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Soil organic carbon storage impacts on crop yields in rice-based cropping systems under different long-term fertilisation

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ABSTRACT

Rice production in the Yangtze River Basin accounts for 44.4 % of China's total rice production. Exploring the response of crop yields to soil organic carbon (SOC) storage under various fertilisation treatments for maintaining high and sustainable crop yields is an urgent issue. A database containing information on crop yields, SOC content, environmental factors (climate and soil properties), and nutrient input from fertilisation was established from seven long-term experimental sites located in the middle and lower reaches of the Yangtze River Basin (operational since the 1980s/1990s) in two lowland rice-based cropping systems (i.e., rice–wheat rotation and rice–rice rotation systems). The study considered four treatments: no fertiliser application (CK); application of chemical nitrogen, phosphorus, and potassium fertilisers (NPK); application of manure (M); and a combination of NPK and M (NPKM). Results showed that the NPKM treatment produced the highest crop yields, followed by the NPK/M and CK treatments. The NPK and NPKM treatments generally had higher sustainable yield indices (SYI, 0.34–0.74) and lower coefficients of variation (CV, 11–32 %) than the M and CK treatments (SYI: 0.29–0.62 and CV: 15–44 %) in both cropping systems across all sites. Crop grain yields were significantly increased with increasing SOC storage (0–20 cm) and followed a logarithmic regression in both systems, suggesting that a further increase in SOC content could lead to higher yields. Structural equation modelling indicated that fertilisation, soil properties, and climate together explained 75–77 % of the variance in crop yield in the two systems. The primary contributing factors were fertilisation and its associated changes in soil nutrients. Chemical fertilisers mainly had direct effects on crop yields, while manure had both direct and indirect (through improvements in soil properties) effects on crop yields. In the rice–rice system, SOC alone had both direct and indirect (through the improved availability of soil nutrients) positive effects on crop yields. Our findings emphasise the potential benefits of sequestering SOC not only for enhancing crop production but also for improving the stability and sustainability of crop yield from paddy fields.

1. Introduction

Rice, a staple food source for almost half of the global population, has shown a recent trend to stabilize regarding the maximum yield (USDA). China is the world's leading rice producer, contributing 30 % of the global total rice production (USDA). In the last six decades, rice production in China has increased more than threefold, primarily due to advancements in field management practices such as the cultivation of high yield varieties and the increased application of nitrogen (N) fertiliser and irrigation (Peng et al., 2009). However, Ray et al. (2012)

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highlighted the stagnation in rice yield in southern China based on the global rice production during 1961–2008. Moreover, the total rice planting area in China will likely continue to decrease in the future (Deng et al., 2019). Chen et al. (2020) predicted a decrease in rice production by 13.5 % for the year 2060 compared to 2015. Therefore, increasing agricultural resource efficiency is critical to ensuring sustainable rice production (Chen et al., 2023).

As soil organic carbon (SOC) content affects soil physical, chemical and biological properties and agro-ecological processes, it is considered one of the key factors for ensuring soil quality and maintaining high crop yields (Lal, 2014). An increasing number of studies have demonstrated the benefits of increasing SOC on crop production and yield stability (Lal, 2006, 2010; Ma et al., 2023; Oldfield et al., 2019; Pan et al., 2009; Waqas et al., 2020). For example, linear and non-linear regression have been employed to describe the correlation between SOC and grain yield (e.g., Ma et al., 2023; Wang et al., 2021b; Wang et al., 2021c; Zhang et al., 2016). According to Lal (2006), rice yield could increase by 10–50 kg ha^{-1} for every 1 t ha^{-1} increase in the SOC pool. Similarly, Pan et al. (2009) concluded that an increase of 0.43 t ha^{-1} in cereal productivity could be achieved with a 1 % increase of soil organic matter (SOM). A recent study indicated that global production of the three most important staple crops could increase by 4.3 % through increasing current SOC to optimum levels (Ma et al., 2023).

Defining a specific SOC threshold beyond which its increase will no longer have an impact on crop production remains unclear as this depends on local conditions such as climate and soil properties (Lal, 2020b; Schjønning et al., 2018). Oldfield et al. (2019) indicated that the increases in grain yield have levelled off at approximately 2 % SOC for maize and wheat. Seremesic et al. (2011) reported that this SOC threshold might be less than 1 % in certain stable soils. A recent study quantified the optimum SOC level as between 12.7 and 43.9 g kg^{-1} for the three major crops (i.e., wheat, rice, and maize) (Ma et al., 2023). Conversely, some studies claimed that high SOC content is unnecessary for maximising crop grain yields as long as there are sufficient nutrient and water supplies (Hijbeek et al., 2016; Oelofse et al., 2015). However, Vendig et al. (2023) stated that N fertilisers could not substitute for the effects of SOC on crop productivity.

In addition, the cause-effect relationship between SOC and crop yield is difficult to characterise due to its complex interactions with climate factors (e.g., temperature, precipitation), soil properties (e.g., initial SOC content, soil texture), and agronomic management practices (e.g., fertiliser, irrigation, tillage, residue, and cropping systems) (Lal, 2020a; Schjønning et al., 2018). It has been argued that the positive effects of enhancing SOC on crop production may be attributed to the improvement of soil properties (Schjønning et al., 2018), and study has challenged the importance of SOC in crop production under similar soil and climate conditions (Oelofse et al., 2015). Lin et al. (2023) found that even though enhancing SOC could improve crop performance through nutrient-mediated effects on yield, there was no significant causal relationship. Therefore, exploring the cause-effect relationship between SOC and crop yield using data from long-term experiments would be beneficial to the development of sustainable agriculture (Lal, 2020a).

Paddy soils are more conducive to SOC accumulation compared to upland soils due to their anaerobic conditions (Wu, 2011). Rice production in the Yangtze River Basin accounts for 44.4 % of China's rice production (Liu et al., 2010). Long-term experiments spanning 30–40 years in paddy soils in the Yangtze River Basin provide opportunities to (a) evaluate crop yield and its stability and sustainability under prolonged application of chemical fertilisers and/or manure; (b) explore the relationships between SOC and grain yield, and (c) establish the cause-effect relationship between SOC and grain yield in the context of variation in soil properties using structural equation modelling.

2. Materials and methods

2.1. Site description

In this study, data were collected from seven long-term field experiments established in the 1980s and 1990s based on two dominant rice-based cropping systems (i.e., rice–wheat and rice–rice) and located in the middle and lower reaches of the Yangtze River Basin (Fig. 1). This area has a subtropical climate with high amounts of rainfall and high temperatures in summer. Information concerning the location, climate, initial soil properties, and the starting year of each experiment is listed in Table S1.

2.2. Experimental design

Four treatments were selected for this study: (1) no fertiliser application (CK); (2) application of chemical nitrogen, phosphorus, and potassium fertilisers (NPK); (3) application of manure (M); and (4) a combination of NPK and M (NPKM). The fertiliser application rates during the growing season for each crop of the seven experimental sites including the two cropping systems are listed in Table S2.

2.3. Field management and measurements

In the rice–wheat system, rice was transplanted between late May and early June and harvested between late September and early October. Wheat was sown between late October and early November and harvested in late May. In the rice–rice system, early rice was transplanted between late April and early May and harvested during mid to late July. Late rice was transplanted in late July and harvested between late October and early November. Local conventional field management practices were adopted, including pesticide application and tillage. Irrigation was applied during the rice growing season. The aboveground biomass was taken during harvesting.

In each experimental site, we collected the grains and we sampled the top soil (upper 20 cm) to estimate SOC content, soil total nitrogen (TN), total phosphorous (TP) and total potassium (TK), available nitrogen (AN), available phosphorus (AP) and available potassium (AK), soil pH, and soil bulk density (BD). These soil samples were collected after rice harvest in October or November each year. Mean annual

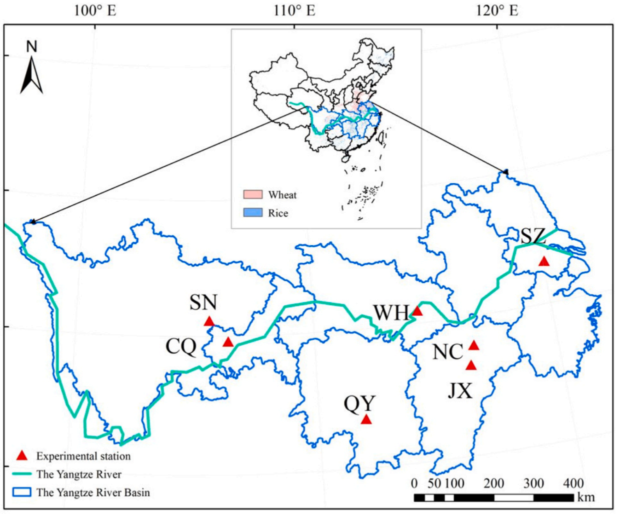


Fig. 1. The spatial distribution of seven long-term experimental stations based on rice–wheat system and rice–rice system located in the middle and lower reaches of the Yangtze River Basin. Rice–wheat system: WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; Rice–rice system: NC, Nanchang; JX, Jinxian; QY, Qiyang.

temperature (MAT) and annual precipitation (MAP) were computed using the data downloaded from the National Meteorological Information Center (http://data.cma.cn/).

2.4. Calculation

Relative grain yield (RY) for different treatments of each crop was used to quantify the influence of fertiliser application measures on enhancing crop grain yields compared to the conventional fertilisation measure (NPK):

$$RY = Y_T / Y_{NPK} \tag{1}$$

where Y_T is the grain yield of a given crop in the CK, NPK, M or NPKM treatment and Y_{NPK} is the grain yield of the crop in the NPK treatment.

The sustainable yield index (SYI) and the coefficient of variation (CV) were used to quantify the yield sustainability and yield stability under different fertilisation treatments. Higher SYI values (close to 1) and lower CV values indicate higher yield sustainability and stability (Han et al., 2020; Qiao et al., 2022a). They are calculated as:

$$SYI = (Y_{mean} - SD) / Y_{max} \tag{2}$$

$$CV = SD / Y_{mean} * 100\% \tag{3}$$

where Y_{mean} and Y_{max} (kg ha^{-1}) are the average and maximum grain yield of a given crop during the experimental period for a fertilisation treatment, respectively, and SD is the standard deviation of the crop yield.

Total soil organic carbon storage (SOC, t C ha^{-1}) is calculated as follows:

$$SOC = SOC_C \times BD \times H \times 0.1 \tag{4}$$

where SOC_C is SOC content (g kg^{-1}), H is the depth of soil sampling, which is set to 20 cm in this study, and 0.1 is a conversion coefficient.

2.5. Statistical analysis

The statistically significant differences in relative crop grain yield among fertilisation treatments were analysed by one-way ANOVA (LSD, $P < 0.05$). Logarithmic regression analysis was performed to evaluate the relationship between SOC storage and relative crop grain yield. Structural equation modelling (SEM) was conducted to establish relationships between relative crop grain yield and environmental variables, including climate (MAT and MAP), soil properties (i.e., TN, TP, TK, AN, AP, AK, SOC, BD, and pH) and fertiliser input in the two cropping systems by using AMOS 21.0 (Amos Development Corporation, Chicago, IL, USA). SEM can be defined as "using two or more structural [cause-effect] equations to model multivariate relationships". It allows to test the direct and indirect relationships between multiple variables in a single model (Grace, 2006). The direct effect describes the pathway from the exogenous variable to the outcome while controlling for the mediator. The indirect effect is the pathway from the exogenous variable to the outcome through the mediator. The total effect is the sum of the direct and indirect effects of the exogenous variable on the outcome (Gunzler et al., 2013). The model was evaluated by the following criteria: a chi-square to degrees of freedom ratio (χ^2/df) lower than 2, a probability level (*P*) higher than 0.05, a comparative fit index (CFI) higher than 0.9, a root mean square error of approximation (RMSEA) lower than 0.08 and a low value for the Akaike information criterion (AIC) (Wen et al., 2004).

3. Results

3.1. Relative grain yield, yield stability, and yield sustainability

The relative grain yield under different fertilisation treatments in the two cropping systems are shown in Fig. 2. Across all sites in the rice–wheat system, the average relative grain yield for rice under CK, NPK, M, and NPKM treatments were 0.59, 1, 0.81, and 1.04, respectively and 0.45, 1, 0.73, and 1.19, respectively, for wheat. In the rice–rice system, the averages for early rice were 0.61, 1, 1.03, and 1.14 and 0.71, 1, 1.04, and 1.15 for late rice under the same treatments. Among all treatments, NPKM produced the highest relative grain yield for both rice and wheat in two cropping systems. On average, NPKM yielded 4.5–18.8 %, 28.9–63.4 %, and 60.4–167 % higher grain yield compared to NPK, M, and CK, respectively, considering the two systems.

The SYI and CV values for grain yield under different fertilisation treatments at each site during the experimental period are shown in Table 1. The SYI values for rice and wheat under all treatments in the rice–wheat system were in the ranges 0.47–0.74 and 0.29–0.6, respectively, while the corresponding values for early rice and late rice under all treatments in the rice–rice system were in the ranges 0.44–0.64 and 0.34–0.68, respectively. The CV values for rice and wheat grain yield under all treatments in the rice–wheat system ranged from 11 % to 26 % and 17–44 %, respectively, while for early rice and late rice in the rice–rice system, the corresponding values ranged from 14 % to 30 % and 15–32 %, respectively. Similar to the relative grain yield, NPK and NPKM generally had higher SYI and lower CV values than the M and CK in both cropping systems (Table 1).

3.2. Relationship between soil organic carbon storage and relative grain yield

Significant correlations between SOC storage and relative grain yield were observed with a logarithmic function in the two cropping systems. Relative grain yield increased with SOC storage for both rice and wheat, and there was no levelling off in these systems (Fig. 3). The magnitude of the increase in grain yield with SOC storage was higher for wheat than for rice in the rice–wheat system (Fig. 3a), while in the rice–rice system, the benefit was greater for early rice than for late rice (Fig. 3b).

3.3. Factors influencing relative grain yield

Structural equation modelling of the relative grain yield with explanatory variables is presented in Fig. 4. The analysis indicated that climate, fertilisation and soil properties together explained 75 and 77 % of the variance in relative grain yield in the rice–wheat and rice–rice systems, respectively. The direct effect of chemical fertilisers (rice–wheat system: 0.63; rice–rice system: 0.73) on relative grain yield was higher than that of manure (rice–wheat system: 0.21; rice–rice system: 0.14). However, the indirect effect of chemical fertilisers (rice–wheat system: 0.05; rice–rice system: 0) on relative grain yield was lower than that of manure (rice–wheat system: 0.06; rice–rice system: 0.16). In the rice–wheat system, SOC together with other soil nutrients (i.e., TN, AN, TP, AP, TK, and AK) had direct positive effects on relative grain yield (total effect of 0.26) (Fig. 4a), while in the rice–rice system, SOC alone had both direct (0.17) and indirect (0.08) positive effects on relative grain yield (Fig. 4b).

4. Discussion

4.1. Fertilisation impacts on crop yield, stability, and sustainability

Fertilisation is considered one of the most effective strategies for enhancing crop yield. In our study, fertilisation produced 37–167 % higher crop yield than the unfertilised treatment (CK), with the maximum benefits observed in the NPKM treatment (Fig. 2). Moreover,

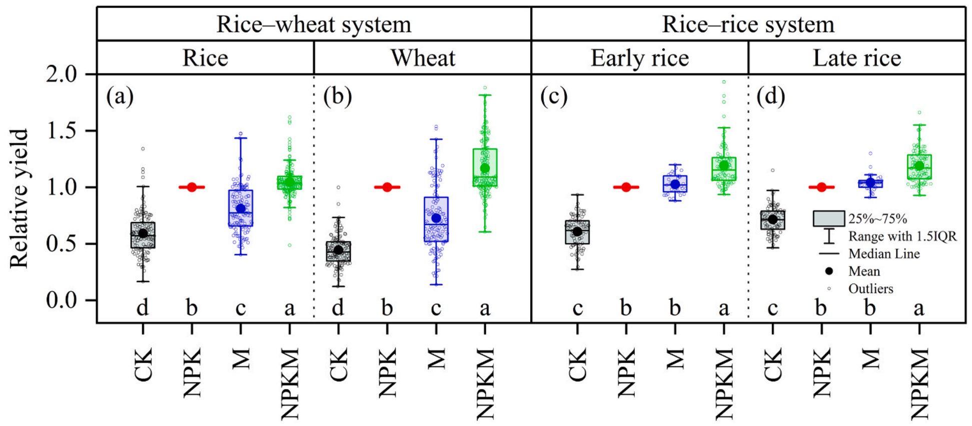


Fig. 2. Relative crop grain yields with different fertilisation treatments in the rice–wheat system (a–b) and rice–rice system (c–d). CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, application of manure; NPKM, a combination of NPK and M.

Table 1
Sustainable yield index (SYI) and coefficient of variation (CV, %) in crop grain yields under different fertilisation treatments in two rice-based cropping systems at the seven long-term experimental sites.

Rotation system	Sites	SYI of rice/early rice				SYI of wheat/late rice			
		CK	NPK	M	NPKM	CK	NPK	M	NPKM
Rice–wheat system	WH	0.49	0.62	0.62	0.62	0.29	0.50	0.30	0.47
	SN	0.52	0.74	0.56	0.74	0.38	0.50	0.49	0.48
	CQ	0.47	0.54	0.49	0.52	0.57	0.60	0.56	0.54
	SZ	0.52	0.61	0.57	0.63	0.39	0.44	0.49	0.48
Rice–rice system	NC	0.44	0.64	NA	0.62	0.61	0.66	NA	0.68
	JX	0.46	0.61	NA	0.51	0.45	0.53	NA	0.52
	QY	-	0.51	0.50	0.59	-	0.34	0.37	0.43
Rotation system	Sites	CV of rice/early rice (%)				CV of wheat/late rice (%)			
		CK	NPK	M	NPKM	CK	NPK	M	NPKM
Rice–wheat system	WH	25	14	15	14	44	28	41	30
	SN	26	11	19	11	35	25	24	25
	CQ	21	17	19	21	22	17	29	19
	SZ	19	16	18	18	32	28	27	28
Rice–rice system	NC	30	14	NA	14	19	15	NA	15
	JX	23	19	NA	18	23	19	NA	21
	QY	-	22	22	17	-	32	31	27

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang;
CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application; NPKM, a combination of NPK and M;
SYI: sustainable yield index of rice or wheat; CV(%): coefficient of variation in crop grain yield;
NA, not available;
-, this treatment was obtained in 2000 on the basis of NPK treatment.

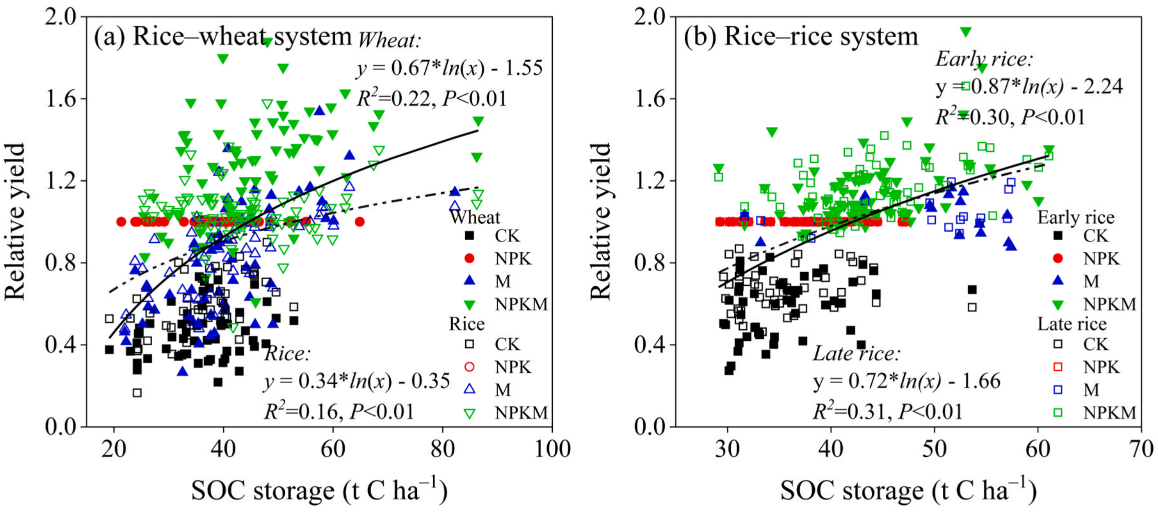
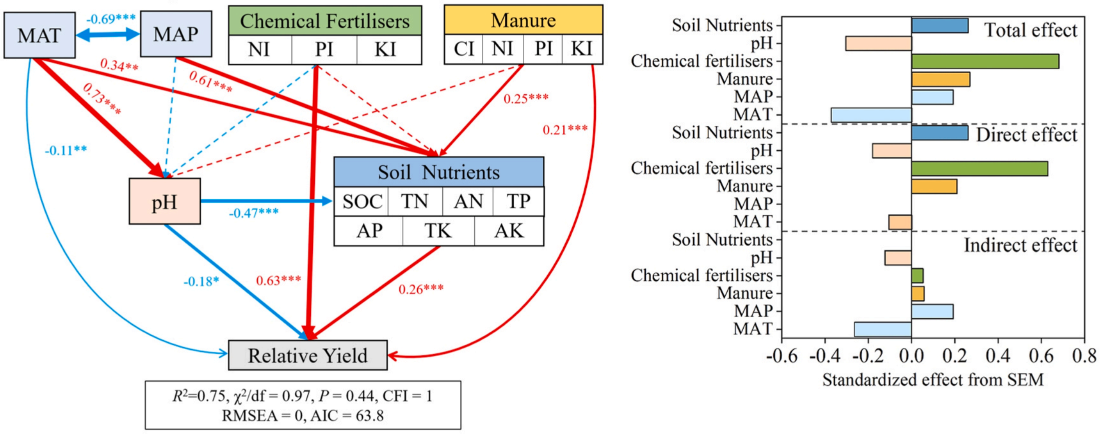


Fig. 3. The relationships between SOC storage (0–20 cm) and relative crop grain yields in both the rice–wheat system (a) and rice–rice system (b). CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, application of manure; NPKM, a combination of NPK and M.

(a) Rice–wheat system



(b) Rice–rice system

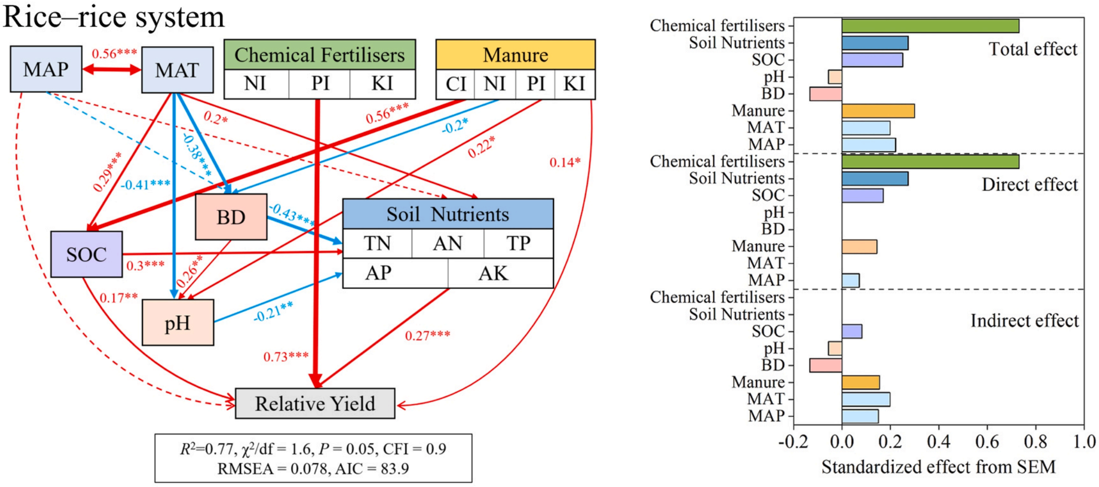


Fig. 4. Structural equation modelling (SEM) analysis of the relative grain yields with explanatory variables (climate, fertiliser input and soil properties) in the rice–wheat system (a) and rice–rice system (b). The red and blue lines represent positive and negative effects, respectively. The line width and numbers above the lines reflect the strength of the path and the standardised path coefficients, respectively. Solid and dashed lines represent significant and non-significant paths, respectively (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). The R^2 value indicates the proportion of variance explained by all variables. MAT, mean annual temperature; MAP, annual precipitation; TN, soil total nitrogen content; AN, available nitrogen content, TP, total phosphorus content, AP, available phosphorus content, TK, total potassium content, AK, available potassium content, SOC, soil organic carbon storage (0–20 cm), BD, soil bulk density, pH, soil pH, CI, amount of carbon input, NI, amount of nitrogen input, PI, amount of phosphorus input, KI, amount of potassium input.

the NPKM treatment produced comparable or even higher grain yield stability and sustainability compared to mineral-only fertilisation (Table 1), emphasising the critical role of manure application in sustaining high crop yield. This result can be attributed to the positive impact of manure on soil nutrient availability. The present study showed that the NPKM treatment generally resulted in the highest levels of SOC, AN, AP, and AK contents after long-term fertilisation across all experimental sites (Table S3), thereby improving nutrient availability for plant uptake (Table S4) and contributing to increased crop yield. This was consistent with the results of previous studies (Cai et al., 2019; Qaswar et al., 2020). The combined application of manure and chemical fertilisers not only provides abundant nutrients to crops but also improves soil structure that in turn enhances water and nutrient uptake by crops (Du et al., 2020; Wang et al., 2017). Manure amendment can also increase crop yield by enhancing microbial biomass and enzyme activity (Luo et al., 2018). Studies have demonstrated that increases in bacterial abundance and improvements in the microbial community structure can effectively increase rice yield (e.g., Wang et al., 2021a; Gu et al., 2009). Furthermore, the slow release of nutrients from manure can sustain nutrient availability for many years after application (Demelash et al., 2014), which may have contributed to the sustainability and stability of soil productivity under the NPKM treatment. In this study, the yields of rice and wheat under the M treatment were lower than those under the NPK treatment in the rice–wheat system. However, in the rice–rice system, the yields of early and late rice under the M treatment were similar to those under the NPK treatment. One potential reason for this result could be the difference in N inputs between M and NPK in the two cropping systems (Table S5).

Our results indicated a positive influence of manure amendment on SOC, subsequently benefiting crop yield in the rice–rice system (Fig. 4b). This implies that manure application could potentially contribute to global reductions in N fertiliser consumption. The enhanced yield associated with higher SOC content may be related to improving N use efficiency by crops, given that the increase in SOC following manure application can reduce N loss through leaching (Wei et al., 2021). Numerous studies have shown similar results. For example, Xue et al. (2014) found that organic supplements combined with appropriate N reduction in the chemical application could sustainably benefit the rice–wheat system. Oldfield et al. (2019, 2020) reported that crop productivity of unfertilised soils with 4 % SOM was comparable to that of fertilised soils with 2 % SOM. As such, it was concluded that inputs from N fertiliser could compensate for the yield loss caused by declines in SOM levels. Additionally, Ma et al. (2023) suggested that SOC increases could be considered as a complementary strategy to N fertiliser application. Because securing food productivity while reducing environmental pollution is one of the most serious challenges facing the human population (Springmann et al., 2018), our results provide potential measures by which to mitigate chemical N pollution from agricultural fields while maintaining high crop productivity.

4.2. Driving factors of crop yields under long-term fertilisation

Our analysis revealed that chemical fertiliser, manure amendment, soil nutrients, pH, and MAT had significant direct effects on crop yield in the rice–wheat system (Fig. 4a), while chemical fertiliser, manure amendment, soil nutrients, and SOC had significant direct effects on crop yield in the rice–rice system (Fig. 4b). Consistent with previous studies (e.g., Iizumi et al., 2021; Ma et al., 2023; Oldfield et al., 2019), application of chemical fertiliser was undoubtedly the most important factor regulating crop yield in the two studied cropping systems. With the increase of chemical N fertiliser input, crop yield will first increase and then remain unchanged (Li et al., 2020). Ren et al. (2022) indicated that the optimum inorganic N rates were 170 and 178 kg ha^{-1} for rice and wheat, respectively, after considering data from 20,460 on-farm fertilisation experiments in China. Our analysis indicated that the direct effect of SOC (0.17) on crop yield was 23.3 % of that attributed to chemical fertilisers (0.73) in the rice–rice cropping system (Fig. 4b). This is comparable to a previous study reporting that the yield benefit due to increasing SOC levels was ca. 20 % that of N fertilisation (Ma et al., 2023). Interestingly, the impact of SOC on crop yield varied depending on the cropping system. In the rice–rice system, SOC was an important factor affecting crop yield, whereas its influence, along with soil nutrients, was significant in the rice–wheat system. The difference may have been due to the different soil conditions in the two cropping systems. Soil pH primarily affects crop yields by influencing soil nutrient availability and microbial activity (Neina, 2019). Consistent with previous studies (Huang et al., 2017; Luo et al., 2018), there was a negative impact of pH on crop yield in the two cropping systems (Fig. 4). Although relatively high model performance was achieved using the selected explanatory variables for the two cropping systems (Fig. 4), some details of the determinants of crop yields may have been missed. Consistent with previous studies (Luo et al., 2018; Lin et al., 2023; Liu et al., 2023), we used the mean annual temperature and annual precipitation to represent the dynamic changes in annual climate conditions over the long-term experimental period at different experimental sites (Fig. S1). However, this approach ignores the fluctuation in climate conditions during the year. Therefore, using explanatory variables with more specific time series (e.g., maximum, minimum and average temperatures or accumulated precipitation amount in a growing season) should be considered in future research.

4.3. Contribution of soil organic carbon to crop yields

Increasing studies have been conducted to investigate the relationship between crop production and management-induced increase in SOC (e.g., chemical fertilisation, manure amendment, residue retention, tillage methods, and cover cropping) (Vendig et al., 2023; Wang et al., 2021b; Xu et al., 2019; Zhang et al., 2016). Our results support the finding that an increase in SOC can positively influence crop production, highlighting potential synergies between climate mitigation and food security goals in intensive agricultural systems. Consistent with previous studies, increasing SOC was more beneficial to wheat than to rice (Iizumi et al., 2021; Lal, 2010). Furthermore, the total effects of SOC (0.25) on yield in the rice–rice system were close to those of manure (0.30) and soil nutrients (0.27), highlighting the critical role of SOC in crop yield (Fig. 4b). It is worth mentioning that the current maximum SOC levels measured in our soils (2.4 % in the rice–wheat system and 3.4 % in the rice–rice system) (Fig. 3) were above the critical level of 2 % (0–20 cm soil depth) that is generally considered optimal for soil function (Loveland and Webb, 2003; Oldfield et al., 2019). However, the maximum SOC levels in our study were close to the values reported by Ma et al. (2023), suggesting that the optimal SOC for crop yield is between 3.1 % and 3.2 % for rice, and by Iizumi et al. (2021), who suggested that the threshold SOC stock leading to the yield plateau is approximately 60 t C ha^{-1} for rice. This inconsistency could be attributed to differences in soil types, crops, climate zones, and agronomic management practices (Lal, 2020a). Our conclusion points in the direction of the highest SOC content. Previous studies have also produced contradictory results. For example, one study indicated that the magnitude of the increase in cereal grain yield due to an increase in SOC content is generally higher in the tropics than in temperate zones (Hijbeek et al., 2018). Another study demonstrated that the yield benefits of SOC increase were only observed in soils with initial SOC levels below 11.6 g kg^{-1} (Vendig et al., 2023). Therefore, considering different levels for the SOC threshold based on local soil and climate conditions would be more effective in accelerating the transition to sustainable intensive agriculture.

The advantages for crop yields resulting from increased SOC may also be linked to improvements in soil properties. Higher SOC levels generally lead to increased nutrient availability, greater soil water retention, and a more favourable soil structure (Lal, 2010, 2020b; Lin et al., 2023). Our analysis indicated a direct positive influence of SOC on TN, AN, TP, AP, and AK in the rice–rice system that in turn had an indirect positive effect on crop yield (Fig. 4b), supporting the positive nutrient-mediating effect of SOC on yield. Previous research has also demonstrated that an increase in SOC can significantly improve nutrient availability for crops. For example, Lin et al. (2023) found that SOC directly affected TN, TP, and AP and thus had a positive impact on crop yield.

4.4. Implications for soil organic carbon sequestration

Our study has demonstrated that further increasing SOC levels can increase crop yield under both rice–wheat and rice–rice systems (Fig. 3). These results underline the importance of enhancing SOC sequestration through the implementation of improved agricultural techniques. Diverse soils and climate types need to adopt different strategies for enhancing SOC storage (Oldfield et al., 2019; Waqas et al., 2020). For example, studies have suggested that soils with greater yield benefits from increasing SOC should be given priority for adopting improved cropland management practices such as manure application, legume cover crops, and conservation tillage (Deng et al., 2023; Lessmann et al., 2022; Vendig et al., 2023). For areas with excessive N from chemical fertilisers, reducing inorganic N fertiliser application combined with organic inputs could maintain both high crop productivity and SOC sequestration (Vendig et al., 2023). As such, innovative agricultural management that can simultaneously increase SOC and crop yield is a promising approach to benefit both food security and climate resilience.

The anticipated threat to crop productivity posed by climate change has prompted consideration of increasing SOC as a potential measure to mitigate its impact (Deng et al., 2023; Qiao et al., 2022b). Previous studies have indicated that increasing SOC levels could prevent yield losses by 3–5 % with each degree Celsius of warming (Deng et al., 2023). Although the use of manure holds promise for increasing SOC sequestration and ensuring crop productivity in agricultural soils, there may be potential trade-offs due to the emission of greenhouse gases such as methane (Shang et al., 2011). Consequently, future studies should focus on a comprehensive assessment of the crop-soil-environment system, with a specific focus on the potential trade-offs and synergies. Process-based models are widely used for their ability to evaluate changes in crop production and soil C and nutrient cycling under various climate conditions and agronomic practices. These models will play a crucial role in assessment. Therefore, using the modelling approach to develop practical adaptation pathways will be essential to creating agricultural resilience against the impacts of climate change.

5. Conclusion

The present study found that combining organic manure with chemical fertilisers produced the highest crop yields and enhanced yield stability and sustainability for wheat and rice in both the rice–wheat and rice–rice systems. Crop grain yields were significantly increased with increasing SOC storage (0–20 cm) in the two systems. Structural equation modelling indicated that fertilisation, soil properties, and climate together explained 75–77 % of the variance in crop yield in the two systems. Chemical fertilisers had primarily direct effects on crop yield (rice–wheat system: 0.63; rice–rice system: 0.73). In contrast, manure had both direct (rice–wheat system: 0.21; rice–rice system: 0.14) and indirect (rice–wheat system: 0.06; rice–rice system: 0.16) effects on crop yield. In the rice–rice system, SOC alone had both direct (0.17) and indirect (0.08) positive effects on crop yield. The findings supported several key conclusions: (i) increasing SOC levels could contribute to high, stable and sustainable crop production in paddy soils; (ii) higher yields could be expected from further increases in SOC in both the rice–wheat and rice–rice systems; and (iii) increased SOC could affect crop yields through regulating soil nutrients. As such, the present study provided motivation for farmers and society to adopt environmentally friendly and sustainable agricultural practices.

CRediT authorship contribution statement

Nan Sun: Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Shuxiang Zhang:** Formal analysis. **Shuhui Wang:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Minggang Xu:** Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Gilles Colinet:** Formal analysis. **Lianhai Wu:** Writing – review & editing. **Joost Wellens:** Writing – review & editing. **Jeroen Meersmans:** Writing – review & editing, Formal analysis. **Bernard Longdoz:** Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Shuhui Wang: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Nan Sun**: Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Shuxiang Zhang**: Formal analysis. **Bernard Longdoz**: Formal analysis. **Joost Wellens**: Writing – review & editing. **Jeroen Meersmans**: Writing – review & editing, Formal analysis. **Gilles Colinet**: Formal analysis. **Lianhai Wu**: Writing – review & editing. **Minggang Xu**: Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127357.

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