 cm) were linearly positively correlated (correlation coefficient = 0.947), indicating that fertilization had a good synergistic effect on soil SOC and TN contents, although there was no significant linear correlation between SOC and soil TN contents in the subsurface soil (0–20 cm) (correlation coefficient = 0.144; *Fig. 3*). This was because fertilization significantly changed the contents of surface SOC and TN resulting in the formation and migration of TN and organic carbon; hence, there was no good linear relationship. Different treatments also had certain effects on soil C/N interannual variation. In *Figure 6*, fertilization significantly changed the C:N ratio of surface soil, and the C:N ratio with organic fertilizer treatment was higher than that with chemical fertilizer treatment. With the change in fertilization years, the C:N ratio of all fertilization treatments showed an increasing trend, which indicated that the increase of soil carbon content in fertilization was more than that of nitrogen, and the application of mechanized fertilizer could increase the SOC content. Moreover, due to the increase of crop growth, the number of mechanized residues returned to the soil increased. Organic fertilizers contain a large number of carbohydrates and mineral nutrients such as N, P, and K, which provide sufficient energy and other effective nutrients for the growth of bacteria in the soil, thus stimulating the activity of bacteria in the soil, enhancing their decomposition and utilization of organic matter, and increasing the C/N form. However, the amount of SOC mineralization decreases with decrease in soil C/N, and the organic carbon mineralization decreases after fertilization

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treatment, thus improving the soil carbon sequestration ability. In 2018, the value of C:N ratio with CK treatment was 17.43, higher than that with organic and chemical fertilizer treatments. This is due to the lack of long-time fertilization and crops taking nitrogen away from the soil. Low nitrogen input makes the content of available nitrogen required by soil microorganisms insufficient and delays the turnover of SOC; hence, the C:N ratio is the largest. The C:N ratio of the subsurface soil (20–40 cm) ranged from 13.22 to 15.93. Compared with that with CK treatment, the C:N ratio with NP and NPK treatments showed an increasing trend, while the C:N ratio with MP, MN, NK, M, and MNP treatments showed a decreasing trend. NP and NPK in the 20–40-cm soil layer were favorable for organic carbon accumulation, while MP, MN, NK, M, and MNP were favorable for nitrogen accumulation. Compared with no fertilization, fertilization did not significantly change the soil C:N ratio according to the average C:N ratio of different soil treatments over many years. Meanwhile, compared with the initial C:N ratio, that with each treatment showed an increasing trend. In general, regardless of the conventional fertilization, i.e., single or combined application of organic and inorganic fertilizers, the soil C:N ratio has little effect.

Relationship between soil SOC and TN contents and soybean crop yield

After 5 years, we found a significant correlation between SOC, TN contents and soybean yield under different fertilization in the 0–20-cm soil layer; the difference in soil SOC and TN contents directly affected crop yield. The input carbon of soybean residue after harvest can improve soil chemical properties and increase crop yield. High SOC and TN contents can increase their retention, which may help to improve crop yield and reduce the uncertainty of crop yield. SOC accumulation can indirectly affect crop yield by maintaining soil structure and regulating soil microbial activity. The soil SOC and TN contents in the 20–40-cm layer with different fertilization treatments showed no significant correlation with soybean production The relationship between crop SOC and TN contents and crop yield varies with different regions, soil types, and climate conditions. Therefore, more factors affecting crop yield should be considered for better systematic and comprehensive analysis in specific regions.

Conclusions

After 5 consecutive years of experiments, we found that fertilization could significantly improve the contents of SOC and TN in the surface layer, while the changes in the bottom layer were not obvious. Fertilizer combined with organic fertilizer can steadily improve the sustainability index of soybean yield and ensure high and stable yield. Moreover, there was a significant positive correlation between soybean yield and SOC and TN contents after increasing the application of organic fertilizer, indicating that an organic and inorganic combination is an effective strategy to improve soil fertility and to ensure high and stable soybean yield in semi-arid climate areas in China.

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