Effects of green manure planting on soil organic carbon in China: A meta-analysis

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Abstract: Growing green manure, as a sustainable agricultural practice, is widely recognized for its role in improving soil structure and enhancing soil quality. However, despite the significant benefits of green manure, research on how its application specifically influences soil organic carbon content remains insufficient, especially in the context of complex and ever-changing agricultural management models and ecological environments. In this study, 59 papers published from January 1980 to May 2024 were collected, and a database containing 299 groups of comprehensive effects of green manure planting on soil organic carbon content and crop yield, as well as its key regulatory factors, through a meta-analysis system. The research is mainly conducted through several key elements types of green manure, planting seasons, fallow periods of food crops, soil types, climate types, and planting years. The results show that compared with not growing green manure on fallow land, the cultivation of green manure significantly increased the soil organic carbon content (by 6.98%) and the yield of the next staple food crop (by 10.36%). In different planting seasons, both summer and winter planting of green manure can effectively increase the soil organic carbon (SOC) content and crop yield. Among them, the application effect during the fallow period of wheat and rice is particularly significant, while during the fallow period of maize, only the SOC content increases significantly. From the perspective of green manure types, both the single species of leguminous and the mixed species with cruciferous have shown good effects. The research also found that under soil types such as loam and clay loam, as well as climatic conditions like temperate continental climate, temperate monsoon climate, and subtropical monsoon climate, the effect of green manure planting on the increase of SOC and yield is more significant. In addition, the planting years are also an important influencing factor. Green manure planting for ≤3 a or >5 a can significantly improve the SOC content and crop yield. These findings provide important theoretical support for the scientific application and promotion of green manure in China.

Keywords: green manure, soil organic carbon, grain yield, meta analysis
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1 Introduction

China, with only 9% of the world's arable land, sustains nearly 20% of the global population and has achieved continuous growth in grain production. However, excessive land use in agriculture has led to soil degradation, decreased fertility, acidification, and reduced organic matter, which negatively affect crop growth and environmental health[1]. Soil organic carbon (SOC), a key indicator of soil fertility[2,3], is directly related to crop yield[4]. As a sustainable agricultural practice, green manure not only effectively controls weeds, improves fertilizer use efficiency, and enhances soil quality, but also helps reduce soil erosion and lowers the risk of crop failure due to drought, pests, and diseases[5]. Therefore, investigating the impact of green manure on soil organic carbon content and crop yield, as well as the influencing factors, is of great significance for the sustainable development of agriculture in China and provides essential technical and theoretical support for the scientific application of green manure.

Some studies suggest that the content of soil organic carbon (SOC) after planting green manure is influenced by both climatic factors and management practices, which may lead to varying effects of green manure application[6,7]. Studies show that turning down green manure crops and returning them to the field can accelerate the mineralization and decomposition of soil organic matter. After green manure is returned to the field, it also converts its own nutrients into the soil, increasing soil nutrients[8]. Planting and turning green manure during the winter fallow period of continuous cropping tobacco fields can alleviate the obstacles of continuous cropping[9], increase the content of soil organic matter, and also loosen the soil, activate and enrich the available nutrients in the soil[10]. In semi-arid areas, planting green manure can increase SOC to varying degrees, which may be due to the relatively low and

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unevenly distributed precipitation. Precipitation is a crucial factor affecting both the input and decomposition of soil organic carbon. Furthermore, the impact of green manure on soil organic carbon content depends on the type of green manure, environmental factors, and the duration of the experiment. The length of the trial period can affect the accumulation and stability of SOC. For instance, Poeplau's study found that significantly increasing SOC content may require decades of continuous green manure cultivation[11,12]. The impact of different types of green manure on soil organic carbon varies. Leguminous green manures such as Vetch (*Vicia villosa Roth*) and Chinese milk vetch (*Astragalus sinicus* L.) typically have a significant effect on increasing soil organic carbon content. For example, in a study conducted in the dry plateau region of eastern Gansu, the incorporation of Vetch and forage Oilseed rape (*Brassica napus* L.) increased the SOC content in the 0-25 cm soil layer by 12.9%[13]. Additionally, the incorporation of Chinese milk vetch has been shown to significantly increase soil active organic carbon content[14]. Climate directly influences the growth and decomposition rates of green manure[15]. In temperate climates, the growth and decomposition rates of green manure are relatively stable. Suitable temperature and precipitation conditions promote the growth and nutrient accumulation of green manure, while also facilitating its decomposition and nutrient release[16].

In the past, there has been considerable debate regarding the impact of green manure on soil organic carbon content and subsequent crop yield. A single experiment is insufficient to comprehensively evaluate the specific effects of various factors—such as green manure type, soil type, climatic conditions, and planting timing—on soil organic carbon levels and the yield of succeeding crops. To address this, the present study compiled 299 independent experimental datasets from across China, forming a comprehensive database on soil organic carbon content and grain crop yields following green manure incorporation. The objective of this research is to quantitatively assess the influence of green manure on soil organic carbon and grain yield, aiming to provide a scientific basis and theoretical support for improving soil fertility and promoting sustainable agricultural practices.

2 Methods

2.1 Data collection

To quantify the impact of green manure cultivation on soil organic carbon and crop yield, a literature search was conducted on Web of Science and China National Knowledge Infrastructure (CNKI) for relevant publications from June 1980 to April 2024. Search terms included "cover crop," "green manure," "catch crop," "soil organic carbon," "soil organic matter," and "yield," yielding a total of 299 datasets.

The references included in the database must meet the following criteria: 1) with fallow as the control, the treatment must include at least one of cover crops, green manure, or catch crops; 2) the experiment must be replicable; 3) the outcome indicators must include measured soil organic matter and organic carbon content, as well as yield data; 4) the field trials must focus on major field crops such as wheat, rice, and maize. After sorting and screening the literature that met the above conditions, a total of 58 Chinese and English articles that fulfilled the requirements of this study were identified. The following data were extracted from the eligible literature: climatic conditions, green manure type, field crops planted after green manure, green manure planting season, soil type, and duration of the experiment. To determine the influence of different climatic factors on soil organic carbon content and crop yield after planting green manure, the climate types were classified as temperate monsoon climate (NTM), temperate continental climate (NTC), and subtropical monsoon climate (STM)[17]. In this study, the duration of the experiments was divided into less than 3 a, 4-5 a, and more than 5 a, aiming to distinguish between general and long-term experimental durations[18]. The mixed cropping types were classified as Leguminosae+Leguminosae (L+L), Leguminosae+Gramineae (L+G), and Leguminosae+Cruciferaceae (L+C). For the initially established database, outliers were removed, resulting in the final 299 datasets used in this study.

2.2 Data analysis

The classical meta-analysis of response ratios (ln*R*) was used to assess the effects of planting green fertilizer treatment on soil SOC and crop yield.

$$\ln R = \ln\left(\frac{Y_e}{Y_c}\right) \tag{1}$$

where, Y_e and Y_c are the average SOC content of soil and the average crop yield under green fertilizer and fallow conditions, respectively. Variance was calculated as follows:

$$v_i = \frac{(\mathrm{SD_e})^2}{N_e(Y_e)^2} + \frac{(\mathrm{SD_c})^2}{N_c(Y_c)^2} \tag{2}$$

where, v_i is the variance within the case; $\mathrm{SD_e}$ and $\mathrm{SD_c}$ are the standard deviation of SOC content and crop yield under green manure and fallow treatment; N_e and N_c are the number of repeats of SOC content and crop yield under green manure and fallow treatment, respectively.

When the standard error (SE) was given instead of SD in the selected studies, this study converted the SE to SD using the following formula:

$$\mathrm{SD} = \mathrm{SE} \times \sqrt{n} \tag{3}$$

The weighting factor (w_i) for each lnR was calculated using the following equation:

$$w_i = \frac{1}{v_i + \tau^2} \tag{4}$$

where, τ^2 is the variance between cases. To better explain the effect of planting green manure on SOC content and crop yield, the mean response ratio (ln*R*) was converted into a percentage to explain the results:

$$Percentchange = \left(\exp^{\ln R} - 1\right) \times 100\% \tag{5}$$

The conversion formula of organic matter and organic carbon:

$$\mathrm{SOM} = \mathrm{SOC} \times 1.724 \tag{6}$$

This study utilizes Webplot Digitizer to obtain chart data from literature. For meteorological and geographical coordinate data not provided in the literature, methods from the "National Meteorological Information Center Database" and "Geospatial Data Cloud" are employed for querying and supplementation. This article adopts GIS masking to extract given soil textures. Meta-analysis is conducted using the meta package in R 4.3.0 (R studio). Origin 2022 and Graphpad Prism 8.4.3 are used for drawing graphs, and Q-Q plots are employed to test publication bias.

3 Results

3.1 Distribution characteristics of green manure crops in different ecological zones

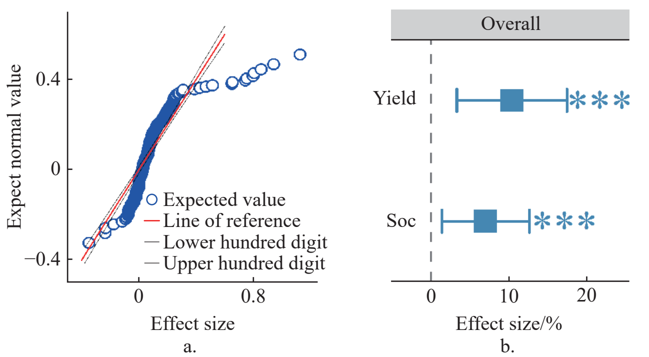
As listed in Table 1, there are differences in the types of green manure crops planted in northern and southern China. The southern region has more case studies but fewer types of green manure, while the northern region has fewer case studies but a greater variety of green manure crops. Chinese milk vetch is the most frequently used green manure, being a major choice in multiple regions and provinces. In northern China, leguminous green manures include Pea, Chinese milk vetch, Vetch, Alfalfa, Melilotus officinalis, Soybean, Astragalus, and Green bean. Cruciferous green manures include Oilseed rape and February orchid, while grasses like Rye grass are also used. In southern China, leguminous green manures encompass Chinese milk vetch, Pea, Melilotus officinalis, Soybean, Vetch, Fava bean, and Green bean; cruciferous green manure is represented by Oilseed rape, and grasses like Rye grass are also found.

Table 1 Planting status of cover crops

Area	Province	Main cover crop
Central China	Hubei	Chinese milk vetch, Rye grass
Central China	Hunan	Chinese milk vetch, Rye grass, Oilseed rape
Northwest China	Gansu	Chinese milk vetch, Vetch, Pea, Melilotus officinalis
Northwest China	Shaanxi	Green bean, Alfalfa
North China	Henan	Chinese milk vetch
North China	Beijing	Chinese milk vetch, Rye grass, Oilseed rape, February orchid
North China	Tianjin	February orchid, Green bean, Pea, Vetch
North China	Shanxi	Soybean, Oilseed rape, Astragalus
Northeast China	Dongbei	Pea
Southwest China	Sichuan	Chinese milk vetch, Rye grass, Alfalfa
Southwest China	Guizhou	Vetch, Pea
South China	Guangdong	Chinese milk vetch, Oilseed rape, Green bean
South China	Guangxi	Chinese milk vetch, Oilseed rape, Vetch
East China	Jiangsu	Chinese milk vetch, Soybean, Oilseed rape
East China	Jiangxi	Chinese milk vetch, Rye grass, Rape
East China	Anhui	Chinese milk vetch
East China	Shanghai	Chinese milk vetch, Oilseed rape, Fava bean
East China	Zhejiang	Chinese milk vetch, Oilseed rape, Pea

3.2 Impact of green manure cultivation on soil organic carbon and crop yield

Figure 1a shows the normality test results of the total data set.



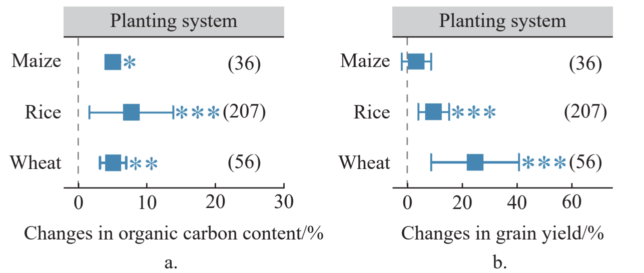
Note: a. Q-Q plot of the normal distribution of the entire dataset; b. The overall effect of green manure cultivation on soil organic carbon content and crop yield. The zero line represents the limit between a positive and negative response. Data points represent average values, with error bars showing 95% confidence intervals. Significance symbols (*p<0.05, **p<0.01, ***p<0.001) apply throughout all figures and tables unless otherwise stated.

Figure 1 Overall effect of green manure cultivation on soil organic carbon content and yield

It can be seen from the figure that all the blue data points are roughly distributed along a straight line, indicating that the data is close to a normal distribution (Figure 1a). Compared to the absence of green manure cultivation, the implementation of green manure during the fallow period significantly enhances both the organic carbon content in the soil and crop yield (p<0.001), with average increases of 6.99% and 10.36%, respectively (Figure 1b).

3.3 Impact of planting green manure crops during fallow periods of different crop types on soil organic carbon and crop yield

Figures 2a and 2b respectively show the effects of planting green manure during the fallow period of different crops on soil organic carbon and the yield of staple food crops. Figure 2a shows that the application of green manure during the fallow period of rice led to the highest increase in soil organic carbon, reaching 7.77%, followed by 5.09% during the fallow period of wheat and 5.07% during the fallow period of maize. Figure 2b shows that after planting green manure during the wheat fallow period, the yield of the next crop increased the most, reaching 24.69%, followed by the rice fallow period (9.58%), and then the maize fallow period (3.27%).

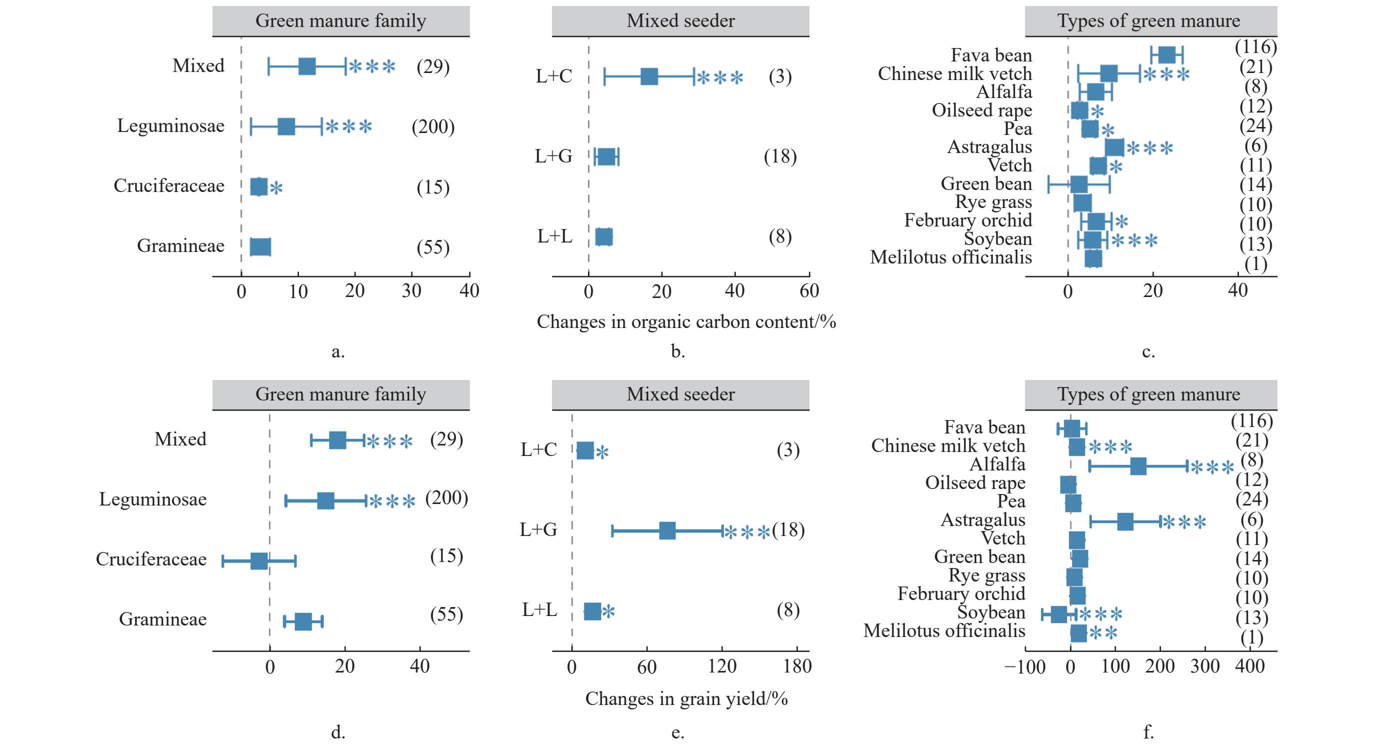


Note: a. The influence of planting green manure during the fallow period of different food crops on soil organic carbon content; b. The effect of planting green manure during the fallow period of different food crops on crop yield. Values in parentheses denote the number of observations; this convention applies to all subsequent figures and tables unless otherwise specified.

Figure 2 Effects of fallow period of different staple crops on soil organic carbon and yield

3.4 Impact of different types of green manure crops on soil organic carbon and the yield of the next crop

Figure 3 shows the effects of different green manure families, mixed seeder and types on soil SOC content and crop yield. Mixed sowing of green manure and single leguminous green manure significantly increased soil SOC content and the yield of the next crop season (p<0.001). The mixed cropping of leguminous and gramineous plants had the most significant effect on increasing the yield of the next crop season, with an increase of 75.91% (Figure 3e). The mixed sowing of leguminous and cruciferous plants significantly increased the soil SOC content and crop yield, with average increases of 16.53% and 10.35%, respectively (Figures 3b and 3e). However, the treatment of single poaceae green manure had no significant effect on these two indicators (Figures 3a and 3d). In addition, subgroup analyses were conducted on the effects of different types of green manure on soil organic carbon content (Figure 3c) and the yields of major crops (Figure 3f). The results showed that the cultivation of Chinese milk vetch and Astragalus could significantly increase the soil SOC content and crop yield (p<0.001). Among them, the cultivation of Astragalus had a better effect on increasing the soil SOC content and crop yield, with the growth rates reaching 10.82% and 121.29%, respectively.

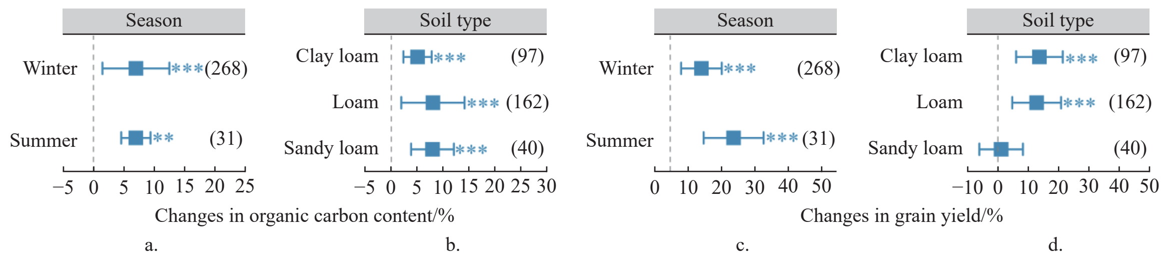


Note: a. The influence of different family and genus of green manure on soil organic carbon content; b. The influence of mixed green manure combination on soil organic carbon content; c. The influence of the types of green manure planted on soil organic carbon content; d. The influence of different family and genus of green manure on crop yield; e. The influence of mixed green manure combination on crop yield; f. The influence of the types of green manure planted on crop yield. The mixed cropping types were classified as Leguminosae+Leguminosae (L+L), Leguminosae+Gramineous (L+G), and Leguminosae+Cruciferaceae (L+C).

Figure 3 Effects of different types of green fertilizer on soil organic carbon and crop yield

3.5 Impact of planting green manure crops in different seasons and soil types on soil organic carbon and the yield of the next crop

Figure 4 shows the effects of green manure planting season and soil type for green manure planting on soil organic carbon content and the yield of the next crop. In the entire dataset, the main seasons for green manure cultivation are summer and winter. The results showed that planting green manure in both summer and winter significantly increased soil SOC content and crop yield (p<0.001). Among them, the SOC content of green manure soil planted in summer increased by 6.98%, and the yield of the next crop increased by 20.89%. Winter planting of green manure increased the soil SOC content by 6.99% (Figure 4a) and the yield of the next crop by 10.29% (Figure 4c).



Note: a. The influence of the season for planting green manure on soil organic carbon content; b. The influence of soil type for growing green manure on soil organic carbon content; c. The influence of the season for planting green manure on crop yield; d. The influence of soil type for growing green manure on crop yield.

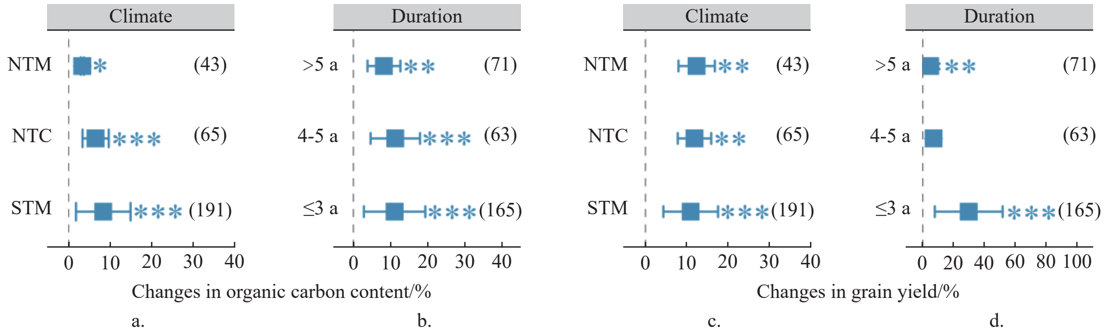
Figure 4 Effects of different seasons and soil types on soil organic carbon and crop yield

The improvement effect of soil SOC was the best when green manure was planted in loam soil, with an increase of 8.0%. The second is sandy loam soil, with an increase of 7.93%. The clay soil increased by 5.05% (p<0.001) (Figure 4b). After green manure was planted in clay loam soil, the crop yield increased the most compared with the control, reaching 13.62%, followed by loam soil (12.72%). After green manure was planted in sandy loam soil, the crop yield increase in the next season was the smallest, only 1.06% (p>0.05) (Figure 4d).

3.6 Impact of different climatic types and durations of planting on soil organic carbon content and the yield of the next crop

Figure 5 describes the effects of climate type and green manure cultivation time on soil organic carbon content and crop yield. Under different climate types, green manure has a significant impact on soil organic carbon content and crop yield. Among them, the planting of green manure under STM conditions had the greatest impact on soil organic carbon content, increasing by 8.34% compared with the control. NTC followed, with an increase of 6.49% in soil SOC content, and NTM came in second, with an increase of 3.30% in soil SOC content (Figure 5a). The cultivation of green manure under NTM had the best effect on the yield of major food crops, increasing by 12.37% compared with the control (Figure 5c), followed by NTC (11.85%) and STM (10.93%).

In the entire dataset, the durations of green manure cultivation range from 1 to 27 a. Among them, 55.1% of the studies lasted for ≤ 3 a, 21% lasted for 4-5 a, and 23.7% lasted for >5 a. Different durations of green manure cultivation had significant effects on increasing soil SOC content (Figure 5b) and crop yield (Figure 5d) (p<0.001). Among them, the effect of green manure planting on the increase of soil SOC content ≤3 a was the greatest, with an increase of 8.64%. When green manure was planted for 4-5 a, the soil SOC content increased by 7.45% compared with the control. When the planting time exceeded 5 a, the increase in soil SOC content was the smallest, at 3.43% (Figure 5b). However, it was precisely >5 a of green manure planting that the increase in yield of the next crop increased the most, reaching 29.58% (Figure 5d).



Note: a. The influence of the climate type for growing green manure on soil organic carbon content; b. The influence of the durations of planting green manure on soil organic carbon content; c. The influence of the climate type for growing green manure on crop yield; d. The influence of the durations of green manure cultivation on crop yield. Temperate monsoon climate (NTM), Temperate continental climate (NTC), and Subtropical monsoon climate (STM).

Figure 5 Effects of different climate types and experiment durations on soil organic carbon and crop yield

3.7 Relationship between SOC and crop yield change

To further clarify the impact of soil organic carbon (SOC) on the yield-increasing effect of green manure crops, a quadratic fitting was conducted on the organic carbon content and yield after planting green manure (Figure 6). The results showed that with the increase in organic carbon content, the yield first increased and then decreased. The highest yield was observed when the organic carbon content reached 22.28 g/kg.

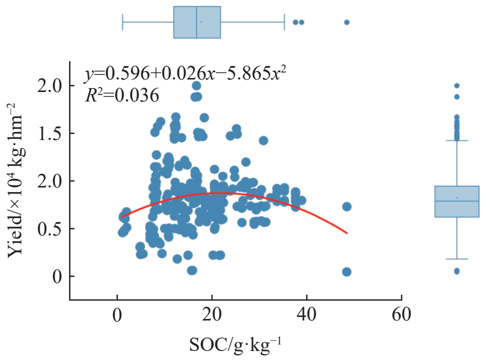


Figure 6 Relationship between soil SOC content and crop yield

4 Discussion

4.1 Effects of planting green manure on SOC and yield

The impact of green manure on soil organic carbon (SOC) is multi-faceted. It can not only directly input a large amount of fresh carbon sources but also indirectly enhance soil fertility and crop yield by improving aggregate structure and microbial community composition[19-24]. The results of this study show that for the increase of soil SOC content and crop yield, the effect is particularly best during the fallow period of rice, and the increase in SOC is on average 34.49% higher than that during the fallow period of wheat and maize. However, the application of green manure during the fallow period of maize does not significantly increase the yield of the subsequent crops, and even has a negative effect. Moreover, the mixed sowing of the two types of green manure or the single sowing of leguminous green manure significantly increased the SOC and crop yield, while the single sowing of cruciferous green manure could increase carbon emissions, but it was difficult to increase the yield simultaneously. The reason lies in that under aerobic conditions in maize fields, the co-decomposition of high C/N ratio straw and low C/N green manure stimulates microbial nitrogen fixation. The SOC is mainly composed of easily decomposable activated carbon, and the steady-state carbon contribution is limited, thereby inhibiting the growth of current crops[25].

4.2 Effects of planting season and climate of green manure on SOC and yield

This study shows that whether green manure is planted in winter or summer, it can significantly increase soil SOC content and crop yield, but the regulatory mechanisms of the two are completely different. Based on the 9 a positioning experiment on the Loess Plateau, the winter ploughing of rye increased the average annual SOC in the 0-20 cm soil layer by 0.36 g/kg, which was 22% higher than that in summer[26]. Studies in the southern rice-growing areas showed that the yield of early rice treated with milk vetch in winter only increased by 6%. The yield of late rice treated with green manure in summer increased by 12%[22]. In winter, with low temperatures and high humidity, green manure decomposes slowly, and more carbon remains in the form of stable organic matter for a long time. High temperature and humidity in summer accelerate decomposition, and carbon is prone to escape in the form of CO_2. Therefore, the increase in SOC in winter is higher than that in summer. Meanwhile, the growth period of green manure in summer is long and the biomass is large. The peak of nitrogen release is synchronized with the critical period of nitrogen demand of crops, and the yield response is better than that in winter. However, nitrogen mineralization lags in winter, and the yield gain is limited.

From the perspective of different climate types, the high temperature and abundant rainfall under STM, on the one hand, promote the rapid growth of green manure and input more biomass carbon. On the other hand, the alternating dry and wet conditions inhibit mineralization. The increase in SOC is significantly higher than that in the NTC and NTM regions. However, NTM has a mild and rainy winter, effectively avoiding drought stress in summer, and the water-nitrogen coupling efficiency between green manure and crops is the highest. In addition, due to the relatively low soil fertility, the yield-increasing effect of green manure is more prominent, and thus the increase in yield is the greatest.

It is worth noting that although STM areas have two harvests a year and abundant water and heat, high temperatures and heavy rainfall can also accelerate crop senescence and waterlogging stress, promoting the rapid decomposition of SOC. Planting green manure can effectively alleviate this loss: In the southwest region, leguminous green manure is mainly used, which can simultaneously fix nitrogen and carbon. In the south, non-leguminous green manure is mainly used, and the SOC reserves are increased through high biomass input to achieve a win-win situation of carbon sequestration and increased production suitable for the region[27].

4.3 Effects of planting green manure soil type and duration on SOC and yield

A large number of long-term positioning experiments have consistently confirmed that the introduction of green manure can significantly increase SOC and simultaneously enhance crop yields: 31 a monitoring of irrigated desert soil in Hexi Oasis shows that long-term turning of green manure increases SOC by 29.0%, and the yields of wheat and maize increase by 8.0% and 20.3%, respectively[28]. A 5 a trial on dry red soil also showed that different functional green manure increased SOC by more than 14% and sweet potato yield by 1.5% to 14.3%[29]. However, this effect shows significant differences with soil texture and durations of cultivation.

From the perspective of soil texture, green manure significantly increased carbon in all types of soil, among which the increase in SOC was the highest in loam soil, followed by clay loam soil. The yield response was optimal in clay loam soil, and even negative effects were observed in sandy loam soil. The reason lies in the fact that sandy loam soil has weak water and nutrient retention capacity, and nitrogen, phosphorus, and potassium are prone to leaching. Green manure decomposes rapidly but cannot replenish available nutrients in time[30]. Clay loam has a high content of clay particles and a large CEC, which can effectively retain nutrients and retain moisture, enabling the nitrogen, phosphorus, and potassium released by green manure to be absorbed simultaneously by crops, thus maximizing the yield increase[31].

In terms of planting durations, although the application of green manure for >5 a still significantly increased SOC and yield, the marginal effect was diminishing: this study found that the increase in SOC and yield of the treatment for >5 a was lower than that of the treatment for ≤3 a. The mechanism lies in the fact that durations of continuous green manure have significantly increased the nitrogen level in the soil. Nitrogen is no longer a yield-limiting factor, while phosphorus, potassium, and trace elements are continuously depleted with cultivation, becoming new bottlenecks and leading to a decline in the potential for increased production[21].

5 Conclusions

This study adopted the meta-analysis method to systematically evaluate the comprehensive effects of green manure cultivation on soil organic carbon (SOC) and crop yield in China. The results show that compared with not planting green manure during the fallow period, the application of green manure increases the SOC by an average of 6.98% and the crop yield by an average of 10.36%. Among them, the summer rice fallow period has the best effect: both SOC and yield growth have reached their peaks. In terms of green manure types, mixed sowing of two types of green manure is superior to single sowing - the combination of leguminous and cruciferous plants has the most significant increase in SOC, and the combination of leguminous and gramineous plants has the most significant increase in yield. Taking into account the factors of climate, season, and durations, planting mixed sowing green manure (or single sowing leguminous green manure) for ≤3 a during the summer fallow period of rice in the southern NTC area is the best model to achieve rapid accumulation of SOC and high crop yields.

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