LIÈGE université
Gembloux
Agro-Bio Tech

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Promotors: Prof. Gilles Colinet & Prof. Shuxiang Zhang

2025

COMMUNAUTÉ FRANÇAISE DE BELGIQUE
UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH

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Dissertation originale présentée (ou essai présenté) en vue de l'obtention du grade de doctorat en sciences agronomiques et ingénierie biologique

Promoteurs: Prof. Gilles Colinet & Prof. Shuxiang Zhang
Année civile: 2025

Abstract

As a natural climate solution, soil organic carbon (SOC) sequestration in agroecosystem contributes to the achievement of global climate goals. Paddy soils store a huge amount of SOC and play a pivotal role in providing ecosystem services (e.g. climate change mitigation and food security). Exploring the magnitude of SOC sequestration in paddies as well as its benefits on crop production is vital for developing strategies to mitigate climate change and ensure food security. Climate change poses a great threat to global food security, and developing climate change mitigation strategies is imperative to improve the sustainability and resiliency of agriculture.

In this study, a dataset from seven long-term field experiments (since 1980s/1990s) in paddies in the Yangtze River Basin was established. We explored the characteristics of SOC sequestration and crop yield as well as their driving factors under different fertilisation treatments (CK: no fertiliser application, NPK: application of chemical nitrogen, phosphorus and potassium fertilisers, M: application of manure; NPKM: a combination of NPK and M) in two rice-based cropping systems (R–W: middle rice–winter wheat system, R–R: early rice–late rice system). The sustainable yield index (SYI) and the coefficient of variation (CV) were used to quantify yield sustainability and stability. Random forest (RF) and structural equation modelling (SEM) were conducted to quantify the relative importance of different driving factors and their direct and indirect effects on SOC sequestration and yield. To identify climate change feedback and propose climate change mitigation strategies in the future (2024–2100), we calibrated and validated the process-based model SPACSYS with dataset from long-term (>30 years) field experiment in R–W system in Southwest China. Two future climate change scenarios (SSP1–2.6 and SSP5–8.5) and baseline scenario and three mitigation management scenarios including reduced N application rate by 20 % (RNA), the introduction of mid-season drainage (MSD) and integrated management combining RNA with MSD (IM) were conducted. The main results are as follows:

(1). The topsoil SOC stock (0–20 cm) significantly increased by 8.6 t ha^{-1} on average under NPKM treatment in R–W system and by 2.5–6.4 t ha^{-1} on average under NPK and NPKM treatments in R–R system compared with CK treatment during the last four decades. A higher SOC sequestration rate and a longer SOC sequestration duration were found in NPKM treatment than that in NPK treatment in both systems. The fertilisation-induced increases of the SOC stock in the R–W system (NPK: 15.5 %, NPKM: 31.5 %) were higher than that in the R–R system (NPK: 7.4 %, NPKM: 21.6 %). The SEM analysis indicates that soil properties, especially initial SOC content, determine the difference in SOC sequestration between the two systems.

(2). The NPKM treatment produced the highest grain yields for both rice and wheat in the two systems, followed by NPK/M and CK treatments. The NPK and NPKM treatments generally had higher SYI (0.34–0.74) and lower CV (11–32 %) than the M and CK treatments (SYI: 0.29–0.62 and CV: 15–44 %). Crop grain yields were significantly increased with increasing SOC stock (0–20 cm) and followed a logarithmic regression in both systems. SEM analysis revealed that SOC had indirect (through improvements in soil properties) positive impacts on crop yields in the R–R system.

(3). The SPACSYS model performed effectively in simulating yield and nitrogen content in grain and straw, SOC stock and methane (CH_4) and nitrous oxide (N_2O) emissions in R–W system. Compared to the baseline scenario, the climate under the SSP1–2.6 scenario considering the carbon dioxide (CO_2) fertilisation effects may benefit wheat yield (28 %) and had no effects on rice yield. In contrast, under SSP5–8.5 scenario, whether CO_2 fertilisation effects are considered or not, both rice and wheat yield could face great loss (i.e., 11.8–29.9 % for rice, 8.3–19.4 % for wheat). The winter wheat would not be suitable for planting in the distant future (2070–2100) due to the incomplete vernalisation caused by warming. The switching from winter wheat to spring wheat from 2070 onward could totally avoid the yield loss. Under SSP1–2.6 and SSP5–8.5 scenarios, the SOC sequestration rate (0–20 cm) could decrease, the IM scenarios could significantly reduce CH_4 emissions by 55 % and 57 % and N_2O emissions by 23 %, as such reducing the net global warming potential by 69 % compared to no adaptation.

In conclusion, our study reveals that manure amendment on the basis of chemical fertilisation is beneficial for both SOC sequestration and crop production in paddies. There is a synergy between SOC stock and crop production. In future, crop substitution combined with integrated management can achieve the synergy between global warming mitigation and food security services from rice paddies in Southwest China. Our study provides insights into sustainable agricultural management for food security and ecosystem services in paddies.

Keywords: Food Security; Global Warming Mitigation; Soil organic carbon; Crop yield; Greenhouse gas emissions; Process-based model

Résumé

La séquestration du carbone organique dans les sols (SOC) des agroécosystèmes contribue à la réalisation des objectifs climatiques mondiaux. Les sols de rizières peuvent stocker une énorme quantité de SOC et jouent un rôle central dans la fourniture de services écosystémiques (par exemple, l'atténuation du changement climatique et la sécurité alimentaire). Il est essentiel d'évaluer l'état et le potentiel de séquestration du SOC dans les champs ainsi que ses bénéfices sur la production agricole pour élaborer des stratégies visant à atténuer le changement climatique et à assurer la sécurité alimentaire. Le changement climatique représente une grande menace pour la sécurité alimentaire mondiale, et le développement de stratégies d'atténuation du changement climatique est en effet impératif pour améliorer la durabilité et la résilience de l'agriculture.

Dans cette étude, une base de données provenant de sept dispositifs expérimentaux de terrain de longue durée (depuis les années 1980 /1990) dans le bassin du fleuve Yangtze a été établie. Nous avons exploré les caractéristiques liées à la séquestration du SOC et au rendement des cultures ainsi que leurs facteurs moteurs sous différents traitements de fertilisation (CK: pas d'application d'engrais, NPK: application d'engrais chimiques d'azote, de phosphore et de potassium, M: application de fumier; NPKM: combinaison de NPK et de M) dans deux systèmes de culture à base de riz (R–W: système moyen riz - blé d'hiver, R–R: système de riz précoce et de riz tardif). L'indice de rendement durable (SYI) et le coefficient de variation (CV) ont été utilisés pour quantifier la durabilité et la stabilité du rendement. Des modélisations par forêts aléatoires (RF) et sous forme d'équations structurelles (SEM) ont été effectuées pour quantifier l'importance relative des différents facteurs et leurs effets directs et indirects sur la séquestration du SOC et le rendement. Afin d'identifier les rétroactions sur le changement climatique et de proposer des stratégies d'atténuation du changement climatique dans le futur (2024–2100), nous avons calibré et validé le modèle SPACSYS à l'aide d'un ensemble de données provenant d'expériences de terrain à long terme (>30 ans) dans un système de R–W dans le sud-ouest de la Chine. Deux scénarios de changements climatiques futurs (SSP1–2.6 et SSP5–8.5), le scénario de référence et trois scénarios de gestion d'atténuation, y compris la réduction du taux d'application de N de 20 % (RNA), l'introduction du drainage à mi-saison (MSD) et la gestion intégrée combinant RNA et MSD (IM) ont été réalisés. Les principaux résultats sont les suivants:

(1). Le stock de SOC de la couche arable (0–20 cm) a augmenté de manière significative de 8.6 t ha^{-1} en moyenne sous traitement NPKM dans le système R–W et de 2.5 à 6.4 t ha^{-1} en moyenne sous traitement NPK et NPKM dans le système R–R par rapport au traitement CK au cours des quatre dernières décennies. Un taux de séquestration du SOC plus élevé et une durée de séquestration du SOC plus longue ont été observés dans le traitement NPKM par rapport au traitement NPK dans les deux systèmes. Les augmentations induites par la fertilisation du stock de SOC dans le système R–W (NPK: 15.5 %, NPKM: 31.5 %) étaient plus élevées que dans le système R–R (NPK: 7.4 %, NPKM:

21.6 %). L'analyse par SEM indique que les propriétés du sol, en particulier la teneur initiale en SOC, déterminent la différence de séquestration du SOC entre les deux systèmes.

(2). Le traitement NPKM a produit les rendements céréaliers les plus élevés pour le riz et le blé dans les deux systèmes, suivi des traitements NPK/M et CK. Les traitements NPK et NPKM présentaient généralement un SYI plus élevé (0.34–0.74) et un CV plus bas (11–32 %) que les traitements M et CK (SYI: 0.29–0.62 et CV: 15–44 %). Les rendements céréaliers ont augmenté de façon significative avec l'augmentation du stock SOC (0–20 cm) et ont suivi une régression logarithmique dans les deux systèmes. L'analyse par SEM a montré que le SOC avait des effets positifs indirects (grâce à l'amélioration des propriétés du sol) sur les rendements des cultures dans le système R–R.

(3). Le modèle SPACSYS a réussi à simuler efficacement le rendement et la teneur en azote dans le grain et la paille, le stock de SOC et les émissions de méthane (CH_4) et d'oxyde nitreux (N_2O) dans le système R–W. Par rapport au scénario de référence, le climat dans le scénario SSP1–2.6 prenant en compte les effets de fertilisation du dioxyde de carbone (CO_2) pourrait être bénéfique pour le rendement du blé (28 %) et n'a eu aucun effet sur le rendement du riz. En revanche, dans le scénario SSP5–8.5, que les effets de fertilisation par le CO_2 soient pris en compte ou non, le rendement du riz et du blé pourrait subir de fortes pertes (11.8 à 29.9 % pour le riz, 8.3 à 19.4 % pour le blé). Le blé d'hiver ne serait pas adapté à la plantation dans un avenir lointain (2070–2100) en raison de la vernalisation incomplète causée par le réchauffement climatique. Le passage du blé d'hiver au blé de printemps à partir de 2070 pourrait totalement éviter la perte de rendement. Dans les scénarios SSP1–2.6 et SSP5–8.5, le taux de séquestration du SOC (0–20 cm) pourrait diminuer, les scénarios IM pourraient réduire considérablement les émissions de CH_4 de 55 % et 57 % et les émissions de N_2O de 23 %, réduisant ainsi le potentiel net de réchauffement planétaire de 69 % par rapport à l'absence d'adaptation.

En conclusion, notre étude montre que l'amendement avec du fumier en complément de la fertilisation chimique est bénéfique tant pour la séquestration du SOC que pour la production agricole dans les rizières. Il existe une synergie entre le stock de SOC et la production végétale. À l'avenir, la substitution des cultures combinée à la gestion intégrée peut créer une synergie entre l'atténuation du réchauffement climatique et les services de sécurité alimentaire des rizières du sud-ouest de la Chine. Notre étude fournit un aperçu d'une gestion agricole durable pour la sécurité alimentaire et les services écosystémiques dans les agrosystèmes rizicoles.

Mots clés: Sécurité alimentaire; Atténuation du réchauffement climatique; Carbone organique du sol; Rendement des cultures; Émissions de gaz à effet de serre; Modèle basé sur les processus

Acknowledgements

It has been a precious journey in persuing my doctoral degree. I would like to express my sincere gratitude to the people who supported and helped me throughout this journey.

I would like to express my deepest gratitude to my supervisors Prof. Gilles Colinet and Prof. Shuxiang Zhang for their invaluable supervision, exceptional academic expertise, and constant support during the course of my PhD degree. Their insights and dedication have been pivotal to the success of this study. I would also like to extend my sincere thanks to Prof. Nan Sun and Prof. Minggang Xu for their expert guidance, constructive feedback, and unwavering support all through my studies. Special thanks to Prof. Nan Sun, her boundless patience, understanding, and encouragement have been the cornerstones of my PhD journey. I'm particularly grateful to Prof. Jeroen Meersmans for his expert advice, insightful discussions, positive energy and enthusiasm. His guidance and encouragement have been invaluable. I want to express my heartfelt appreciation to Prof. Lianhai Wu for his profound knowledge, rigorous scientific attitude, and thought-provoking questions, which have made significant contributions to publications during my PhD. I am also thankful to all the thesis committee and jury members Prof. Bernard Longdoz, Prof. Joost Wellens, Prof. Jan Bogaert and Prof. Georges Martial Ndzana for their valuable comments and suggestions throughout this academic pursuit, which have helped to improve the quality of my work.

I would like to thank the China Scholarship Council for the funding opportunity to undertake my studies at Water, Soil & Plant Exchanges Laboratory at Gembloux Agro-Bio Tech, University of Liège (ULiège). Additionally, thanks to the Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS) for providing the valuable opportunity to study abroad. Thanks to Mr. Mingjun Zhang for organising this wonderful joint PhD program between ULiège and CAAS.

I acknowledge the financial support I received from the National Key Research and Development Program of China (2021YFD1901205), the National Natural Science Foundation of China (42177341), the UK–China Joint Centre for Sustainable Intensification in Agriculture (CSIA) and National Key R&D Program of China (2021YFD190100202). Thanks to all the colleagues from the long-term fertilisation experimental sites for their support.

Thanks to teachers Prof. Wenju Zhang, Prof. Changai Lu, Prof. Huimin Zhang, Prof. Yinghua Duan, Prof. XiaoJun Shi, Prof. Chunsheng Hu, Zhijian Mu, Junqi Yang, Lei Wu, Chuang Liu, Andong Cai, Bin Wang, Xianmei Zhang, Xubo Zhang, for their constructive comments and motivation in my studies.

I would like to thank my friends, colleagues and research team – Hu Xu, Qiong Wang, Shuo Liang, Sibylle Comeliau, Katia Berghmans, Nicolas Kovacs, Xingjuan Zhu, Mengni Zhang, Xulun Man, Yangyang Liu, Hongbo Yang, Ning Ding, Shengchang Huai, Xin Li, Yuqiao Long, Jinshan Lian, He Zhang, Tao Sun, Qiqi Wang, Jintong Zhao, Zixin Li, for a cherished time spent together in Belgium. And thanks to Lingyun Tang, Fengling Ren, Yalin Li, Jianghua Jiao, Xinchun Gu, Yashi Zhang, Luping Zhang, Miaomiao Li, Naiyu Zhang, Ran Li, Yinjie Zhang, Liping Xu, Dou Ye, for making my academic experience and life in China truly wonderful through their generous help and support.

Finally, I would like to thank my family. My parents, sisters and brother, you've supported me every step of the way. Thank you for always being there for me. Thanks to my niblings for bringing laughter and joy into our family.

Shuhui Wang
December 2024 in Beijing, China

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$[CO_2]$	Carbon dioxide concentration
AK	Available potassium
Al	Aluminum
AN	Available nitrogen
AP	Available phosphorus
BD	Bulk density
CH_4	Methane
Fe	Iron
GHG	Greenhouse gas
Gt	Gigatons
GWP	Global warming potential
GWP_N	Net global warming potential
IPCC	The Intergovernmental Panel on Climate Change
iPOM	Intra-aggregate particulate organic matter
K	Potassium
MAP	Annual precipitation
MAT	Mean annual temperature
Mha	Million hectares
Mts	Million tons
N	Nitrogen
N_2O	Nitrous oxide
NH_4^+	Ammonium
NO_3^-	Nitrate
Non-CO_2	Non-carbon dioxide
O_2	Oxygen
P	Phosphorus
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
TK	Total potassium
TN	Total nitrogen
TP	Total phosphorus

Chapter 1

General introduction

Part of it was extracted from: Shuhui Wang, Nan Sun, Xubo Zhang, Chunsheng Hu, Yuying Wang, Wei Xiong, Shuxiang Zhang, Gilles Colinet, Minggang Xu, Lianhai Wu. Assessing the impacts of climate change on crop yields, SOC sequestration and N_2O emissions in wheat–maize rotation system. Soil & Tillage Research, 2024, 240, 106088. https://doi.org/10.1016/j.still.2024.106088

1. Background

Rice (Oryza sativa L.) is a staple food for over half of the global population, providing about 20 % of the global calories consumed by humans with 11 % of global cropland (Wailes, 2005; FAO, 2019). Ensuring rice production is crucial for global food security. Rice paddies store large amounts of soil organic carbon (SOC) due to retarded decomposition of soil organic matter (SOM) under anaerobic conditions (Liu et al., 2021). However, rice paddies are a main source of non-carbon dioxide (non-CO_2) greenhouse gas (GHG) emissions such as methane (CH_4) and nitrous oxide (N_2O). Globally, CH_4 and N_2O emissions from paddies have been estimated as 6,300 kg CO_2-eq ha^{-1} yr^{-1} (FAO, 2018) and 280 kg CO_2-eq ha^{-1} yr^{-1} (Carlson et al., 2017), contributes about 22 % and 11 % to the total anthropogenic CH_4 and N_2O emissions (IPCC, 2021; FAO, 2020). Nowadays, rice paddies are facing serious challenges in the context of climate change such as increased food demand, shortened growth periods, decreased planting area, shortage of irrigation water source, scarcity of labor availability, and degraded soil quality (Tilman et al., 2011; Haefele et al., 2014). Producing more food while safeguarding the environment is an important issue for mankind. Therefore, adaptation measures that increase SOC stock, reduce GHG emissions and maintain rice production must be adopted to enhance the sustainability and resilience of rice cropping systems in the future.

1.1. Rice production

Globally, rice paddy fields occupy an area of 165 million hectares (Mha), producing 776 million tons (Mts) of milled rice in 2022 (Figure 1-1a, b). Paddy fields account for 23 % of the total area of cereal crop cultivation (FAO, 2020). Over the past six decades, rice yield has improved by 152 % from 1869 to 4705 kg ha^{-1} between 1961 and 2022 (Figure 1-1c). Rice grows in 115 countries in 2020 (FAO, 2022), the top ten countries produce 84 % of the world's rice production, with the top nine producers located in Asia (Figure 1-2).

China is the world's largest rice producer and consumer, rice production reached 210 Mts in 2022 (Figure 1-1b), accounting for 28 % of the global total rice production, followed by India (23.5 %), Indonesia/Bangladesh (7.2 %), and Vietnam (5.7 %) (Figure 1-2). Over past four decades, China's rice production has increased by 47 % compared to 1980 despite a 14 % decrease in the harvested area. This was attributed to the significant increase in grain yield. Rice yield has increased by 70 % from 4144 to 7076 kg ha^{-1} between 1980 and 2022 (Figure 1-1c). In China, rice is usually cultivated in three types of cropping systems, including single rice, middle rice−upland rotation and early rice−late rice rotation, which account for 15.5, 43.4, and 41.1 %, respectively, of the total rice production (Guo et al., 2017) (Table 1-1).

Rice production is influenced by the interactions between cultivars, climate conditions, soil properties, and agronomic management practices. Since the onset of the Green Revolution in the late 1960s, many technological and agronomic improvements have been developed to maintain high crop yield, including the adoption of high-yielding cultivars, intensive use of fertiliser and irrigation water, and improved planting methods (Cassman, 1999).

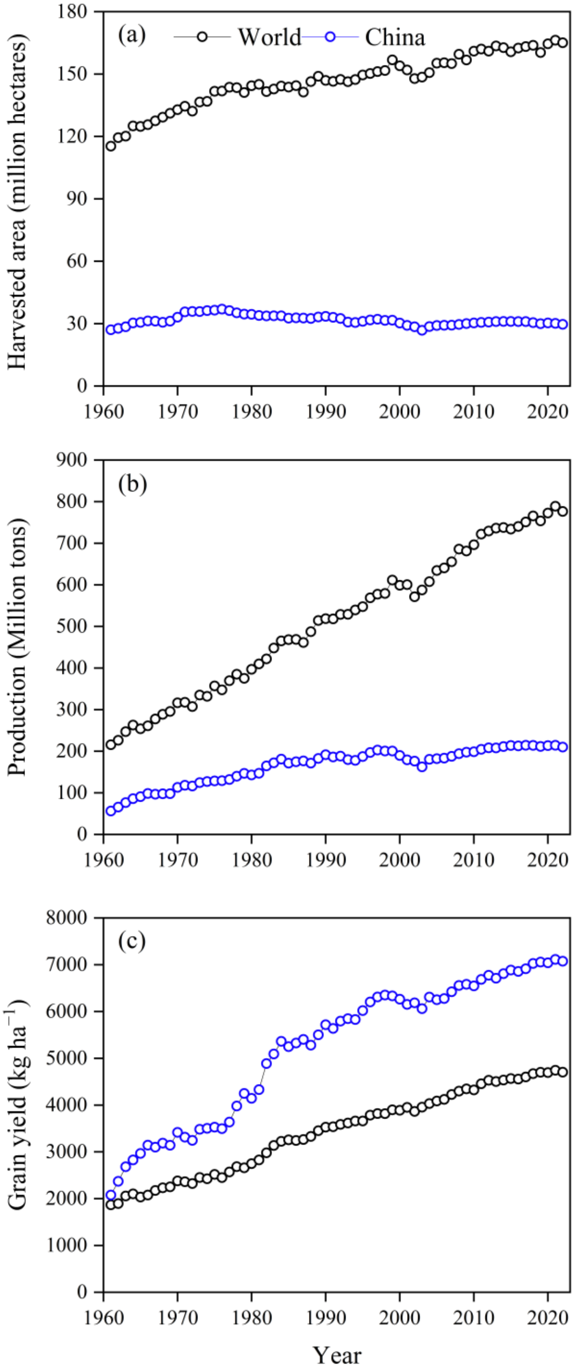


Figure 1-1: Rice harvested area (a), total production (b) and grain yield (c) in the world and China from 1961 to 2022 (FAO).

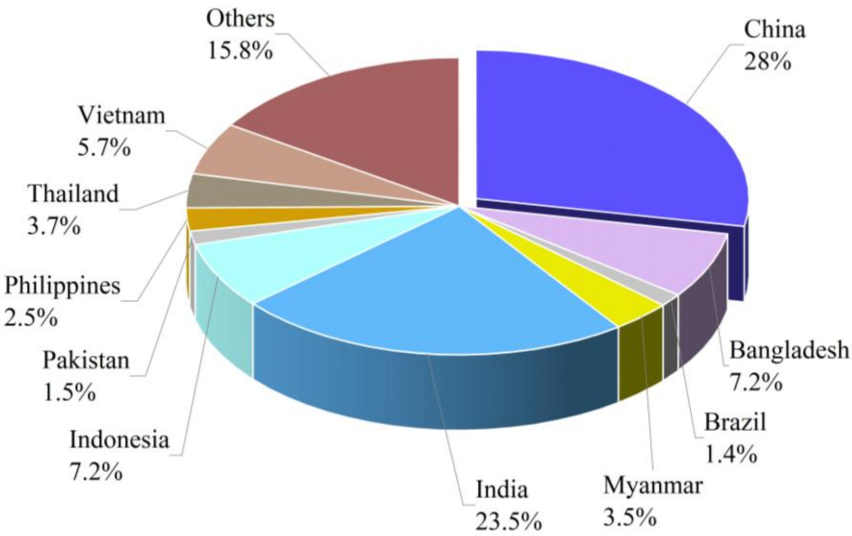


Figure 1-2: Percentage of rice production in different countries in 2019 (FAOSTAT, USDA).

Table 1-1: Classification of rice types under different rice cropping systems in China.

Rice type	Transplanting date	Harvest date	Rotation system	Growing region	Percent of rice production
Single rice	Mid-early May	Mid-late September	One-season rice in a year	Northern China	15.5 %
Middle rice	Late May-early June	Late September-early October	Paddy-upland rotation	Southwestern and Central China	43.4 %
Early rice	Late April-early May	Mid to late July	Double season rice in a year	Southern China	41.1 %
Late rice	Late July	Late October-early November			

1.2. SOC sequestration

The global terrestrial ecosystem contains 2500 gigatons (Gt) soil carbon (to 1 m depth), including 1550 Gt of SOC and 950 Gt of soil inorganic carbon (SIC). The C pool is about 3.3 times that of atmospheric pool (760 Gt) and 4.5 times that of biotic pool (560 Gt), therefore, C sequestration in soils has been considered a promising measure for mitigating the increasing CO_2 concentration in the atmosphere (Lal, 2004). In agroecosystems, the amount of soil organic carbon (SOC) stored within the soil profile is the ultimate result of the balance between C input, mainly come from manure amendment, crop residues incorporation (straw, stubble, and roots) and rhizodeposition, and C loss through the decomposition of SOM by microorganisms or erosion (Álvaro-Fuentes et al., 2012). When C input > C loss, SOC stock will increase;

while when C input < C loss, SOC stock will decrease. SOC sequestration refers to transferring atmospheric CO_2 into the soil C pool as part of the SOM or by slowing decomposition (Smith, 2005; Lal, 2014). Therefore, any factor that affects the C input or output process could have an influence on SOC sequestration. SOC sequestration mainly depends on edaphic, climate conditions and agricultural management practices (e.g. manure addition, fertilisation, irrigation, tillage, straw retention, cropping systems, cover crops) (Lal, 2004; West and Six, 2007). Similarly, the decomposition of SOM mainly depends on the internal soil properties, including soil physical, chemical and biological properties, and environmental factors such as climatic conditions (temperature, precipitation) and agronomic management practices (land uses, cropping systems, and tillage) (West and Six, 2007; Wan et al., 2011).

Enhancing SOC stock in terrestrial ecosystem is considered as a cost-effective and environmentally friendly measure to sequester anthropogenic CO_2 emission (Fang et al., 2007). In 2015, the “4 per 1000” (4 ‰) initiative was launched in Paris, suggested that an annual increase of 4 ‰ of the world soil surface C stocks (top 30 to 40 cm, 860 Gt) would nearly compensate the annual atmospheric CO_2 increase (4.3 Gt). Study has indicated that the sequestration rate of 4 ‰ can be achieved under the best management practices in global soils (SOC unsaturated), and higher sequestration rate might be viable in soils with low initial SOC stock (< 30 t C ha^{-1} in the topsoil) (Minasny et al., 2017). However, the potential for C sequestration in soil is finite (Stewart et al., 2007), soil C will approach a new steady state following a change in land use (West and Six, 2007). When the land management changes again, soil may sequester additional C until the maximum SOC level, which represents SOC saturation. SOC saturation level depends on soil texture (silt- and clay-protected), soil structure (microaggregate-protected), and the biochemical complexity of SOM compounds (Six et al., 2002). SOC sequestration duration refers to the time to which soil C steady state is reached (West and Six, 2007).

Rice paddies cover 11 % of the world’s cropland (Wailes, 2005; FAO, 2019). Paddy soils are anthropogenic soils (Anthrosols) for rice cultivation, characterised by frequent flooding and puddles (Liu et al., 2021). Paddy soils are a quantitively important organic carbon pool, contain 18 Pg SOC worldwide (0–100 cm soil), in which China, India and Indonesia together contributes more than half of the global paddy SOC pool (Liu et al., 2021). Flooded paddy soils usually store more C than adjacent upland soils, this may be ascribed to their differences in C input, SOM decomposition rate, SOC sequestration efficiency, and their SOC stabilisation (Yan et al., 2013). The management-induced periodic flooding and drainage processes in paddy soils lead to the repeated redox alternations, which intensify mineral weathering and leaching processes, increase the total iron oxide contents and its crystallinity, accelerate the formation of ferrihydrite, thus contribute to the accumulation of SOC (Kögel-Knabner et al., 2010). In subtropics and tropics climatic zones, the high temperature and abundant rainfall allows two or three rice cropping seasons per year. Study demonstrated that the belowground C input in rice cropping system is usually higher than that in upland cropping system (e.g. maize, wheat) due to the higher root biomass (Liu et al., 2019a), this contributes to the formation of stable

SOC (Sokol and Bradford, 2018). The decomposition of SOM is much slower in paddy soils due to the lack of oxygen (O_2) and other terminal electron acceptors under waterlogging than that in upland soils, this result in the accumulation of SOM (Wu, 2011a). Paddy soils are enriched with plant-derived C rather than microbial-derived C due to the retarded microbial decomposition under anaerobic conditions caused by flooding (Chen et al., 2021). In paddy soils, the mechanisms of SOM stabilisation are suggested as its occlusion in aggregates and its interactions with clay minerals and iron oxides (Kögel-Knabner et al., 2010).

1.2.1. Measures to increase SOC stock

Optimising agricultural management for increasing SOC accumulation is vital for the mitigation of climate change. Different agricultural management can result in changed C inputs or C losses, thereby affecting SOC stock (West and Six, 2007). The cropland management practices aimed at enhancing SOC stock include organic (Li et al., 2021a) and chemical fertilisation (Tang et al., 2023), straw retention (Hao et al., 2022), no tillage (Kan et al., 2021), diversified crop rotation (Witcombe et al., 2023), cover crop (Jian et al., 2020), and biochar addition (Xu et al., 2024). Increasing C input into soil is regarded as the most efficient practice to increase SOC stock in agricultural soils (Fujisaki et al., 2018). Liner and logarithmic relation have been employed to reveal the relationship between SOC sequestration and C input (Mandal et al., 2008; Cai et al., 2019). C sequestration efficiency (i.e. ΔSOC/ΔC input) was used to quantify the conversion efficiency of applied organic matter in enhancing SOC stock in cropland. Studies have reported that the C sequestration efficiency ranged between 8.2 % and 12 % in global cropland soils from C-enhanced management practices (e.g. manure application, tillage reduction, crop rotation ect.) (Maillard and Angers, 2014; Fujisaki et al., 2018).

(1). Organic fertilisation

Organic fertilisation can increase SOC directly as an external C input. In addition, it can increase soil fertility and improve soil structure by increasing soil nutrient and SOM content and thereby enhancing SOC indirectly by increasing C input from crop biomass (Liang et al., 2011; Kidd et al., 2017; Luo et al., 2018). Based on a balanced database, study has indicated that manure-C input was the most important factor influencing SOC stock changes in global agricultural soils, contributing 72 % and 34 % of the increase in SOC stock compared to mineral fertilised and unfertilised treatments (Li et al., 2021a).

(2). Chemical fertilisation

The application of chemical fertilisers can promote the production of crop biomass, thus increasing the organic C input to soil through the return of crop residues and root exudates, and subsequent SOC stock. Nitrogen (N) and phosphorus (P) additions significantly increased SOC stock in global terrestrial ecosystem by 8.3 % (Tang et al., 2023) and 2.6 % (Luo et al., 2023). N deficiency accelerates SOC decomposition in temperate degraded grasslands (Zeng et al., 2023). Studies has indicated that the SOC sequestration in China's cropland was attributed to the increased input of chemical fertilisers (Wu, 2011b; Zhao et al., 2018).

(3). Straw retention

Crop residues are an important source of increasing SOC stock in agro-ecosystems, with an estimated production of 4 Gt yr^{-1} globally (Lal, 2008). Study has reported that straw return can increase SOC content by 12.8 % in global agricultural soils (Liu et al., 2014). Plant residues can be converted to microbial-derived C by microorganisms, which has recently been considered more stable than plant-derived C in some cases (Sokol and Bradford, 2018).

(4). No-tillage

Tillage can affect soil physical properties including soil compaction, soil hydraulic properties, and soil aggregate stability, thus influencing the root penetration, water and nutrients availability, and C sequestration (Blanco-Canqui and Ruis, 2018). Study has revealed that no-tillage increased the macroaggregate (>2 mm) content, soil structural stability, mean weight diameter, and the SOC stock (Qi et al., 2022).

(5). Cover crop

Cover cropping has been recognized as effective to reduce erosion, reduce N leaching, suppressing weeds, increase crop production, improve soil health, and mitigate climate change (Blanco-Canqui et al., 2015; Kaye and Quemada, 2017; Vendig et al., 2023). Study has indicated that incorporating cover crops into crop rotations leads to a significant SOC increase by 15.5 % in global agricultural soils (Jian et al., 2020).

(6). Diversified cropping systems

Monocropping systems are widespread all over the world, which have been considered to result in soil quality degradation and the aggravation of pests and diseases (Wang et al., 2022a). Diversified cropping systems (i.e. crop rotation, multiple cropping, or intercropping) promote soil microbiome functions and soil health (Wang et al., 2022a; Yang et al., 2024). Research has demonstrated that diversified cropping systems enhance SOC stock by increasing soil aggregation and stability (Yan et al., 2022).

(7). Biochar addition

Biochar is a C-rich solid formed by pyrolysis of biomass, which is highly recalcitrant. The Intergovernmental Panel on Climate Change (IPCC) has suggested biochar application as carbon dioxide removal (CDR) method for abating climate change by SOC sequestration (Masson-Delmotte et al., 2008; Woolf et al., 2010). Study has identified that biochar application can increase SOC stock indirectly by promoting aggregation and the physical stabilisation of SOM (Burrell et al., 2016; Wang et al., 2017a). Biochar applications can also benefit crop yields, improve soil health, and enhance ecosystem services (Lal, 2010b; Amelung et al., 2020; Lehmann et al., 2020).

1.2.2. Relationship between SOC and crop yield

Organic C in agricultural soils contributes positively to soil quality and crop productivity (Lal, 2004, 2006, 2010b; Oldfield et al., 2019; Wiesmeier et al., 2019; Lin et al., 2023; Ma et al., 2023; Vendig et al., 2023). The low SOM content may lead to low agronomic productivity, especially for degraded soils (Lal, 2020a). Numerous studies have investigated the relationships between SOC stock and crop yield (Pan et al., 2009; Zhang et al., 2016a; Schjønning et al., 2018). For example, study reported that with every 1 t ha^{-1} increase in SOC stock in the root zone, the crop yield for wheat, rice, and maize could increase by 20–70, 10–50, and 30–300 kg ha^{-1}, respectively (Lal, 2006). Another research quantified that increasing the current SOC levels to optimum could increase the global three most important crop production (wheat, rice and maize) by 120 Tg yr^{-1} (4.3 %) (Ma et al., 2023). Three mechanisms could explain the benefit of enhancing SOC stock on crop yields: (1) increase plant available water capacity; (2) improve soil structure or other physical properties; (3) increase plant available nutrients (Lal, 2006, 2020b).

The effects of SOC on crop yield depend on different endogenous and exogenous factors, and the interaction among them as influenced by land use and agronomic management (Lal, 2020a). Due to the complex and interacting factors influencing SOC and crop yield, making the direct cause-effect relationship between them difficult to establish (Lal, 2020b). Moreover, the positive effect between SOC and crop yield operates in both directions (Ma et al., 2023). Studies indicated that the increase in crop production also has a positive impact on SOC stock through increment of crop residues and belowground biomass (Li et al., 2023; Siddique et al., 2024). Therefore, it is necessary to explore the cause-effect relationship between SOC and crop yield using data from long-term field experiments (Lal, 2020a).

Increasing SOC not only benefits crop production, but also contributes to minimising environmental effects (Lal, 2004, 2010a). For example, study estimated that the enhancement of SOC helps to reduce current global chemical N fertiliser application by 5 % and 7 % across global maize and wheat fields (Oldfield et al., 2019). Optimising SOC levels for crop production could substantially reduce the application of chemical N, P and potassium (K) fertilisers, thus resulting in a significant reduction in GHG emissions of 3.36 Mt CO_2-eq in China's Huang-Huai winter wheat cropping system (Dang et al., 2024). As such, exploring SOC-oriented agricultural management practices could be crucial for accelerating the transition to sustainable agriculture.

1.3. GHG emissions in paddies

The atmospheric concentrations of non-CO_2 GHG such as CH_4 and N_2O have increased by 150 % and 20 % since the pre-industrial time (IPCC, 2014). Agriculture is estimated to account for 10–12 % of total anthropogenic GHG emissions (Smith et al., 2007). Although rice is the most important stable crop, rice cropping systems are a substantial source of anthropogenic GHG emissions. Study indicated that rice-based cropping systems produced the highest among all the cereal cropping systems, accounting for 48 % of the global total crop GHG emissions (Carlson et al., 2017). Specifically, rice paddies contribute 22 % and 11 % of the global agricultural CH_4 and N_2O emissions, respectively (IPCC, 2021; FAO, 2020).

1.3.1. CH_4 emission

Rice growth requires a lot of water, every 1 kg of rough rice needs 2.5 cubic meters of water (Bouman, 2009). Flood irrigation is the most commonly used method of irrigation for rice cultivation in many countries (Kumar and Ladha, 2011). This results in large CH_4 emissions due to the decomposition of SOM under anaerobic conditions with absence of O_2 and redox potential below −150 mV (Gupta et al., 2021). CH_4 is a potent greenhouse gas, it can affect the oxidation of the atmosphere by controlling the concentrations of tropospheric hydroxyl radicals (Holmes, 2018). The global warming potential (GWP) is 273 times that of CO_2 over a 100-year time horizon (IPCC, 2021). CH_4 releases to the atmosphere are the result of CH_4 production, oxidation and transport processes (Le Mer and Roger, 2001) (Figure 1-3). Water management and organic C input have been recognized as the two important factors influencing CH_4 emissions from paddies (Yan et al., 2005).

(1). CH_4 production

CH_4 was produced in anaerobic environments by methanogenic bacteria during the anaerobic decomposition of SOM.

(2). CH_4 oxidation

CH_4 can be consumed by aerobic methanotrophs in the rhizosphere and oxidised soil-water interface where O_2 exists.

(3). CH_4 transport

CH_4 is transferred to the atmosphere through three pathways: diffusion through rice aerenchyma, ebullition, and diffusion.

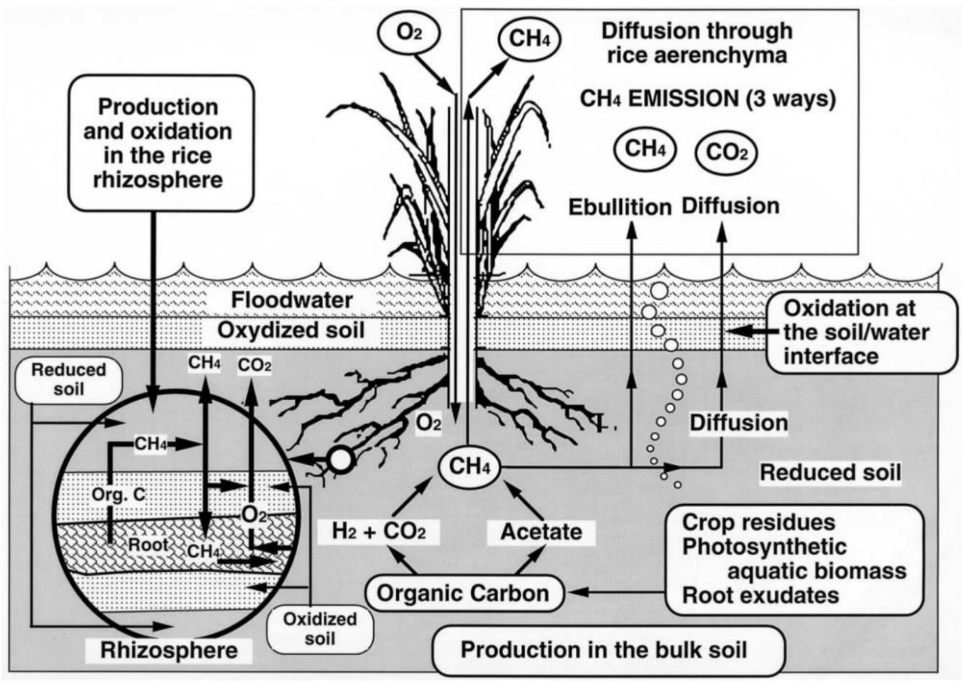


Figure 1-3: CH_4 production, oxidation and emissions from paddies. Derived from (Le Mer and Roger, 2001).

1.3.2. N_2O emission

N_2O is a main potent long-lived greenhouse gas and ozone-depleting substance, the GWP is 27 times that of CO_2 over a 100-year time horizon (IPCC, 2021). Agricultural is the main source of anthropogenic N_2O emissions, accounting for 60 % of global N_2O emissions (Smith et al., 2007). N_2O emissions to the atmosphere are mainly produced through soil nitrification and denitrification processes (Figure 1-4). In paddy soils, N_2O emissions are usually produced under aerobic conditions during the field drainage periods (Pittelkow et al., 2013).

Chemical N fertiliser application is the most important driver of N_2O emissions in agriculture (Yue et al., 2018), which is widely applied in cropland to boost crop production (Vitousek et al., 2009). During 2001–2015, China and India together consumed more than half of the increase in N fertiliser used worldwide (FAO, 2018). The excessive and improper use of chemical fertiliser has resulted in large environmental risks, including nutrient losses (Liu et al., 2019b), GHG emissions (Winiwarter et al., 2018) and soil acidification (Schroder et al., 2011). Previous studies have shown that direct N_2O emissions were highly correlated with chemical N fertiliser application levels in agriculture (McSwiney and Robertson, 2005; Huang et al., 2017a; Takeda et al., 2021). It is estimated that about 0.68 %, 1.21 %, and 1.06 % of the applied N was released as N_2O in rice, wheat and maize field, respectively (Linquist et al., 2012a).

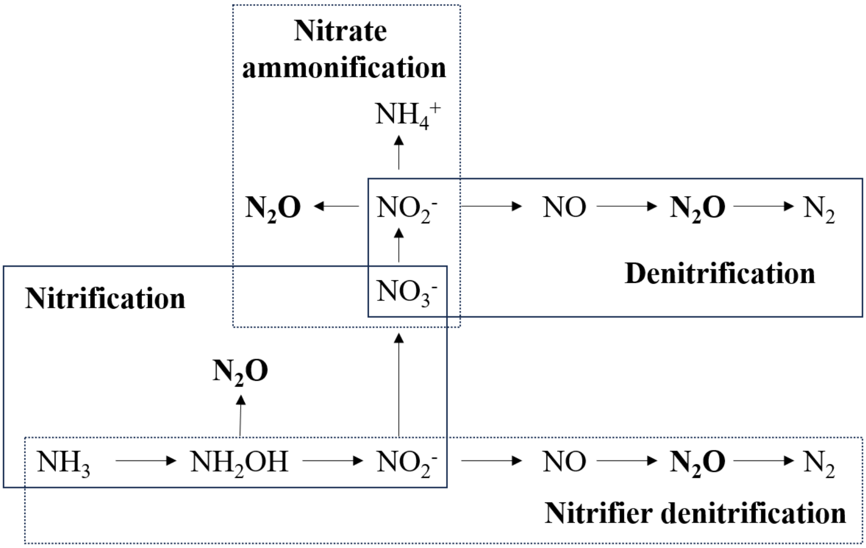


Figure 1-4: Microbial sources of N_2O in soil. Adapted from Baggs (2008).

1.3.3. Global warming potential

The global warming potential (GWP) of CH_4 and N_2O are 27 and 273 times that of CO_2 over a 100-year time horizon (IPCC, 2021). Study reported that the GWP of rice are 5.7 and 2.7 times that of wheat and maize, respectively (Linquist et al., 2012a).

SOC sequestration can compensate for part of the global warming effects caused by GHG emissions. Therefore, both SOC sequestration and GHG emissions should be considered to comprehensively evaluate the global warming impact of agricultural soils (Haque et al., 2014).

1.4. Challenges facing rice fields under climate change

Climate change, caused by the increase in concentrations of GHG in the atmosphere, is a vital challenge facing humanity (Gupta et al., 2021). Many international agreements have been announced to avoid disastrous climate change. For example, IPCC suggested limiting global warming below 1.5 degrees Celsius (°C) at the end of this century in the Paris agreement in 2016 (UNFCC, 2015). A total of 124 nations had pledged to becoming carbon neutral by 2050 or 2060 as of February 2021 to keep global warming to 1.5–2°C above preindustrial levels to mitigate global warming and extreme climate disasters (Black et al., 2021). Carbon neutrality means having a balance between carbon emission and transforming carbon from the atmosphere into carbon sinks (Rogelj et al., 2015). However, the average global temperature in 2023 have already raised by 1.35°C than the pre-industrial period (1850–1900) (Lindsey and Dahlman, 2024).

Climate change with extreme weather conditions such as heat waves, frequent drought, floods, poses challenges in meeting global food demand (Wassmann et al., 2009a, 2009b). The sustainability of rice-based cropping systems is threatened by stagnating or declining yields (Ray et al., 2012), shortened crop growth duration (Zhang et al., 2023), decreased planting area (Chen et al., 2020), shortage of available water resources, reduced soil availability (Haefele et al., 2014) and increased GHG emissions (Sun et al., 2023) under future climate change. Researchers have raised concerns related to rice yield loss (Chen et al., 2020) and increasing GHG emissions in future warming climate (Liu et al., 2018a; Liu et al., 2020b). Future rice-based cropping systems must produce more grain while minimising the negative impacts on the environment (Yuan et al., 2021).

(1). Frequent extreme weather events

Climate change is projected to increase the frequency and intensity of extreme weather events such as heat waves, droughts, wildfires, and floods (AghaKouchak et al., 2020). The climate hazards significantly negatively influence global crop production (Heino et al., 2023). For example, extreme temperatures are predicted to decrease global rice yields by 33.6 % in 2090s (Zhu et al., 2022a).

(2). Increasing food demand

The global population is projected to exceed 9.7 billion by 2050 (United Nations, 2019). Food production must be increased by 60–110 % to meet human demand (FAO, 2012) (Tilman et al., 2011), in which, rice production must be increased by 28 % (Alexandratos and Bruinsma, 2012). However, the rate of growth in rice yield has been declining in recent years, rice yields have stagnated in some regions around the world (Ray et al., 2012). Furthermore, study indicated that food production will be decreased by decreasing cropping frequency and yields under warming (Zhu et al., 2022b).

(3). Shortened crop growing periods

Climate warming will accelerate the development of crop growth and shorten the time for photosynthesis, thus decreasing biomass accumulation and crop yield (Chen et al., 2009; Wang et al., 2014; Ding et al., 2020). Study indicated that the crop growing periods are expected to be shortened in most rice cropping areas in China (Sun et al., 2024).

(4). Shortage of irrigation water resources

Flood-irrigated rice requires two to three times as much water as other cereal crops (Bouman, 2009). Irrigated rice consumes 30 % of the global exploited freshwater (Singh, 2012). However, study reported that climate change has threatened the stable supply of irrigation water resources (Tan et al., 2016).

(5). Reduced soil availability

Globally, one-third of the rice paddies is located in “very poor” soils and about 8.3 million ha of rice is grown on problem soils (e.g. saline, alkaline/sodic, acid-sulfate, and organic soils) (Haefele et al., 2014). Furthermore, study demonstrated that the SOC loss caused by indirect effects of climate change (e.g. wildfires) is higher than that caused by direct effects of climate change (e.g. rising temperature) (Beillouin et al., 2023).

(6). Increasing GHG emissions

Warming increases the substrate availability for methanogens, thereby increasing CH_4 emissions from paddies (Liu et al., 2016; Wang et al., 2018a). Elevated [CO_2] promotes photosynthesis and crop growth (Kuzyakov et al., 2019), this increases C substrate availability (e.g. rhizodeposits, root exudates and residue) for methanogens and their abundance, therefore CH_4 emissions (Inubushi et al., 2003; Wang et al., 2018a). Study estimated that CH_4 emissions from paddies could be increased by 4–40 % and 15–23 %, respectively, under future elevated [CO_2] and temperature conditions (Qian et al., 2023).

Warming accelerates the decomposition of SOM, increase the availability of inorganic N, thereby promoting N_2O emissions (Bai et al., 2013; Li et al., 2019). Numerous studies have revealed that the positive feedback of N_2O emissions in response to climate warming (Griffis et al., 2017; Li et al., 2019). Short-term elevated [CO_2] can increase concentrations of labile soil C and nitrate (NO_3^-), increase methanogens and denitrifier populations, thus promoting N_2O emissions (Bhattacharyya et al., 2013). However, long-term elevated [CO_2] can decrease N_2O emissions through reducing the soil ammonium (NH_4^+) concentration (Yu et al., 2022).

1.5. Adaptation and mitigation strategies

Climate change mitigation refers to reducing anthropogenic forcing of the climate system. Food security is a key target in the Sustainable Development Goals (SDGs). The focus on climate change mitigation raises food security concerns. Agricultural management practices have an important influence on crop yields improvements and GHG emissions in rice paddies (Linquist et al., 2012b; Liu et al., 2023a). However, GHG emission mitigation strategies in paddy fields are facing the trade-off between CH_4 and N_2O emissions. Agricultural management practices (e.g. introduction of mid-season drainage, intermittent irrigation) aimed at reducing CH_4 emissions could inevitably increase N_2O emissions (Feng et al., 2021). For example, study quantified that mid-season drainage decreased CH_4 emissions by 52 % while increased N_2O emission by 242 % in rice paddies (Liu et al., 2019c). Developing GHG mitigation strategies in paddies have been of key concern (Gupta et al., 2021).

Optimising strategies to achieve the synergy between climate change mitigation and food security services are critical for developing sustainable agriculture. Study have revealed that integrated management (slow/controlled-release fertilizer, water-saving irrigation and no-tillage) can decrease GHG emissions without yield compromise in rice–wheat rotation system (Zhang et al., 2024b). Through implementing region-specific adaptation strategies, global rice production is expected to increase by 36 %, while GHG emissions could be reduced by 23 % (Gao et al., 2025a). Therefore, optimised agricultural management measures should be investigated for farmers and policymakers to reduce GHG emissions and maintain crop yield.

(1). Crop cultivar improvement

Improving rice varieties is considered as the most effective strategy to counter the negative effect of climate change on yields (Li et al., 2024a). Many studies have suggested developing new rice cultivars to increase yields such as heat-tolerant cultivars, high-yielding cultivars (Li et al., 2024b). In addition, different rice cultivars have different capacities to transport CH_4 and N_2O from paddy soils to the atmosphere, therefore breeding new cultivars with higher yields and lower CH_4 emissions is promising in ensuring food security while mitigating climate change. Research demonstrated that high-yielding rice cultivars can facilitate CH_4 oxidation through promoting O_2 transport to rhizosphere soils, thus reducing CH_4 emissions by 7.1 % and increase yield by 10 % in Chinese rice agriculture (Jiang et al., 2017).

(2). Planting date shift

Timely adaptation or delayed adaptation of sowing or transplanting dates has been recommended as an effective strategy to cope with climate change (Zheng et al., 2012; Wang et al., 2022b; Zhang et al., 2023). Planting dates shifts can allow crops to grow in a more suitable climate condition. Study quantified that global crop yields can be increased by 12 % through adjusting sowing dates and cultivars under climate change (Minoli et al., 2022).

(3). Cropping system change

Changing cropping systems or crop migration have been discussed as an adaptive strategy to limit the adverse effect of climate change on crop production (Sloat et al., 2020; Guo et al., 2024a, 2024b). Research indicated that climate-sensitive region has the potential for land expansion and cropping frequency increase, it can benefit crop production by 4.4 % and 4.5 % for Chinese single and triple rice cropping system (Guo et al., 2024a).

(4). Irrigation water management

Non-continuous flooding such as mid-season drainage and alternate wetting and drying irrigation in paddies have been considered beneficial to reduce CH_4 emissions without sacrificing rice yields, although they can promote N_2O emissions (Tariq et al., 2017; Liu et al., 2019c; He et al., 2020). A global meta-analysis quantified that non-continuous flooding reduced CH_4 emissions and GWP by 53 % and 44 %, despite N_2O emissions were increased by 105 % from rice paddies (Jiang et al., 2019).

(5). Fertiliser management

The response of GHG emissions to mineral N fertilisation depends on fertiliser type and amount. Direct N_2O emissions increase linearly (Zou et al., 2005a) or exponentially (Shcherbak et al., 2014; Bizimana et al., 2021) with increasing N fertilisation levels from agricultural soils. The response of CH_4 emissions to N input in rice paddies generally increased with the increase of N at low N application levels and decreased at high N application levels (Kim et al., 2016; Liao et al., 2021). N fertilisation can increase plant biomass, which provides more organic substrates for methanogens, and subsequently increase CH_4 production (Schimel, 2009). The decrease in CH_4 emissions at high N fertilisation levels in rice paddies may be attributed to the increased N fertilisation-induced CH_4 consumption (Kim et al., 2016). Mounting studies have revealed that substantial GHG emission mitigations or N losses reductions can be obtained through optimised N fertiliser reduction (Table 1-2). Enhanced-efficiency N fertilisers (e.g. controlled-release fertilisers, nitrification inhibitors and urease inhibitors) can significantly reduce N_2O emissions and increase crop yields (Xia et al., 2016; Lyu et al., 2021b).

Table 1-2: Optimised N fertiliser reduction to reduce GHG emissions or N losses without loss of crop production in rice-based cropping systems in China.

Cropping systems	Chemical N application		Reduction in GHG emissions or N losses	Reference
	Traditional (kg N ha^{-1} yr^{-1})	Recommended reduction		
Rice–wheat	448	27 %	52 % (apparent N losses)	Fan et al., 2007
Rice–wheat	270 (rice), 220 (wheat)	15–25 % (rice), 20–25 % (wheat)	59 % (apparent N losses)	Hofmeier et al., 2015
Rice planting area in nine provinces	186–335	5–35 %	17–40 % (CH_4), 12–60 % (N_2O)	Tian et al., 2018
Single rice	300	20 %	33 % (CH_4 and N_2O)	Zhao et al., 2020

(6). Organic C input management

Manure amendment could offset the global rice yield loss caused by extreme temperatures through increasing net photosynthetic rate and improving plant tolerance to extreme temperatures (Zhu et al., 2022a). However, application of organic materials in paddies such as crop straw and manure, can stimulate CH_4 emissions substantially due to the increased substrate concentration for methanogens (Linquist et al., 2012b). Study showed that straw removal significantly decreased CH_4 emission by 44.7 %

from rice–upland cropping system (Wang et al., 2016). Biochar application has great potential for increasing SOC sequestration and soil fertility (Lehmann, 2007). Study demonstrated that biochar amendment significantly increased rice yields by 9.1 % and decrease GWP by 14 % in global rice paddies (Liao et al., 2021).

1.6. Agroecosystem model

Climate change coupled with agronomic practices will affect agricultural production and nutrient cycling dramatically. The interactions between the components in agricultural systems are complex, making it difficult to use field or laboratory experiments to observe these interactions (Shen et al., 2009). Instead, agroecosystem models, due to their power to evaluate how systems respond to climate change and management practices, have been increasingly used (Lu and Tian, 2013). A number of agroecosystem models have been developed and applied to explore crop yield production (Timsina and Humphreys, 2006; Tian et al., 2018; Li et al., 2021b; Zhou et al., 2023), SOC stock (Yigini and Panagos, 2016; Kaczynski et al., 2017; Mohanty et al., 2020), N_2O and CH_4 (Katayanagi et al., 2016; Tian et al., 2018; Wang et al., 2018b; Musafiri et al., 2021; Shaukat et al., 2022; Guo et al., 2023) emissions at field, regional, and global scales.

Different agroecosystem models are characterized by different objectives and varying levels of complexity (Turkeltaub et al., 2022). DNDC (Denitrification–Decomposition) simulates C and N biogeochemical cycles in agricultural systems, grazed pastures, forests, and wetlands (Li, 1992; Giltrap et al., 2010). APSIM (Agricultural Production Systems Simulator) simulates biophysical process in agricultural systems with a special interest in the economic and ecological effects of different management practices (Keating et al., 2003). DayCent is widely used to simulate ecosystem responses to different climate conditions and agronomic practices in cropland, grassland, forest and savanna systems (Necpálová et al., 2015). DSSAT (Decision Support System for Agrotechnology Transfer) has increasingly been used to evaluate the performance of different cropping systems or production technologies for decision making (Corbeels et al., 2016). Shepherd et al. (2011) explored over 30 agricultural models for evaluating the response of diffuse pollution to adaptations and mitigation strategies under climate change, and concluded that SPACSYS, DayCent, and APSIM performed the best. SPACSYS (Soil-Plant-Atmophere Continuous system) is a model with a proven track record in simulating various cropping systems, rotations or intercropping, interactions between plant and environment (Wu and Shepherd, 2011). It has been widely applied to simulate crop growth and production (Wu et al., 2009; Bingham and Wu, 2011; Liang et al., 2018), SOC and soil N stock (Wu and Shepherd, 2011; Zhang et al., 2016b), the dynamics of soil water content (Wu et al., 2016; Liu et al., 2023b) and N_2O emissions (Wu et al., 2015a; Zhang et al., 2016b) under different soils and climate conditions. Furthermore, the implementation of a biological-based denitrification component in SPACSYS enables it to estimate different nitrogenous gases emissions (N_2O, NO and N_2) (Wu et al., 2015a; Liu et al., 2020a). However, APSIM considers only the denitrification of NO_3^-, the intermediate products NO_2 and NO are neglected (Del Grosso et al., 2020). Moreover, SPACSYS is capable of simulating N and water uptake by plants, as well as input of carbon and nutrients to soil more precisely with a detailed three-dimensional root growth sub-model, while most other models simplify the root system by using root length density (Wu et al., 2007).

2. Scientific questions and hypotheses

In this study, based on the background, we are going to answer the following two questions:

(1). What are the characteristics and driving factors of SOC sequestration and crop yield in response to long-term fertilisation in paddies?

(2). What are the feedbacks of climate change on paddies and how to mitigate global warming while maintaining crop yield in paddies?

We assumed that:

- ✧ Fertilisation can significantly increase SOC stock in paddies over the past four decades. The main difference in drivers of SOC stock between different rice-based cropping systems are initial SOC level, C input and climate factor.
- ✧ Fertilisation can significantly increase crop yield in paddies over the past four decades. The main drivers of crop yield are fertilisation and their associated changes in soil nutrients (SOC, total nitrogen, total phosphorus, etc.).
- ✧ Climate change will promote (low warming scenario) or threat (high warming scenario) crop production depends on different climate scenarios.
- ✧ Reducing chemical N fertiliser application combined with mid-season drainage irrigation in paddies can reduce CH_4 and N_2O emissions while maintaining crop yield in the context of climate change.

3. Overview of the study sites and experimental design

The Yangtze River Basin is a major rice production region in China, accounting for 44.4 % of the total rice production (Liu et al., 2010). Globally, the Yangtze River Basin is one of the hotspots for CH_4 emissions (Zhou et al., 2024). This region represents a subtropical climate characterized by high temperatures and high precipitation in summer. The climate condition allows to planting two to three crops within a year. Paddy–upland rotation system and double rice rotation system are the two most important cropping systems in this region (Chen et al., 2020).

In this study, seven long-term experimental sites (since 1980s/1990s) were selected from the middle and lower reaches of the Yangtze River Basin in two typical cropping systems (i.e. middle rice–winter wheat and early rice–late rice) (Figure 1-5). Basic information about the starting year, geographical location, climate condition, and soil types and properties of the seven long-term experiments was presented in Table 1-3 and Table 1-4. Changes in crop varieties at each site were shown in Table 1-5. Four treatments were selected to explore the influence of different fertilisation on crop yield and SOC sequestration, i.e. no fertiliser (CK), application of chemical nitrogen, phosphorus and potassium fertilisers (NPK), application of organic fertiliser (M) and a combination of NPK and M (NPKM). Table 1-6 and Table 1-7 shows the application rates of chemical fertilisers and organic fertilisers in different treatments.

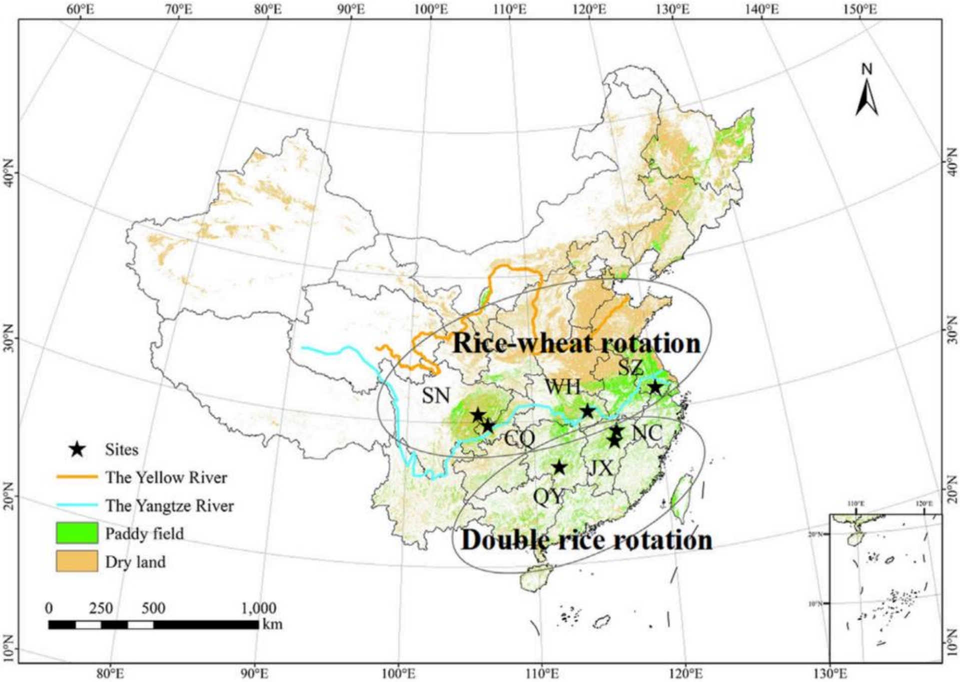


Figure 1-5: The spatial distribution of seven long-term experimental sites in both the middle rice–winter wheat system and early rice–late rice system located across the middle and lower reaches of the Yangtze River Basin. Middle rice–winter wheat system: WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; Early rice–Late rice system: NC, Nanchang; JX, Jinxian; QY, Qiyang.

Table 1-3: Basic information of the seven long-term experimental sites.

Cropping system	Site	Starting year	Geographical location			Climate condition			
			Longitude	Latitude	Altitude (a.s.l.) (m)	MAT (ºC)	MAP (mm)	EAT (ºC)	AE (mm)
Middle rice–winter wheat	WH	1981	30°28'	114°25'	20	16.7	1300	5190	1500
	SN	1982	30°34'	105°37'	284	17.3	993	NA	NA
	CQ	1991	29°48'	106°24'	266	18.3	1293	5600	NA
	SZ	1980	31°32'	120°04'	4	15.7	1100	4947	1576
Early rice–late rice	NC	1984	28°57'	115°94'	25	17.5	1600	5400	1800
	JX	1981	28°15'	116°20'	30	18.1	1537	6480	1150
	QY	1982	26°45'	111°52'	120	18.1	1408	3259	NA

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang. NA, not available.
MAT, mean annual temperature; MAP, annual precipitation; EAT, effective accumulated temperature; AE: annual evaporation.

Table 1-4: Soil types and initial soil properties of the seven long-term experimental sites.

Site	Soil type[a]	Initial soil properties (0–20 cm)								
		SOM ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	AN ($mg\ kg^{-1}$)	TP ($g\ kg^{-1}$)	AP ($mg\ kg^{-1}$)	TK ($g\ kg^{-1}$)	AK ($mg\ kg^{-1}$)	pH	BD ($g\ cm^{-3}$)
WH	Luvisol	27.4	1.80	150.7	1.00	5	30.22	98.5	6.3	1.03
SN	Cambisol	15.9	1.09	66.3	0.59	3.9	22.32	108	8.6	NA
CQ	Cambisol	24.2	1.25	93	0.67	4.3	21.1	88	7.7	1.38
SZ	Anthrosol	24.2	1.43	NA	0.43	8.4	23.7	127	6.8	1.26
NC	Luvisol	25.6	1.36	81.6	0.49	20.8	NA	35	6.5	1.19
JX	Cambisol	28.1	1.49	150.4	1.11	9.5	12.5	97.8	6.9	1.19
QY	Cambisol	19.8	1.5	158	0.48	9.6	14.2	65.9	6.0	NA

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang. NA, not available.
[a] World Reference Base for soil resources (WRB). SOM, soil organic matter; TN, total nitrogen; AN, available nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; AK, available potassium; BD, bulk density.

Table 1-5: Changes in crop varieties at the seven long-term experimental sites.

Experimental site	Crop	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
WH	Wheat	Emai-6			Emai-9							2078								Shenmai-2		Emai-12		Huamai-2128			Emai-23						Emai-24	Emai-25	Emai-26	Emai-27	Emai-28	NA	Zhengmai-9023
	Middle rice	525							3588				89734	3588-S						91-33														91-34	91-35	91-36	91-37	91-38	ER-38
SN	Wheat		NA																		Mianyang-93-124			Mianyang-2	Mianyang-26			Neimai-47	Chuanmai-10		Xikemai-2			Neimai-836	Chuanmai-58		NA		
	Middle rice		NA																		Gangyou-527				Gangyou-151		IIYou-96	Yiyou-520	Chuanxiang-8	Chuanxiang-317	Zhongyou-177	Chuanxiang-838		FYou-498	Fengyouxiang	Gangxiang-707	NA		
CQ	Wheat											NA	Xinongmai-1																Mianyang-31					Chuanmai-45					
	Middle rice											NA	Shanyou-63						IIYou-868				IIYou-7				IIYou-89				Chuanyou-9527	ZYou-272							
SZ	Wheat	Sumai																		Su-9357								Ningmai-14						Yangmai-19		Yangmai-22			Yangmai-16
	Middle rice	Kunnongxuan	Yuanfenzao	Suyujing	Zaodan						Yayiu							Suxiangjing		Wuyujing								Suxiangjing-1				Baolong-34	Suxiangjing-3				Suxiangjing-100		
NC	Early rice				NA	81001	NA	86-66	Huhongzao-1			1640	30682	Jiangnongzao-2	9003	NA		5143	Jiayu-948		9003	M98213		Zaozhenzhu		Xiangyouzao	Zaoxiang-89	Heshen-10	Dexiang-4	Jinyou-458		Chunguang-1				Jinyou-458	Zhong9you-3190	Lingliangyou-229	Xiangzaoxian-42
	Late rice				NA	80230	NA	Weiyou-64	Jiangyou-64	Weiyou-64	Xianyou-2	Xieyou-2374	NA	262	Zayou	NA	NA	9194	923						Zajiaonuo	923		Zayou-307	Jinyougui-99	Yuefeng-318		926			Gan-929			Tianyouhua-9	926
JX	Early rice	Hongmeizao					73-07					2106					Hualian-2					Jinyou-402					Zhuliangyou-02					YouI-156					Tanliangyou-83		
	Late rice	754					Xier-28					Weiyou-64					Wanyou-3					Wanxian-923					Xiannong-26					Xiangfengyou-9					Jiyou-3		
QY	Early rice		Zhuxi-26	V98		V16		V49		V48-2	292Xuan-2	V48-2	V1126	86-70	Zhongzaoyou-3	Zhongzaoyou-1	Zaoyou-5		Xiangzaoxian-18	NA	Xiangliangyou-68	NA			Yueyou-136	NA						Jinyou-974	NA	Lingliangyou-942			NA		
	Late rice		NA	V98		V6	NA	V64	V49	V64				NA	6017			Xianyou-63	V989		V77	NA				Jinyou-974	NA					Jinyou-207		TYou-207			NA		

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang. NA: not available.

Table 1-6: The application rates of chemical fertilisers under NPK and NPKM treatments at the seven long-term experimental sites.

Site	Season	NPK (kg ha^{-1})			NPKM (kg ha^{-1})[a]		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
WH	Middle rice	90	45	90	90	45	90
	Wheat	60	30	60	60	30	60
SN	Middle rice	120	60	60	120	60	60
	Wheat	120	60	60	120	60	60
CQ[b]	Middle rice	150	75/60	75/60	150 (225)	75/60 (113/90)	75/60 (113/90)
	Wheat	150/135	75/60	75/60	150/135 (225/202)	75/60 (113/90)	75/60 (113/90)
SZ	Middle rice	164	56	138	150	56	138
	Wheat	150	56	138	150	56	138
NC	Early rice	150	60	150	150	60	150
	Late rice	180	60	150	180	60	150
JX	Early rice	180	90	150	180	90	150
	Late rice	180	90	150	180	90	150
QY	Early rice	73	56	34	145	112.6	67.6
	Late rice	73	56	73	145	112.6	145

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang.

NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, application of organic fertiliser; NPKM, a combination of NPK and M.

[a] Numbers out and in of brackets represent the application rate of chemical fertilisers at low and high levels.

[b] Numbers before and after / represent the fertiliser application rate in year of 1991–1996 and 1997–2022.

Table 1-7: The types, application rates and nutrient contents of organic fertilisers under M and NPKM treatments at the seven long-term experimental sites.

Site	Season	Organic fertiliser[a]					
		Type	Application rate (t ha^{-1})[b]	C content (%)	N content (%)	P content (%)	K content (%)
WH	Middle rice	Pig manure	11.3 (18.8)	28.2	1.51	2.08	1.36
	Wheat	Pig manure	11.3 (18.8)	28.2	1.51	2.08	1.36
SN	Middle rice	Pig manure	15	47.2	2.1	0.8	2.68
	Wheat	Pig manure	15	47.2	2.1	0.8	2.68
CQ	Middle rice	-	-	-	-	-	-
	Wheat	Cattle manure	22.5	27	0.56	0.48	1.31
SZ[c]	Middle rice	Pig manure	11.4	50	-	-	-
	Wheat	Rapeseed cake	11.4	50			
NC	Early rice	Astragalus sinicus	25 (35)	5.2	0.3	0.08	0.23
	Late rice	Fresh pig manure	18.5 (26)	13.8	0.45	0.19	0.6
JX	Early rice	Astragalus sinicus	22.5	39.2	3.01	0.21	0.96
	Late rice	Pig manure	22.5	41.4	2.09	0.39	0.93
QY	Early rice	Cattle manure	22.5	40	2.24	1.32	1.39
	Late rice	Cattle manure	22.5	40	2.24	1.32	1.39

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang.

M, application of organic fertiliser; NPKM, a combination of NPK and M. There was no M treatment at NC and JX experimental sites, for other experimental sites, the manure application rate of M treatment was the same as that in the NPKM treatment.

[a] Organic fertiliser type includes animal manure, cake manure and green manure; The nutrient contents of organic fertiliser at NC experimental site was fresh based, dry based at other experimental sites.

[b] Numbers out and in of brackets represent the application rate of organic fertiliser at low and high levels.

[c] The input of N, P and K from organic fertiliser are 103.1, 82.7 kg and 70.1 kg ha^{-1} yr^{-1}, respectively.

- No data.

4. SPACSYS model description

The SPACSYS model is a weather-driven, field-scale and daily-time-step process-based model that simulates C and N cycling and water and heat transformation in a soil–plant–atmosphere continuum (Wu and Shepherd, 2011) (Figure 1-6). The model was published in 2007 (Wu et al., 2007). Since then, it has been gradually improved. The processes mainly include plant phenological development, assimilation, respiration, root growth and development, N, P and water uptake, partitioning of photosynthate, absorbed N and P, SOM decomposition, mineralization/immobilization, nitrification/denitrification and N loss pathways (Figure 1-7). A user-defined soil profile contains numbers of soil layers with different thicknesses. The Richards equation and Fourier's equation are utilized to describe soil water and heat transfers, respectively (Johnsson and Jansson, 1991). Sensitivity analysis of the model regarding 61 input parameters and their effects on 27 output variables was conducted (Shan et al., 2021). The model's input information mainly includes initial status, initial soil properties, climate conditions, and field management practices. The model's output variables mainly relate to plant growth dynamics, GHG emissions, water and energy redistribution, loss, and C & N recycling (Figure 1-8). The model has been validated and applied in many countries for different land use types, including grassland, upland and paddy (Table 1-8).

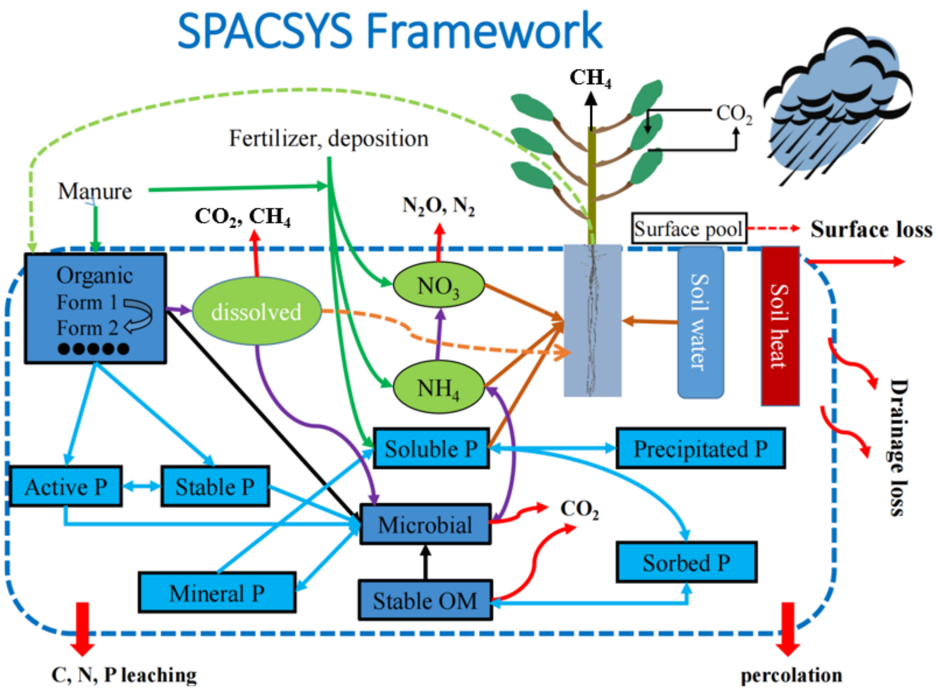


Figure 1-6: The structure of SPACSYS model. Adopted from Wu et al. (2007).

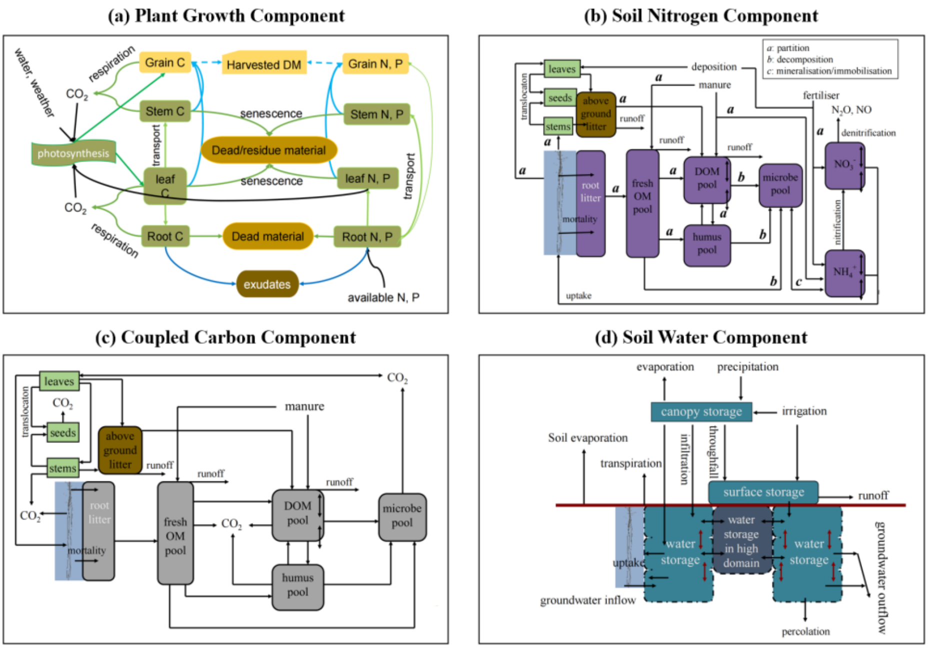


Figure 1-7: The plant growth component, soil N & C component and soil water component of SPACSYS model. Adopted from Wu et al. (2007).

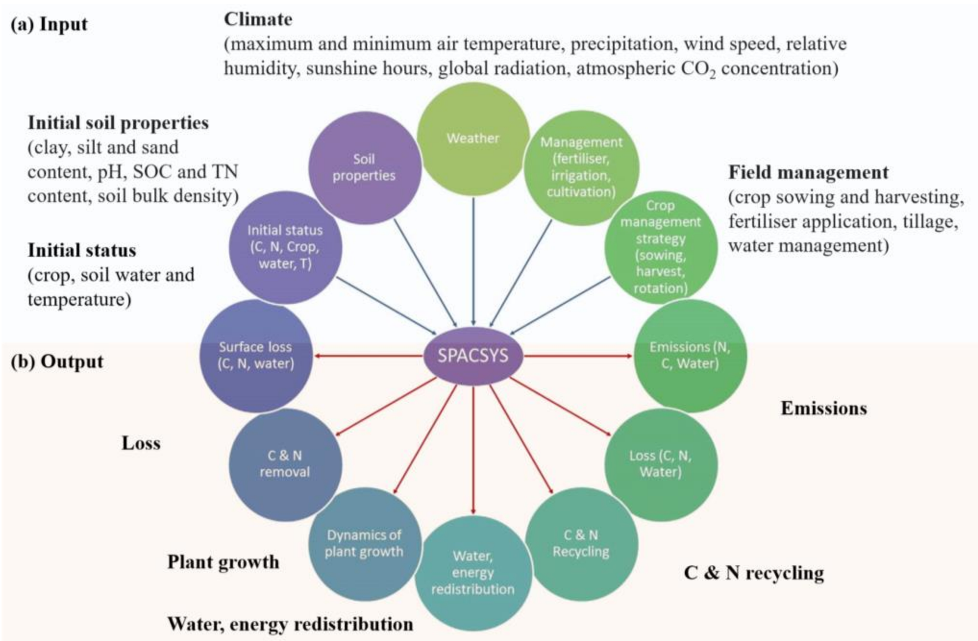


Figure 1-8: The input and output data of SPACSYS model. Adopted from Wu et al. (2015a).

Table 1-8: SPACSYS model's application in the world.

Geographical extent	Land use	Reference
Germany, Italy, Switzerland, Netherlands, UK	Grassland	Wu et al., 2015b
Scotland, UK	Grassland	Wu et al., 2015a
England, UK	Grassland	Liu et al., 2018b
North China Plain, China	Upland, winter wheat–summer maize	Zhang et al., 2018
Middle of the Yangtze River Basin, China (Jingshan)	Paddy, winter wheat–rice	Liu et al., 2020a
Canada, France, India, and UK	Grasslands and croplands (spring and winter cereals, soybean and rapeseed)	Sándor et al., 2020
England, UK	Upland, continuous wheat	Wu et al., 2022
North China Plain, China	Upland, winter wheat–summer maize	Wang et al., 2024a
England, UK	Upland, continuous wheat	Liang et al., 2024
Hetao irrigation district, Northwest China	Upland, spring maize	Quan et al., 2024

5. Objectives

In this study, we focus on exploring the effect of different long-term fertilisation practices on soil carbon sequestration and crop yield in rice-based cropping systems, and based on long-term experimental data, to assess possible consequences under future climate change and to propose possible practices for adaptation and mitigation in rice-based cropping systems (Figure 1-9, 1-10).

(1). Chapter 1 states the importance of rice paddies in ensuring global food security and mitigation GHG emissions and introduces the challenges facing rice paddies under climate change.

(2). Chapter 2 clarifies the characteristics of SOC sequestration in different rice-based cropping systems.

(3). Chapter 3 explores the co-benefits of SOC stock and crop yield with fertilisation in rice-based cropping systems.

(4). Chapter 4 assesses climate change feedback and propose adaptation and mitigation strategies using process-based agricultural model.

(5). Chapter 5 discusses the limitations and opportunities.

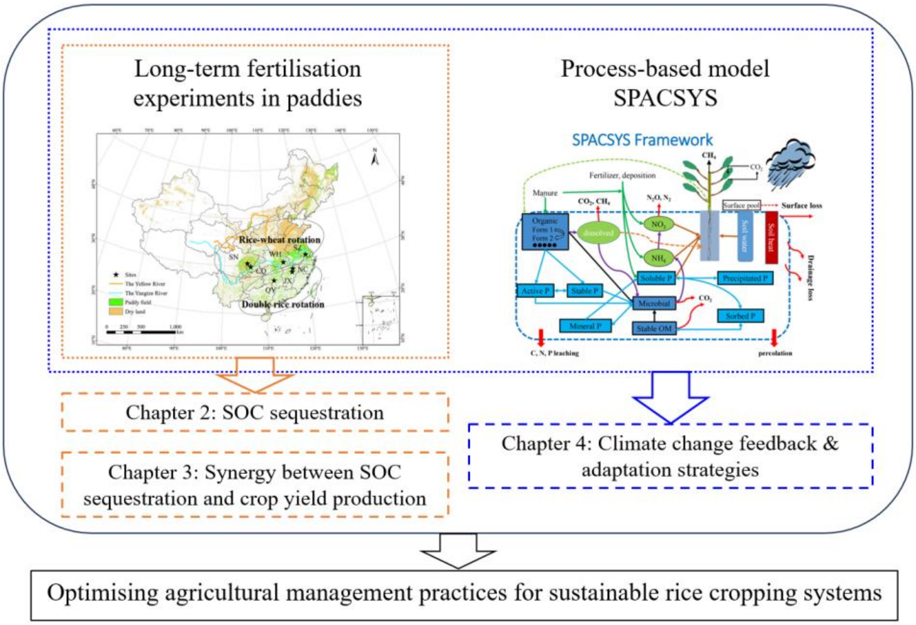


Figure 1-9: The framework of this thesis.

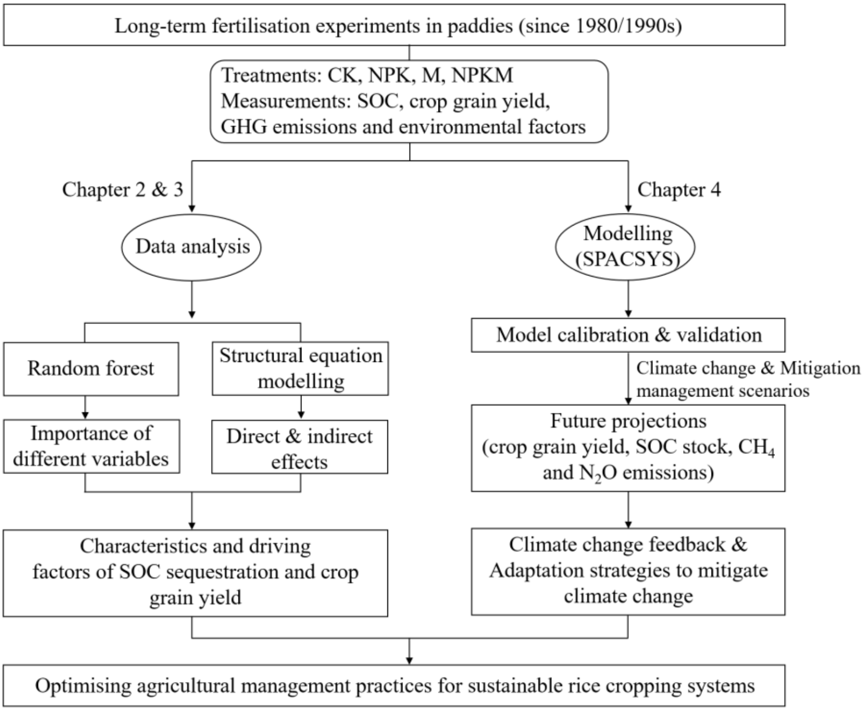


Figure 1-10: The flowchart of this study.

Chapter 2

Soil organic carbon sequestration affected by fertilisation in rice-based cropping systems over the last four decades

From: Shuhui Wang, Nan Sun, Shuo Liang, Shuxiang Zhang, Jeroen Meersmans, Gilles Colinet, Minggang Xu, Lianhai Wu. SOC sequestration affected by fertilisation in rice-based cropping systems over the last four decades. Frontiers in environmental science, 2023, 11: 1152439.
https://doi.org/10.3389/fenvs.2023.1152439

Abstract

Enhancing soil organic carbon (SOC) stocks through fertilisation and crop rotation will contribute to sustaining crop productivity and mitigating global warming. In this study, we analyzed the differences in total SOC stocks and their driving factors in the topsoil (0–20 cm) with various fertilisation measures in two puddled lowland rice-based cropping systems (i.e. rice–wheat rotation and double rice rotation systems) over the last four decades from seven long-term experiments in the Yangtze River Basin. The soil types include Cambisol, Luvisol and Anthrosol. The treatments include no fertilizer application (CK), application of chemical nitrogen, phosphorus and potassium fertilizers (NPK) and a combination of NPK and manure applications (NPKM). Every year, field was ploughed to a depth of 15–20 cm before wheat sowing and rice transplanting. Residue was removed after plant harvesting. Results showed that during the last four decades, the average crop grain yield ranged from 1151 ± 504 kg ha^{-1} yr^{-1} under CK treatment to 7553 ± 1373 kg ha^{-1} yr^{-1} under NPKM treatment. The topsoil SOC stock significantly increased by 8.6 t ha^{-1} on average under NPKM treatment in rice–wheat system and by 2.5–6.4 t ha^{-1} on average under NPK and NPKM treatments in double rice system as compared with CK. A higher SOC sequestration rate and a longer SOC sequestration duration were found in NPKM treatment than that in NPK treatment in both cropping systems. The highest SOC stock ratio (SOC stock in fertilizer treatments to CK) was observed under the NPKM treatment in both cropping systems, though no significant difference was found between these two cropping systems. However, the fertilisation-induced increase of the SOC stock under the NPK and NPKM treatments were 109.5% and 45.8% higher in the rice–wheat system than that in the rice–rice system. This indicates that the rice–wheat system is more conducive for SOC sequestration. RF and SEM analyses revealed that the magnitude and influencing factors driving SOC sequestration varied between two systems. In the double rice system, continuous flooding weakens the influence of precipitation on SOC sequestration and highlights the importance of soil properties and C input. In contrast, soil properties, C input and climate factors all have important impacts on SOC sequestration in rice–wheat system. This study reveals that the rice–wheat system is more favorable for SOC sequestration despite its lower C input compared to the double rice system in China’s paddies.

Keywords:

Crop rotation, fertilisation, soil organic carbon, paddy soils, the Yangtze River Basin.

1. Introduction

Soil constitutes the largest terrestrial soil organic carbon (SOC) pool in the world and plays a key role in ensuring food security and mitigating climate change. Paddy soils are more favorable to the accumulation of organic carbon (OC) than upland soils due to the presence of floodwater causing anaerobic conditions (Pan and Zhao, 2005). All over the world, paddy soils (0–100 cm) contain a considerable SOC pool (i.e. 18 Pg C), of which China, India and Indonesia together contribute to more than half of the global SOC pool of paddies (Liu et al., 2021). More precisely, the surface SOC pool (the plow layer and the plowpan) of paddy soils in China has been estimated at ~1.31 Pg (Pan et al., 2003). Hence, the management of paddy soils may have a great impact on the net soil–atmosphere C exchange at the national scale, and therefore, is of great significance for the delivery of key ecosystem services such as climate regulation.

Soil organic carbon can be sequestrated in soils as the result of C input and mineralization rates which are on its turn affected by climatic conditions, soil properties and agronomic practices (e.g. fertilisation, residue retention, irrigation, crop rotation, tillage, etc.) (Follett, 2001; Wiesmeier et al., 2019). Consequently, any factors that influence the C input and mineralization will influence the SOC stock. Improved agronomic practices, such as chemical fertilisers application, manure amendment or diversified cropping, have been proved to enhance SOC sequestration in agricultural soils (Chen et al., 2014a). For example, a global synthesis with 4803 paired observations from 369 experimental sites indicated that nitrogen fertilisation significantly promoted SOC content by 4.2 % on average (Xu et al., 2021). In addition, based on a global synthesis, Li et al. (2021) showed that manure amendment could increase SOC stock by 8.96 t C ha^{-1} on average as compared to unfertiliser treatment.

Over the last two decades, mounting evidence has demonstrated that the average SOC stocks in paddy soils are higher than those in upland soils at both the regional (Sun et al., 2015) and global (Wei et al., 2021a) scale. This is mainly attributed to the following reasons: (1) the higher residue input in paddy than upland soils (Liu et al., 2019a); (2) the lower decomposition rate and turnover rate due to the lower microbial activity under anaerobic conditions (Qiu et al., 2017); (3) the higher content of recalcitrant C fractions in paddy soils such as cell walls derived components like lignin (Chen et al., 2021); (4) some specific SOM protection mechanisms in paddy soils like “enzyme latch” mechanism or the adsorption of SOM to iron (Fe) oxides (Freeman et al., 2001; Wissing et al., 2013).

In 2021, rice yield accounts for 40 % of China's total grain yield (NBSC, https://data.stats.gov.cn/). Rice is typically planted in three cropping systems in China: single rice cropping, mainly located in North China, rice–upland cropping, mainly located in Central China and double rice cropping, mainly located in South China (Huang et al., 2012). The rice production in the three cropping systems accounts for 15.5 %, 43.4 % and 41.1 %, respectively of China’s total rice production (Guo et al., 2017). Various cropping systems are characterized by different climatic and soil conditions as well as different agronomic practices (e.g. crop varieties, residue retention rate and duration of flooding). For example, the average soil temperature in the three cropping systems are 15, 26 and 25℃, respectively (Cai et al., 2003; Yue et al., 2005; Yang et al., 2010). Among the three cropping systems, the residue retention rate in the single rice cropping is the lowest and the duration of flooding in the double rice cropping is the longest (Feng et al., 2013). In the context of climate change, many factors constrain the rice planting and production in China, such as the shortage of irrigation water resources (Piao et al., 2010), the shortened crop growth duration (Zhang et al., 2013a) and the changes in the planting structure (Chen et al., 2020). As such, the adoption of new cultivars, shifted sowing date and the optimised usage of water and fertilisers is proposed to mitigate the negative effects of global warming (Hu et al., 2017; Hussain et al., 2017).

Cropping systems may affect SOC stocks by influencing the balance between C input and C decomposition (Deog-Bae et al., 2005). Previous studies have shown that the SOC dynamics in paddy soils are influenced to a large extent by the different C input levels depending on the crop rotation (Cha-un et al., 2017). In addition, the specific agro-management practices in different rice cropping systems are other important drivers of the long-term SOC trends in paddy soils. It is generally considered that continuous flooded paddy soils have the greatest potential for sequestering SOC as compared to other cropping systems, as continuous flooding can retard the microbial decomposition and thus stimulate long-term SOC accumulation (Marschner, 2021). For example, Huang et al. (2012) indicated that the double rice cropping system leads to a higher increase of the SOC stock than rice-wheat and single rice cropping systems under the application of chemical N, P and K fertilisers when no SOC saturation trend was found. In addition, the periodic wetting-drying cycles in rice–wheat system may affect the aggregate stability and thus decrease the physical protection of SOC (Jastrow et al., 2007). However, some studies come to the opposite conclusion. For example, Mehmood et al. (2020) showed that the maize–rice cropping system enhanced aggregate stability through increasing of small macro-aggregates (0.25–2 mm), resulting in more SOC sequestration in comparison with adjacent continuous flooded rice following biochar addition. Moreover, the increased diversity of soil microbes (Zhou et al., 2014) and the high efficiency of microbial assimilation of organic C (Wei et al., 2022) in paddy-upland system than continuous flooded paddies may also contributed to the accumulation of SOC. This inconsistency between different studies results from the various conditions of the climate, soil and agronomic management (Yu et al., 2009; Huang et al., 2012; Tian et al., 2015; Mehmood et al., 2020). Therefore, an improved understanding of the SOC dynamics in paddy soils in response to different cropping systems as well as various fertilisation strategies, is critical to improve SOC sequestration in paddy soils and make a contribution to mitigating climate change.

The middle and lower reaches of the Yangtze River Basin is a major rice production area in China, which accounts for 44.2 % of the total rice planting area and 44.4 % of the total rice production in China (Liu et al., 2011). The long-term experiments established in 1980s/1990s in paddies in the middle and lower reaches of the Yangtze River Basin provide a good opportunity to explore the SOC sequestration and its influencing factors under different fertilisation measures and rice-based cropping systems. Therefore, our study uses this particular data resource to address following objectives: 1) explore the impacts of different fertilisation measures and rice-based cropping systems (rice–wheat system and double rice system) on SOC sequestration; and 2) assess the main influencing factors of SOC sequestration for the two cropping systems under fertilisation treatment.

2. Materials and methods

2.1. *Site description*

Datasets from long-term experiment (i.e. 1980s/1990s until 2010s) from puddled lowland paddy fields located along seven locations along the middle and lower reaches of the Yangtze River were used for this study (Figure 2-1). The study area is characterized by a subtropical climate with typical cropping systems of rice–wheat and double rice rotation. Information about the location, weather condition and soil properties at the beginning of the experiments are presented in Table 2-1.

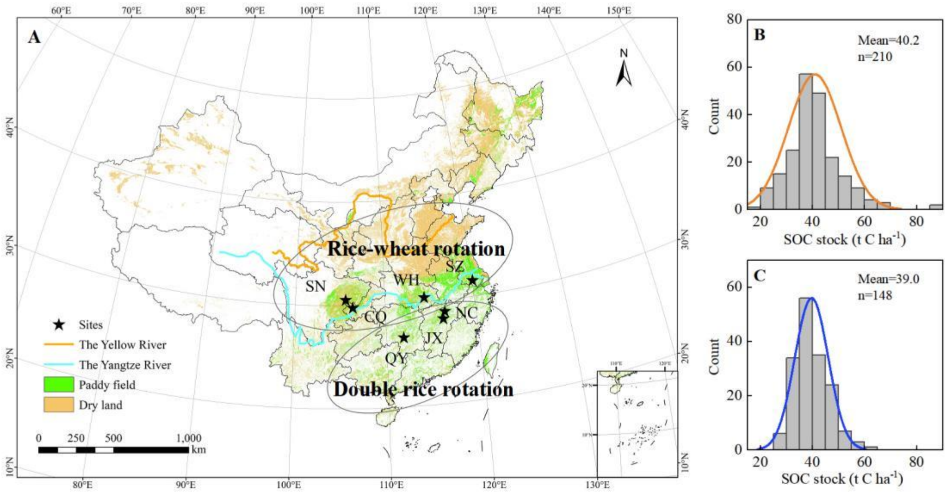


Figure 2-1: Geographic locations of seven long-term experimental sites **(A)** and distributions of soil organic carbon stock in the topsoil (0–20 cm) under different fertilisation treatments over the last four decades with the rice–wheat system **(B)** and double rice system **(C)**. Rice–wheat system: WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; Double rice system: NC, Nanchang; JX, Jinxian; QY, Qiyang.

2.2. *Experimental design*

The rice–wheat rotation was established at sites located in Wuhan (WH), Suining (SN), Chongqing (CQ) and Suzhou (SZ), while the rotation of double rice at sites in Nanchang (NC), Jinxian (JX) and Qiyang (QY) (Figure 2-1). The treatments include (i) no fertiliser application (CK), (ii) application of chemical nitrogen, phosphorus and potassium fertilisers (NPK) and (iii) a combination of NPK and manure applications

(NPKM). Table 2-2 shows the application rates of urea derived inorganic N, P (Calcium superphosphate or monoammonium phosphate), K (Potassium Chloride or potassium sulphate) fertilisers as well as manure at the sites.

2.3. Agronomic management and soil sampling

Each year, plots were ploughed to a depth of between 15 and 20 cm before wheat sowing and rice transplanting. In the rice–wheat system, rice transplanting took place somewhere between late May and early June, whereas harvest occurred between late September and early October. Subsequently, wheat sowing and harvesting took place the following year in late October–early November and late May, respectively. In the double rice system, early rice transplanting and harvesting occurred in late April–early May and mid to late July, respectively, whereas late rice transplanting and harvesting were at late July and late October–early November, respectively. Irrigation was implemented in rice season, while no irrigation in wheat season. Pesticide was used to control pests and weeds when necessary. Crop plants were harvested manually leaving stubbles with a height of 6–15 cm. Harvested plants were collected, air-dried and oven-dried for 30 min at 105°C, then heated at 70°C to a constant weight for determination of nutrient contents. Soils were sampled until a depth of 20 cm every year. Air-dried soils were sieved through a 2 mm mesh to measure soil pH. Subset soil samples were passed through a 0.25 mm sieve for the determination of total SOC with a modified Walkley & Black method (Heating solution for 12 minutes under 220°C, and a correction factor of 1.1 was applied) (Walkley and Black, 1934; Meersmans et al., 2009) and total N (TN) content (Black, 1965). Soil bulk density (BD) was measured with steel ring (inner diameter, 5 cm) (Vomocil, 1957).

2.4. C input

C inputs include crop residues (roots and stubble) and animal manure. A ratio of belowground biomass to aboveground biomass was used to estimate the C input of roots (Jiang et al., 2014). Root biomass was assumed as 30 % of the total plant biomass for wheat with the assumption that 75.3 % of roots are located in the top 20 cm of soil (Jiang et al., 2014). Belowground biomass to aboveground biomass ratio was assumed as 30 % for rice (Kundu et al., 2007). For wheat, the stubble quantity was estimated as 13.1 % (fertiliser treatments) and 18.3 % (control) of the straw yield (t ha^{-1} yr^{-1}) (Xu et al., 2006; Jiang et al., 2014). For rice, the stubble quantity was estimated as 5.6 % of the straw yield (t ha^{-1} yr^{-1}) considering all treatments (Huang et al., 2015). We applied the national average carbon contents for wheat residues, rice roots and rice straw (i. e. 399, 418 and 444 g C kg^{-1}, respectively) on oven-dried basis (NCATS, 1994).

Table 2-1: Location, weather condition and soil properties at the beginning of the seven long-term experiments in the Yangtze River Basin.

Site[a]	Initial year	Location		Climate			Soil properties (0–20 cm)						
		Longitude	Latitude	Altitude (a.s.l.)	MAT	MAP	Soil type[b]	SOM	TN	TP (P_2O_5)	TK (K_2O)	pH	BD
				m	ºC	mm		g kg^{-1}					g cm^{-3}
WH	1981	30°28'	114°25'	20	16.7	1300	Luvisol	27.4	1.80	1.00	30.22	6.3	1.03
SN	1982	30°34'	105°37'	284	17.3	993	Cambisol	15.9	1.09	0.59	22.32	8.6	NA
CQ	1991	29°48'	106°24'	266	18.3	1293	Cambisol	24.2	1.25	0.67	21.1	7.7	1.38
SZ	1980	31°32'	120°04'	4	15.7	1100	Anthrosol	24.2	1.43	0.43	23.7	6.8	1.26
NC	1984	28°57'	115°94'	25	17.5	1600	Luvisol	25.6	1.36	0.49	NA	6.5	1.19
JX	1981	28°15'	116°20'	30	18.1	1537	Cambisol	28.1	1.49	1.11	12.5	6.9	1.19
QY	1982	26°45'	111°52'	120	18.1	1408	Cambisol	19.8	1.5	0.48	14.2	6.0	NA

[a] WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang.

[b] World Reference Base for soil resources (WRB).

MAT, mean annual temperature; MAP, annual precipitation; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TK, total potassium; BD, bulk density.

Table 2-2: Inorganic nitrogen (N), phosphorus (P), potassium (K) fertilisers (kg ha^{-1}) and manure application rates in each cropping season under different fertilisation treatments at seven long-term experimental sites in the Yangtze River Basin.

Site	Season	Area (m^2)	Replicates	NPK (kg ha^{-1})			NPKM (kg ha^{-1})[a]			Manure (Animal manure, cake manure and green manure)		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O	Type	Amount (t ha^{-1})[a]	C content (%)[b]
WH	Rice	40	3	90	45	90	90	45	90	Pig manure	11.3 (18.8)	28.2
	Wheat	40	3	60	30	60	60	30	60	Pig manure	11.3 (18.8)	28.2
SN	Rice	13	2, 4[c]	120	60	60	120	60	60	Pig manure	15	47.2
	Wheat	13	2, 4[c]	120	60	60	120	60	60	Pig manure	15	47.2
CQ[d]	Rice	120, 90[c]	1	150	75/60	75/60	150 (225)	75/60 (113/90)	75/60 (113/90)	-	-	-
	Wheat	120, 90[c]	1	150/135	75/60	75/60	150/135 (225/202)	75/60 (113/90)	75/60 (113/90)	Cattle manure	22.5	27
SZ	Rice	20	2	164	56	138	150	56	138	Pig manure	11.4	50
	Wheat	20	2	150	56	138	150	56	138	Rapeseed cake	11.4	50
NC	Early rice	33	3	150	60	150	150	60	150	Astragalus sinicus	25 (35)	5.2
	Late rice	33	3	180	60	150	180	60	150	Fresh pig manure	18.5 (26)	13.8
JX	Early rice	50	3	180	90	150	180	90	150	Astragalus sinicus	22.5	39.2

	Late rice	50	3	180	90	150	180	90	150	Pig manure	22.5	41.4
QY	Early rice	27	2, 3[c]	73	56	34	145	112.6	67.6	Cattle manure	22.5	40
	Late rice	27	2, 3[c]	73	56	73	145	112.6	145	Cattle manure	22.5	40

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang.

NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; NPKM, a combination of NPK and manure applications.

-, No fertilizer.

[a] Numbers out and in of brackets represent fertiliser application rate with low and high level of chemical fertilisers or manure.

[b] The C content of manure at NC site was fresh based, dry based at other sites.

[c] Numbers before and after comma represent CK treatment and other treatments at SN and CQ sites, CK and other treatments at QY site.

[d] Numbers before and after / represent the fertiliser application rate in year of 1991–1996 and 1997–2022.

2.5. Calculations

The total soil organic carbon stock (SOC, t C ha^{-1}) in the top 20 cm soil is estimated as:

$$SOC = SOC_C \times BD \times H \times 0.1 \quad (2\text{-}1)$$

where SOC_C is soil C content (g kg^{-1}), BD is soil bulk density (g cm^{-3}), H is the thickness (cm), and 0.1 is a conversion coefficient.

The SOC stock change (ΔSOC) and its change rate (SOC_R) are calculated by:

$$\Delta SOC = SOC_n - SOC_i \quad (2\text{-}2)$$

$$SOC_R = \Delta SOC / n \quad (2\text{-}3)$$

where SOC_n (t C ha^{-1}) is SOC stock in different treatment (CK, NPK and NPKM) of the year n, SOC_i is the initial SOC stock, n is the experimental duration (year).

Following Li et al. (2021), SOC stock ratio (%SOC) between a fertiliser treatment and CK is defined as:

$$\%SOC = SOC_{Tn} / SOC_{Cn} \times 100\ \% \quad (2\text{-}4)$$

where SOC_{Tn} and SOC_{Cn} (t C ha^{-1}) are SOC stocks in fertiliser (NPK, NPKM) and CK treatments in the year n, respectively.

According to Berhane et al. (2019), the fertilisation-induced changes of the SOC stock ($\%\Delta SOC$) in fertiliser treatments relative to CK are calculated by the following formula, in which a positive value indicates fertilisation-induced increase of the SOC stock and a negative value indicates fertilisation-induced decrease as compared to its initial level.

$$\%\Delta SOC = (SOC_{Tn} - SOC_{Cn}) / SOC_i \times 100\ \% \quad (2\text{-}5)$$

2.6. Statistical analysis

The statistical software R 4.1.1 has been used for all the analyses. The statistically significant differences in SOC stocks among fertilisation treatments and the statistically significant differences in SOC stock ratio or the fertilisation-induced changes of the SOC stock between the two cropping systems were analyzed by one-way ANOVA followed by the Fisher's LSD test ($P = 0.05$). The relationships of SOC stock changes and its change rate with cumulative C input and experimental duration were fitted by logarithmic regression. According to Six et al. (2002), soil C saturation occurs when the soil is incapable of accumulating additional C following changes in cropland management, and as such a new equilibrium has been reached. SOC sequestration duration refers to the time during which sequestration occurs (West and Six, 2007). With the assumption that a new SOC steady state occurs when the rate of SOC stock changes is lower than 0.01 t C ha^{-1} yr^{-1}, we estimated the SOC sequestration duration.

Random forest (RF) with percentage increases in the MSE (mean squared error) was applied to quantify the relative importance of different environmental variables (MAT, MAP, C input, TN, initial SOC content and soil pH) (Breiman, 2001). With the "A3" package, we obtained the significance of the model and the cross-validated R^2 value by considering 5000 permutations of the response variable. Using the "rfPermute" package, we determined the significance of each driving factor on the response variable (Jiao et al., 2018). Based on the identified factors regulating SOC sequestration, a structural equation modelling (SEM) (IBM SPSS Amos 21.0 software) was used to clarify the direct and indirect effects of climatic condition (MAT and MAP), soil properties (TN, initial SOC content and soil pH) and C input on the fertilisation-induced changes of the SOC stock in the two cropping systems. The following criteria were used to evaluate the overall performance of the model: The chi-square to degrees of freedom ratio (χ^2 / df < 2), probability level (P > 0.05), comparative fit index (CFI > 0.9), root mean square error of approximation (RMSEA < 0.08) and the Akaike information criterion (AIC: the model has a good fit when AIC is low) (Wen et al., 2004) (Figure 2-2).

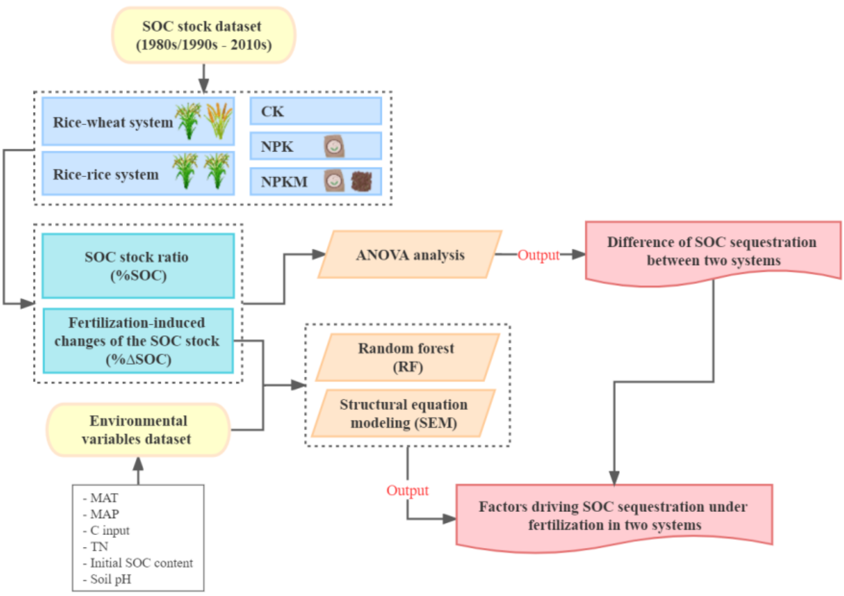


Figure 2-2: Flowchart of the methodology.

3. Results

3.1. *Average crop grain yield, straw yield and C input under different fertilisation treatments*

The average and dynamic changes of grain and straw yield of wheat and rice in two cropping systems are shown in Table 2-3, Table 2-4 and Figure 2-S1. Overall, NPKM treatment produced the highest grain and straw yield for both rice and wheat in two systems. In rice–wheat system, the C inputs under NPKM treatment are double that of NPK treatment and four times that of CK treatment (Figure 2-3A). In double rice system, the C inputs under NPKM treatment are threefold that of NPK treatment and five times that of CK treatment (Figure 2-3B).

Table 2-3: Average grain yield of wheat and rice in two cropping systems from the seven long-term experiments in the Yangtze River Basin.

Rotation	Site	Average grain yield of Wheat/Early rice (kg ha^{-1})			Average grain yield of Rice/Late rice (kg ha^{-1})		
		CK	NPK	NPKM	CK	NPK	NPKM
Wheat–rice rotation	WH	1151 ± 504	2322 ± 645	3224 ± 946	4184 ± 1041	6011 ± 851	6454 ± 914
	SN	1188 ± 413	3216 ± 790	3337 ± 825	3065 ± 784	7147 ± 767	7500 ± 802
	CQ	1283 ± 287	3045 ± 528	3028 ± 599	3487 ± 735	7081 ± 1094	6961 ± 1330
	SZ	2084 ± 672	4200 ± 1195	4660 ± 1284	5013 ± 983	7118 ± 1207	7553 ± 1373
Rice–rice rotation	NC	2923 ± 864	5553 ± 788	5963 ± 833	4175 ± 765	5816 ± 885	6461 ± 921
	JX	2585 ± 597	4041 ± 750	5184 ± 941	2998 ± 678	4173 ± 788	5201 ± 1083
	QY	3454 ± 527	5113 ± 1100	6153 ± 1055	2774 ± 812	4282 ± 1367	5209 ± 1389

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; NPKM, a combination of NPK and manure applications.

Values are means ± standard deviations.

Table 2-4: Average straw yield of wheat and rice in two cropping systems from the seven long-term experiments in the Yangtze River Basin.

Rotation	Site	Average straw yield of Wheat/Early rice (kg ha^{-1})			Average straw yield of Rice/Late rice (kg ha^{-1})		
		CK	NPK	NPKM	CK	NPK	NPKM
Wheat–rice rotation	WH	1589 ± 588	3066 ± 840	4383 ± 1333	4733 ± 1348	6131 ± 1142	6837 ± 1269
	SN	803 ± 431	3537 ± 869	3670 ± 908	1240 ± 572	6416 ± 685	6758 ± 726
	CQ	1167 ± 273	2770 ± 492	2764 ± 539	3795 ± 766	7783 ± 1358	7648 ± 1512
	SZ	2292 ± 739	4620 ± 1314	5126 ± 1413	4406 ± 827	6281 ± 1031	6691 ± 1221
Rice–rice rotation	NC	2334 ± 694	4602 ± 658	4653 ± 638	3212 ± 606	4984 ± 897	5193 ± 974
	JX	1550 ± 377	2715 ± 588	3552 ± 643	1986 ± 497	2894 ± 603	4143 ± 776
	QY	2096 ± 552	3846 ± 1542	4891 ± 1535	1876 ± 564	3656 ± 1529	4972 ± 1963

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; NPKM, a combination of NPK and manure applications.
Values are means ± standard deviations.

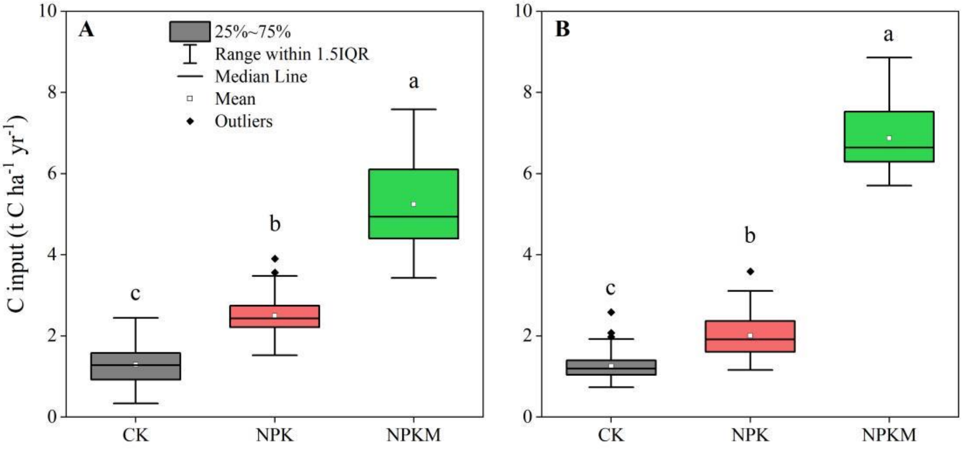


Figure 2-3: C input under different fertilisation treatments in rice–wheat system (A) and double rice system (B) during the last four decades. Small letters indicate significant differences between treatments at $P < 0.05$. CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; NPKM, a combination of NPK and manure applications. IQR: interquartile range.

3.2. SOC stocks under different fertilisation treatments

The topsoil SOC stocks (0–20 cm) were 36.2, 39.5 and 44.8 t C ha^{-1} on average under CK, NPK and NPKM treatments, respectively in the rice-wheat system, and were 36.0, 38.5 and 42.4 t C ha^{-1} on average under CK, NPK and NPKM treatments, respectively in the double rice system (Figure 2-4). During the last four decades, the topsoil SOC stocks significantly increased by 8.6 t ha^{-1} on average under NPKM treatment in the rice–wheat system and by 2.5–6.4 t ha^{-1} on average under NPK and NPKM treatments in the double rice system compared with CK.

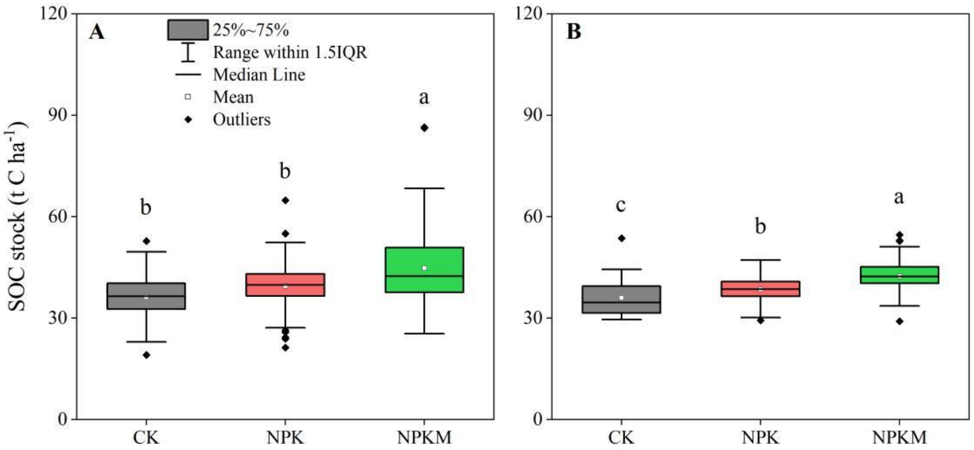


Figure 2-4: The total soil organic carbon (SOC) stock (0–20 cm) under different fertilisation treatments in rice–wheat system **(A)** and double rice system **(B)** during the last four decades. Small letters indicate significant differences between treatments at $P < 0.05$. CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; NPKM, a combination of NPK and manure applications. IQR: interquartile range.

3.3. Relationships of SOC stock changes (0–20 cm) and its change rate with cumulative C input and experimental duration

The SOC stock changes in rice paddies showed a significant logarithmic correlation with cumulative C input under all fertilisation treatments (Figure 2-5A). According to the regressions of different treatments, the increase in cumulative C input caused significant SOC stock increases in the initial stage and then showed non-significant SOC stock increases over a longer period of time. And the potential SOC stock increases in NPK treatment are much lower than that in NPKM treatment (Figure 2-5A). The rate of SOC stock changes decreased significantly with increasing fertilisation duration and gradually approached zero in NPK and NPKM treatments (Figure 2-5B). Moreover, a higher SOC sequestration rate and a longer SOC sequestration duration were found in NPKM treatment compared to NPK treatment (Figure 2-5B).

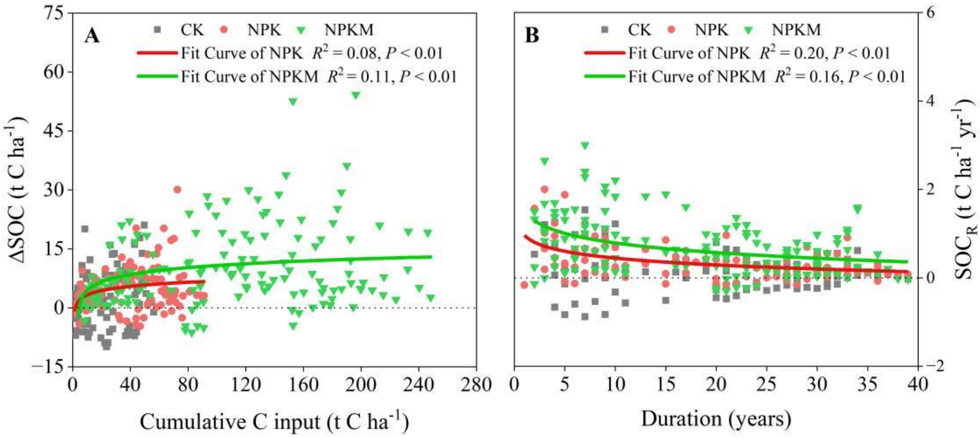


Figure 2-5: Relationships of SOC stock changes (ΔSOC) (0–20 cm) **(A)** and its change rate (SOCR) **(B)** with cumulative C input and experimental duration under different fertilisation treatments (CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; NPKM, a combination of NPK and manure applications) in paddies during the last four decades.

3.4. SOC stock ratio and the fertilisation-induced changes of the SOC stock under different fertilisation treatments

The SOC stock ratio of NPK and NPKM treatments were 109.3 ± 1.4 % (mean ± standard error) and 120.4 ± 1.8 %, respectively, in rice–wheat system, and were 108.6 ± 2.2 % and 123.6 ± 2.3 %, respectively, in double rice system (Figure 2-6A). The highest SOC stock ratio was observed under NPKM treatment in both cropping systems, and no significant difference was found between these two cropping systems both in NPK and NPKM treatments (Figure 2-6A). However, the fertilisation-induced changes of the SOC stock from its initial level in fertiliser treatments relative to CK was higher in rice–wheat system (i.e. NPK: 15.5 %, NPKM: 31.5 %) than that in double rice system (i.e. NPK: 7.4 %, NPKM: 21.6 %) (Figure 2-6B). This indicates a greater fertilisation-induced increase of the SOC stock under rice–wheat system as compared to its initial SOC stock during the 30–40 years of fertilisation.

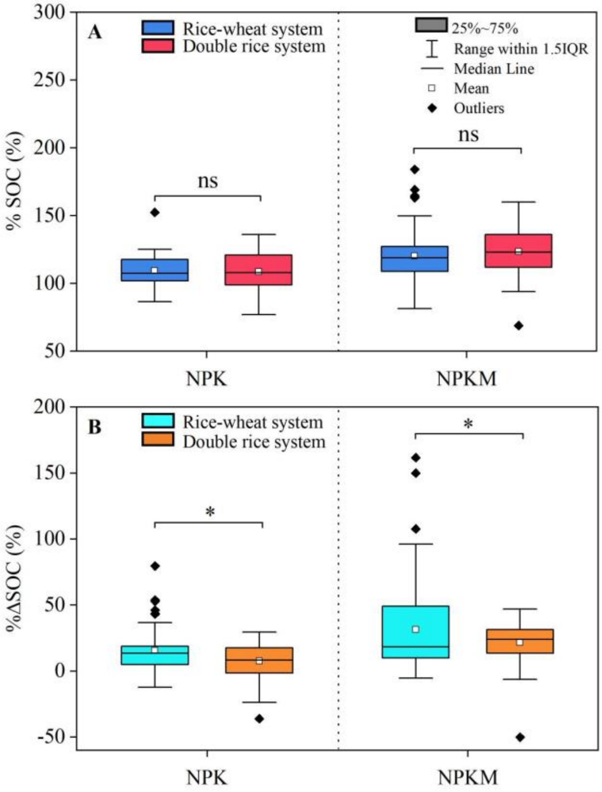


Figure 2-6: Differences in SOC stock ratio (%SOC) **(A)** and the fertilisation-induced changes of the SOC stock (%ΔSOC) **(B)** between the two systems (rice–wheat system and double rice system) under NPK and NPKM treatments. Symbols above the paired boxplots indicate statistic differences between the systems (one-way ANOVA, ns: non significance, **P* < 0.05). NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; NPKM, a combination of NPK and manure applications. IQR: interquartile range.

3.5. Factors driving SOC sequestration in rice-based cropping systems

The RF and SEM analyses showed that the dominant factors regulating the SOC sequestration differed between the two cropping systems (Figure 2-7). RF analysis indicated that soil properties (TN, initial SOC content and pH) and climate factors (MAT and MAP) together impacts on SOC sequestration in the rice–wheat system (Figure 2-7C). Whereas soil properties (initial SOC and TN content), C input and MAT play an important role in controlling SOC sequestration in the double rice system (Figure 2-7D). SEM confirmed the importance of soil properties with a total standardised direct effect of 1.09 in the rice–wheat system. And meanwhile highlighted the importance of C input in regulating SOC sequestration, with a standardised direct effect of 0.22 in the rice–wheat system (Figure 2-7A and Figure

2-S2). While SOC sequestration was dominantly and directly affected by initial SOC content, TN content and C input, with standardised direct effects of -0.89, 0.44 and 0.28, respectively, in the double rice system (Figure 2-7B and Figure 2-S2).

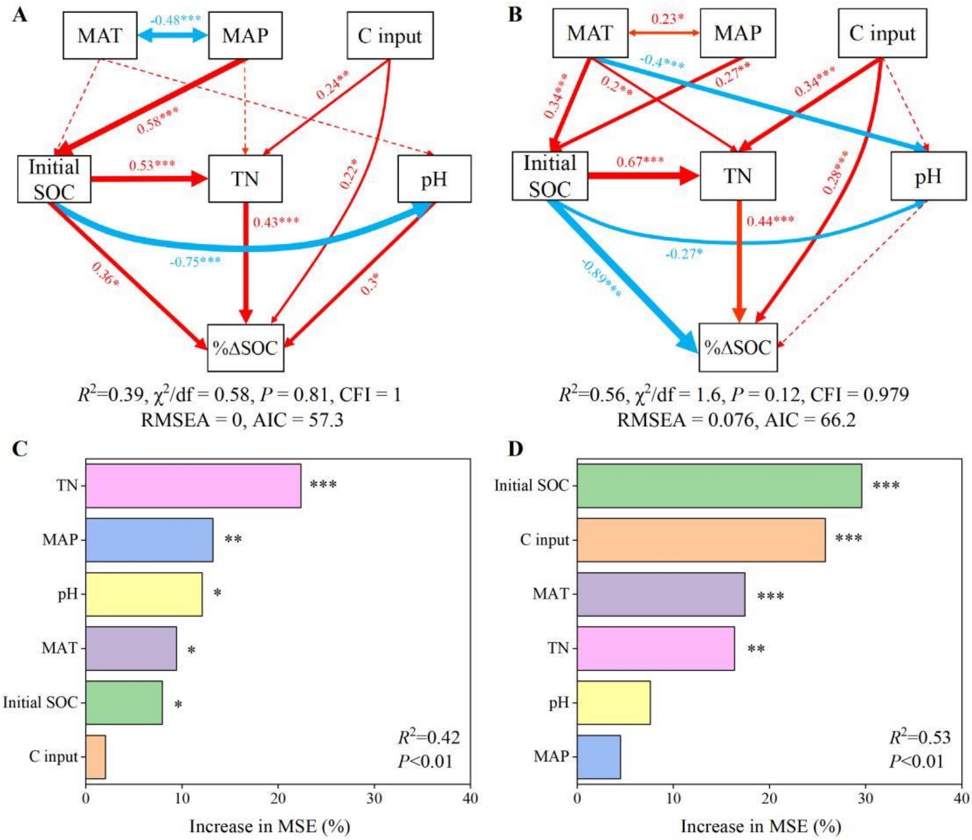


Figure 2-7: Structural equation modelling (SEM) **(A, B)** and random forest (RF) **(C, D)** analyses of the fertilisation-induced changes of the SOC stock (%ΔSOC) with explanatory variables in rice–wheat system **(A, C)** and double rice system **(B, D)**. The red and blue lines in **(A)** and **(B)** represent positive and negative effects, respectively. The line width and the numbers above the lines (standardised path coefficient) corresponding to the strength of the path. Solid and dashed lines represent significant and nonsignificant 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, mean annual precipitation; Initial SOC, soil organic carbon content at the beginning of the experiment; TN, soil total nitrogen content; pH, soil pH.

4. Discussion

4.1. Fertilisation and crop rotation effects on SOC stock

Many studies have shown the benefits of fertiliser application, manure amendments, straw retention, crop rotation and conservation tillage for SOC sequestration (West and Post, 2002; Lu et al., 2009). Based on the long-term experimental dataset, our study re-quantified the magnitude of SOC stock changes induced by chemical fertilisers and manure application in China's paddies. Our result of SOC increment in rice–wheat system (Figure 2-4) is close to the value of 8.96 t C ha^{-1} reported by Li et al. (2021), and the result in double rice system is within the range of 2.5–13.5 t C ha^{-1} yr^{-1} as being reported by Maillard and Angers (2014). Similarly, Rui and Zhang (2010) synthesized results from 26 long-term field experiments and concluded that the application of crop residue and manure enhanced SOC stock by 0.41 and 0.34 t C ha^{-1} yr^{-1} over approximately four decades in paddy soils as compared to fields where no fertiliser were applied, respectively. Among fertilisation practices, chemical fertilisers combined with manure (NPKM) showed the highest SOC stock (Figure 2-4, Table 2-S1), which seems to be in agreement with the results obtained in previous studies (e.g. Brar et al., 2013; Zhu et al., 2015; Atere et al., 2020). This result might be explained by the following factors: firstly, in contrary to chemical fertilisers, manure applications are causing a direct C input into soil; Secondly, manure amendments can increase C input indirectly through enhancing plant productivity; Thirdly, the manure amendment derived fresh organic matter input can accelerate the formation of microaggregates within macroaggregates, and therefore results in an improved sequestration of more stable intra-aggregate particulate organic matter (iPOM) (Six et al., 1998, 1999, 2000).

Our results indicated that fertilisation-induced increase of the SOC stock was higher in rice–wheat system than that in double rice system (Figure 2-6B). This may be caused by the following reasons: firstly, in rice–wheat system, the aerobic and anaerobic cycles caused by flooding and drainage will accelerate the process of iron (Fe) or aluminum (Al) oxides being adsorbed by organic compounds (Wei et al., 2022), and meanwhile more amorphous Fe oxides are formed with greater reactive mineral surface area for C accumulation than crystalline Fe oxides (Wissing et al., 2014); Secondly, the frequent drying-rewetting cycles can increase the quantity and diversity of soil organisms (Zhou et al., 2014), and as such the higher ratio of microbial biomass C to SOC lead to a high microbial C use efficiency (Wei et al., 2022); Thirdly, in comparison with continuous waterlogging, drying-rewetting cycles combined with the application of manure can improve soil water stable aggregation (Yang et al., 2005).

4.2. SOC sequestration rate and duration

The logarithmic correlation between the SOC stock changes and cumulative C input under fertiliser treatments indicates that C input acts as the main driving factor of SOC stock increases (Figure 2-5A). Furthermore, these results are showing that China's paddy soils are being characterized by a steady state C trend under the current land management, indicating C saturation. Based on the equations, we estimated that the

SOC sequestration duration is between 50 and 85 years for NPK and NPKM treatments in China's paddy soils (Figure 2-5B). This means that the paddy soils in China can continue sequestering C for 11 and 46 years under NPK and NPKM treatments, respectively. This result is higher than the estimations from previous studies. For example, Tian et al. (2015) reported that the SOC sequestration duration are 28–34 and 46–51 years for NPK and NPKM treatments, respectively. Similarly, Zhu et al. (2015) estimated that the SOC sequestration duration is 46–55 years under NPK and NPKM treatments. The difference between our results and others is probably the result of the differences in site-specific conditions, including soil texture, climate condition and field management (West and Six, 2007). Specifically, many studies have shown that SOC sequestration rates are higher in soils characterized by higher clay content (Hassink, 1997; Liu et al., 2014; Gross and Glaser, 2021). In addition, differences in field management and land use may result in different C input rates (e.g. crop residues and manure) or C losses through decomposition (Ma et al., 2021). Hence, in essence, our results seem to confirm the advantage in SOC sequestration in paddy soils as compared to other land uses as being highlighted by numerous other studies (e.g. Huang et al., 2014; Wissing et al., 2014; Hou et al., 2018).

Consistent with previous researches (Mandal et al., 2008, Tian et al 2015, Fujisaki et al., 2018), in this study, greater SOC sequestration rate and longer SOC sequestration duration were found in the NPKM treatment as compared to the NPK treatment (Figure 2-5). This is probably the consequence of a higher direct C input rate from manure addition as well as enhanced indirect C input rates (e.g. crop residue and root derived C) due to higher crop productivity in the NPKM treatment. In essence, our study clearly indicates that the application of chemical fertilisers combined with manure (NPKM) can be considered as an effective measure to enhance SOC sequestration in paddy soils.

4.3. Factors driving SOC sequestration

Our results showed that the magnitude and influencing factors driving SOC sequestration varied between rice-based cropping systems (Figure 2-7 and Figure 2-S2). In double rice system, continues flooding weakens the impact of precipitation on SOC sequestration and then highlights the importance of soil properties (initial SOC and TN content) and field management practice (C input), which control SOC sequestration. In contrast, soil properties (TN, initial SOC content and pH), field management practice (C input) and climate factors (temperature and precipitation) all have important impacts on SOC sequestration in rice–wheat system. Similar results have been found in previous studies. For example, Wei et al. (2021) identified a smaller impact of climate on SOC stock dynamics in paddy soils as compared to corresponding upland soils. Furthermore, a global synthesis indicated that mean annual temperature and soil pH are having an important effect on SOC stock changes in paddy soils, but the impact of annual total precipitation amount and soil clay content is rather limited (Liu et al., 2021).

Initial SOC content was an important explanatory variable for SOC sequestration, which was similar to the findings of Zhao et al. (2018), who found that the initial SOC content explained ~30 % of the variation in SOC stock changes in Chinese croplands. This can be explained by the fact that, according to the concept of soil C saturation theory, soils with a lower initial SOC content level have a larger potential and a longer total duration of C sequestration (Stewart et al., 2007, 2008). In this study, the impact of initial SOC content on SOC sequestration is opposite in two systems (Figure 2-7), this may be because of the difference in initial SOC content. In rice–wheat system, the initial SOC content is relatively lower than that in double rice system (Table 2-1), which may have contributed to the higher SOC sequestration.

Furthermore, our results are in line with previous studies, such as Virto et al. (2012), who indicates that C input was another important factor driving SOC sequestration in rice-based cropping systems. In this regard, Fujisaki et al. (2018) concluded that the SOC stock increases in tropical croplands are mainly driven by C input. Furthermore, Zhao et al. (2018) reported that the SOC sequestration in China's croplands was primarily caused by increased OC input (crop residues) due to economic and policy changes during 1980–2010. More specifically, according to global synthesis, the C retention coefficient of added manure and straw are 12 % and 16 % in cropland, respectively (Maillard and Angers, 2014; Liu et al., 2014). The relatively higher total effect of C input on SOC sequestration in double rice system (0.43) as compared to rice–wheat system (0.32) (Figure 2-7) may be attributed to its higher C input associated with its aerobic conditions. In the double rice system, the soil was submerged for about 7–8 months throughout the year, which hampered the decomposition rate of freshly added organic materials as well as the native SOM as compared to the aerobic conditions (Mandal et al., 2008).

4.4. Limitation of this study

The results of our study identified the advantage of SOC sequestration under long-term fertilisation in two puddled lowland rice-based cropping systems, which may help to make adaptations of cropping systems in a changing climate, such as a conversion from continuous paddies to alternative paddy–upland systems, especially in a future context of irrigation water shortages (Schewe et al., 2014). However, the climate benefit of SOC sequestration in paddy soils is generally offset by inducing GHG emissions (e.g. CH_4, N_2O). As reported, rice accounts for about half of the total crop emissions due to high CH_4 emissions (Carlson et al., 2017). Specifically, CH_4 and N_2O emissions in paddies have been estimated as 6300 kg CO_2-eq ha^{-1} yr^{-1} and 280 kg CO_2-eq ha^{-1} yr^{-1} globally (Carlson et al., 2017; FAO, 2018). In which the yield-scaled global warming potential (GWP) of the double rice system is higher than that of the paddy–upland system (Feng et al., 2013; Zhang et al., 2019). As such, a more comprehensive assessment of SOC sequestration, crop production and GHG emissions in terms of CO_2 equivalents in paddy soils is needed in further research to achieve sustainable rice cultivation.

5. Conclusion

This study explored the difference in total SOC stocks (0–20 cm) and their driving factors under different fertilisation treatments in two puddled lowland rice-based cropping systems over the last four decades. Results showed that the SOC stock significantly increased by 2.5–8.6 t ha^{-1} on average under fertilisation in two cropping systems as compared to CK over the last four decades. The relationship between the rate of SOC stock changes and duration suggests that China's paddy soils are having the potential to continue sequestering carbon for approximately 11–46 years under fertilisation. The relatively higher fertilisation-induced increase of the SOC stock from its initial level in rice–wheat system than that in double rice system suggesting that rice–wheat system is more beneficial to SOC sequestration. Soil properties, C input and MAT driving SOC sequestration in double rice system, in contrast, soil properties, C input and climate factors all have important impacts on SOC sequestration in rice–wheat system.

6. Supplementary material

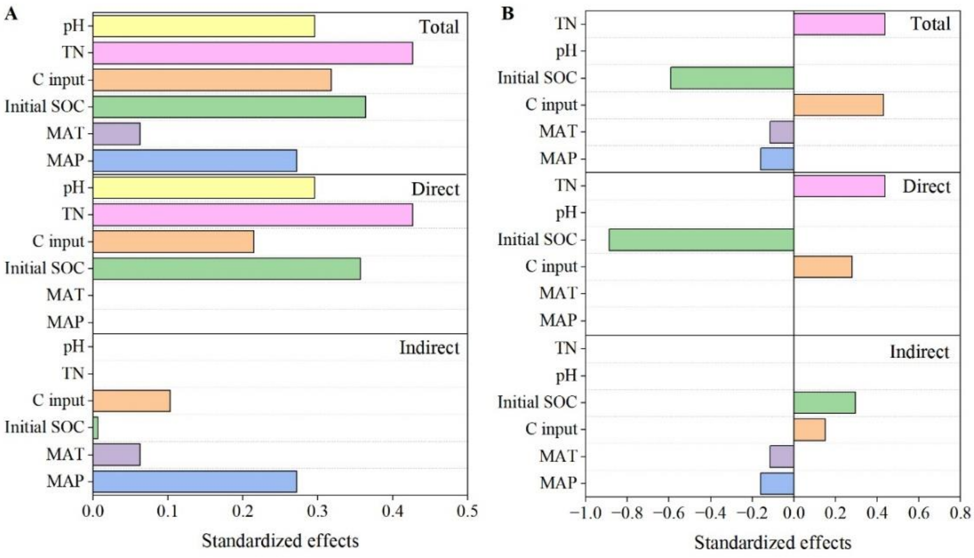
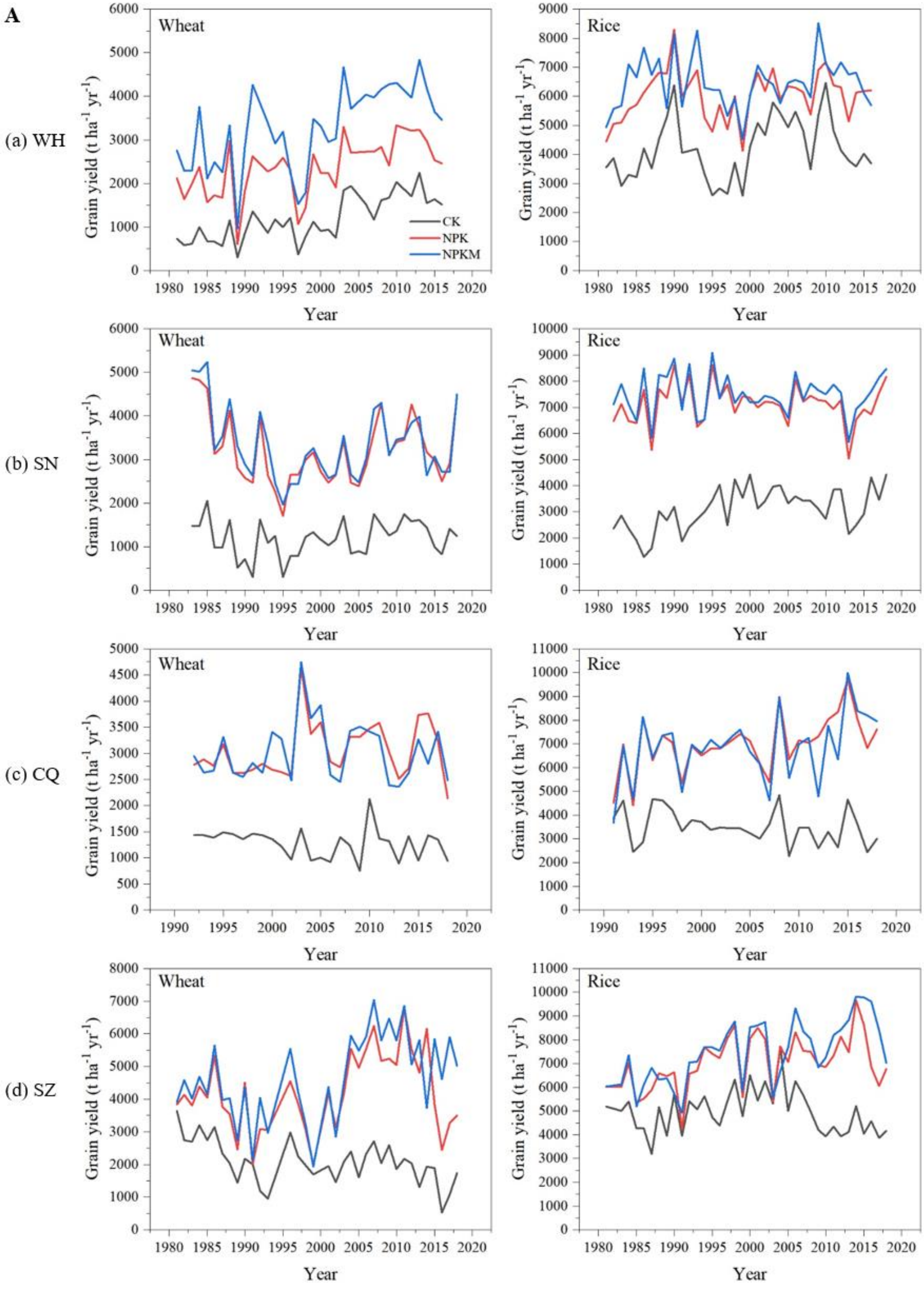
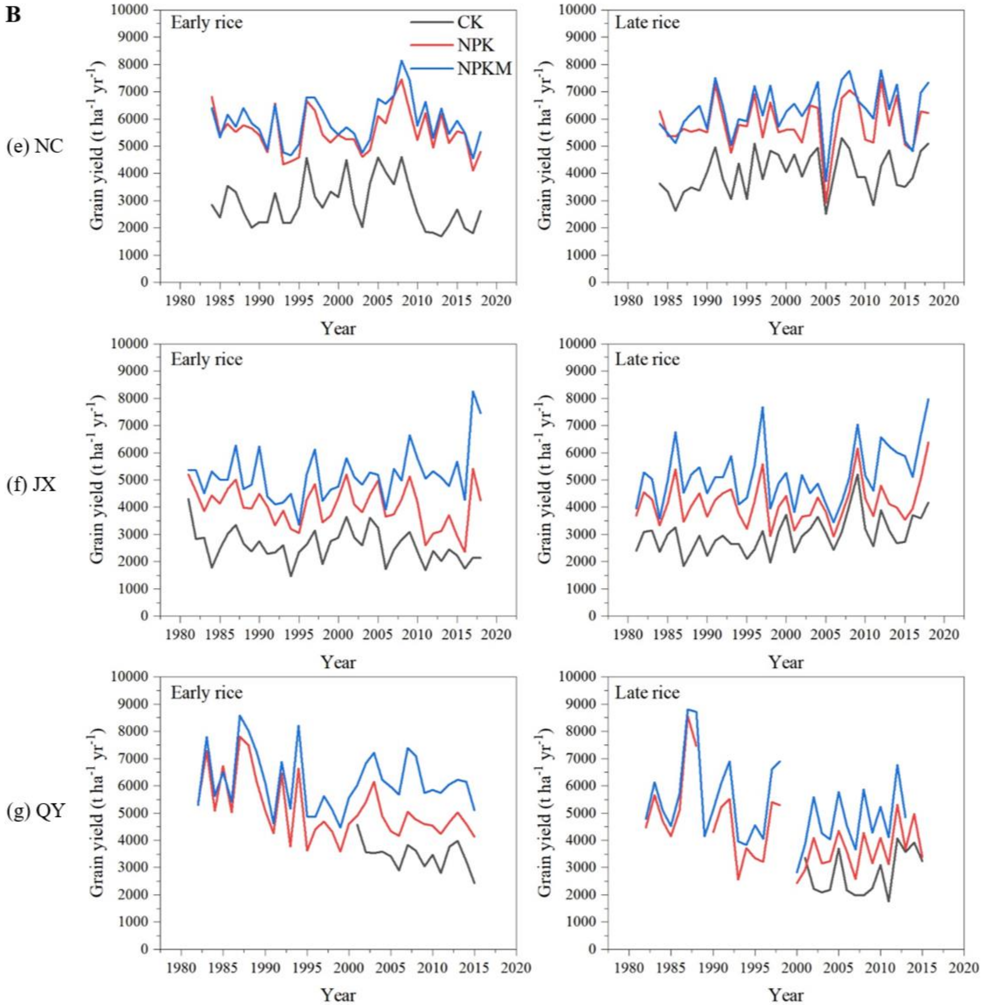
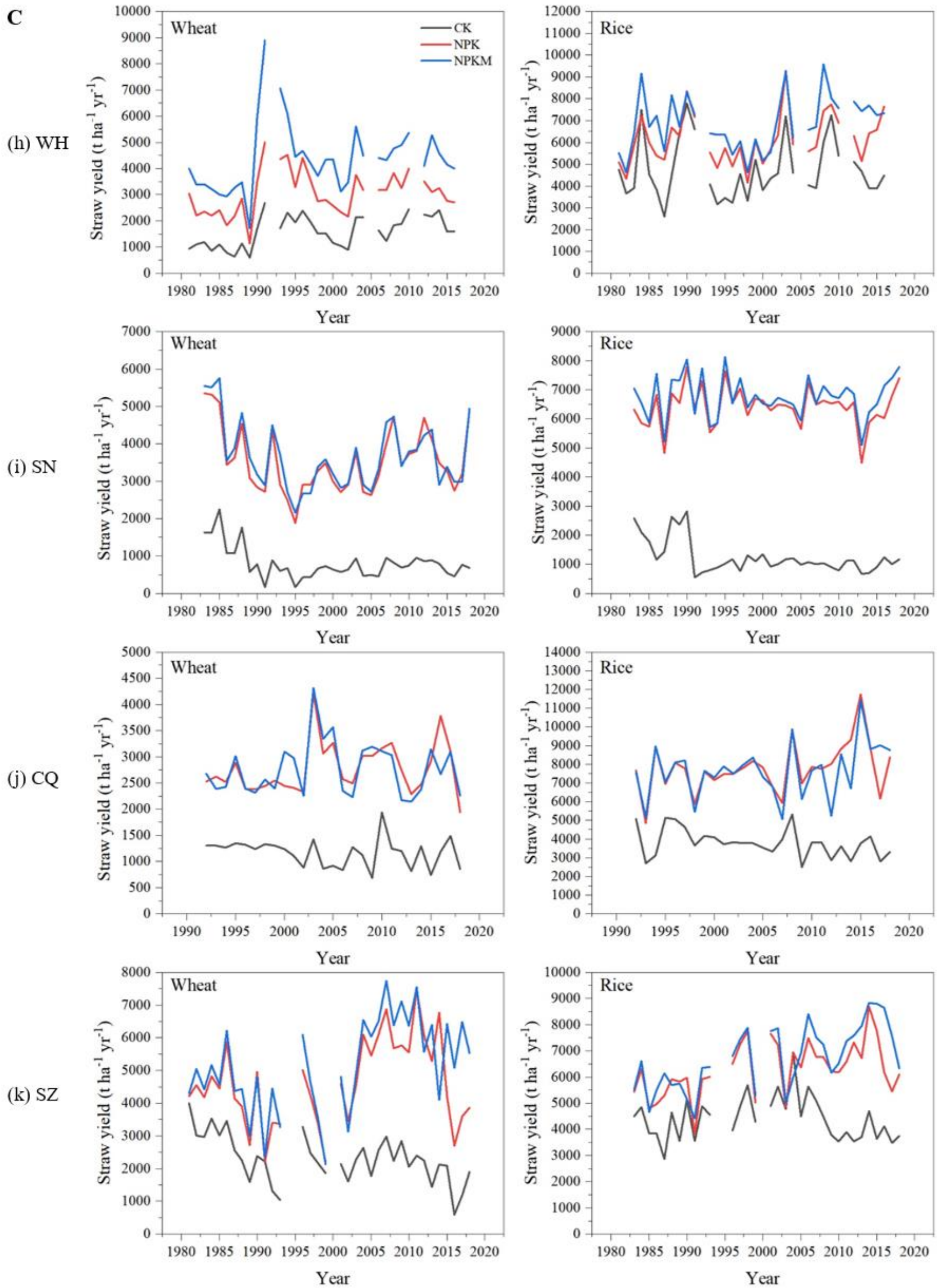


Figure 2-S1: Standardised total, direct and indirect effects of each variable from the structural equation modelling (SEM) analysis in rice–wheat system (A) and double rice system (B). MAT, mean annual temperature; MAP, mean annual precipitation; Initial SOC, soil organic carbon content at the beginning of the experiment; TN, soil total nitrogen content; pH, soil pH.


A
(a) WH
(b) SN
(c) CQ
(d) SZ
Wheat
Rice
Grain yield (t ha-1 yr-1)
Year
CK
NPK
NPKM


B
(e) NC
(f) JX
(g) QY
Early rice
Late rice
CK
NPK
NPKM
Grain yield (t ha-1 yr-1)
Year


C
(h) WH
(i) SN
(j) CQ
(k) SZ
Wheat
Rice
CK
NPK
NPKM
Straw yield (t ha^{-1} yr^{-1})
Year

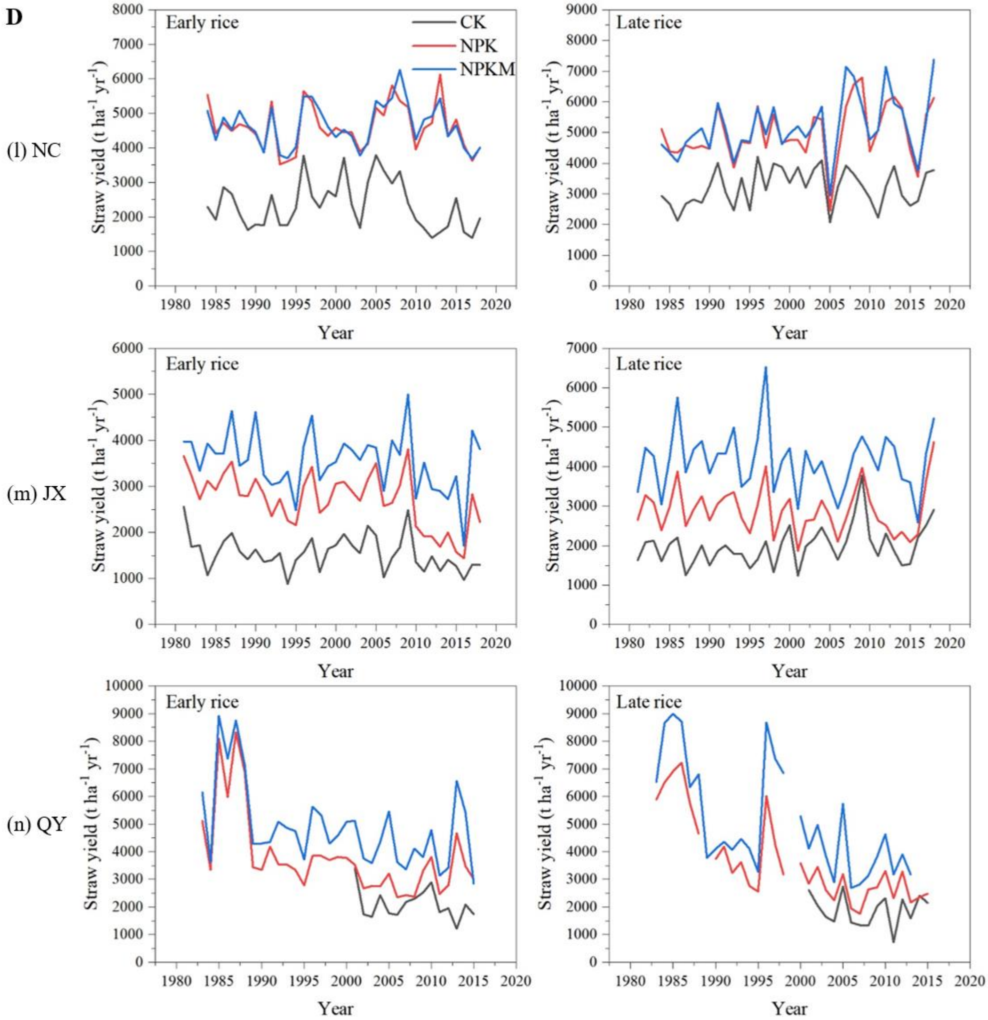


Figure 2-S2: The dynamic changes of crop grain yield (A, B) and straw yield (C, D) in rice–wheat system (A, C) and double rice system (B, D) under different fertilisation treatments (CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; NPKM, a combination of NPK and manure applications) in paddies during the last four decades. WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang. The discontinuity in some years at the WH, SZ and QY sites represents other crops were planted in that year. For CK treatment at QY site, the beginning year is 2001.

Table 2-S1: Soil organic matter (SOM) content (0–20 cm) under long-term fertilisation at the seven experimental sites in the Yangtze River Basin.

Sites	Year	SOM content (g kg^{-1})		
		CK	NPK	NPKM
WH	2015	21.36 ± 4.83	25.54 ± 5.80	34.04 ± 7.11
SN	2017	18.67 ± 1.83	17.01 ± 0.97	22.98 ± 2.44
CQ	2018	22.49 ± 1.48	28.15 ± 2.06	29.21 ± 1.10
SZ	2019	27.23 ± 2.14	31.48 ± 1.95	34.52 ± 3.51
NC	2017	22.38 ± 0.40	28.62 ± 0.53	37.74 ± 0.61
JX	2017	31.71 ± 0.63	31.75 ± 0.11	39.11 ± 0.13
QY	2012	20.70 ± 0.06	26.20 ± 3.40	33.80 ± 4.73

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; NPKM, a combination of NPK and manure applications.

Values are means ± standard deviations.

Chapter 3

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

From: Shuhui Wang, Nan Sun, Shuxiang Zhang, Bernard Longdoz, Joost Wellens, Jeroen Meersmans, Gilles Colinet, Lianhai Wu, Minggang Xu. Soil organic carbon storage impacts on crop yields in rice-based cropping systems under different long-term fertilisation. European Journal of Agronomy 2024, 161, 127357. https://doi.org/10.1016/j.eja.2024.127357

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) stock 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 stock (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.

Keywords:

Crop yield, soil organic carbon stock, rice-based cropping system, long-term fertilisation, Yangtze River Basin.

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) 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., 2021a; Wang et al., 2021b; Zhang et al., 2016a). 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 conditionssuch 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 (Figure 3-1). 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 3-S1.

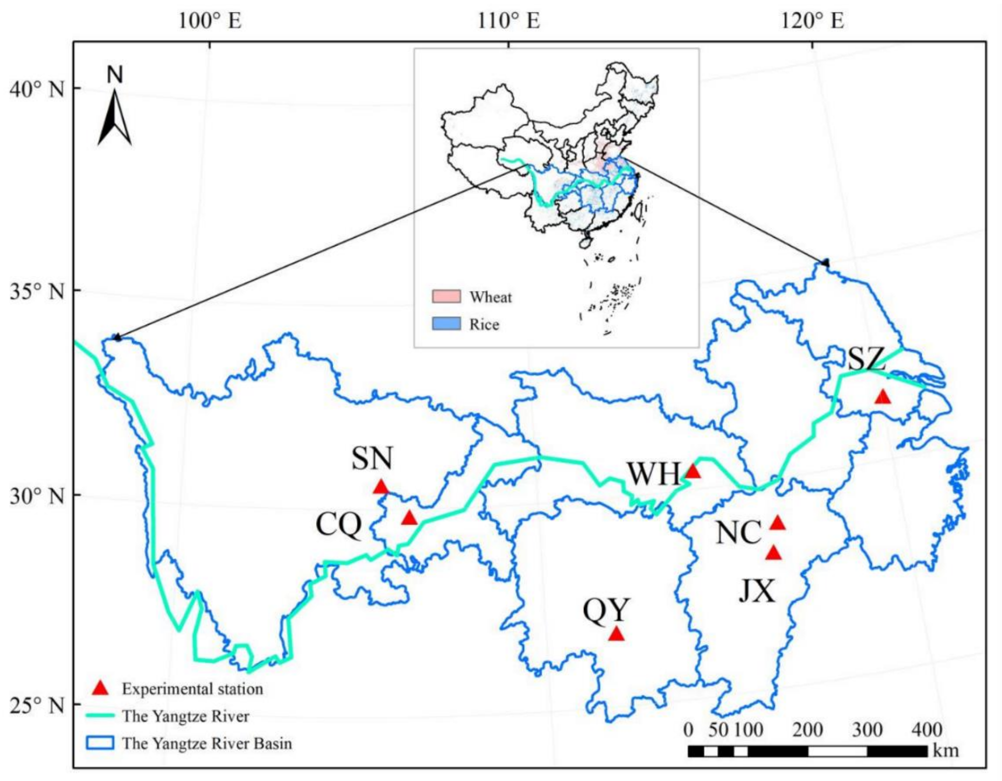


Figure 3-1: The spatial distribution of seven long-term experimental stations based on rice–wheat system and rice–rice system located in the middle and lower reaches of the Yangtze River Basin. Rice–wheat system: WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; Rice–rice system: NC, Nanchang; JX, Jinxian; QY, Qiyang.

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 3-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 topsoil (upper 20 cm) to estimate SOC content, soil total nitrogen (TN), total phosphorus (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 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):

$$RY = Y_T / Y_{NPK} \tag{3-1}$$

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:

$$SYI = (Y_{mean} - SD) / Y_{max} \tag{3-2}$$

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

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 stock (SOC, t C ha^{-1}) is calculated as follows:

$$SOC = SOC_C \times BD \times H \times 0.1 \tag{3-4}$$

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 stock 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. Result

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 Figure 3-2. 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 3-1. 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 3-1).

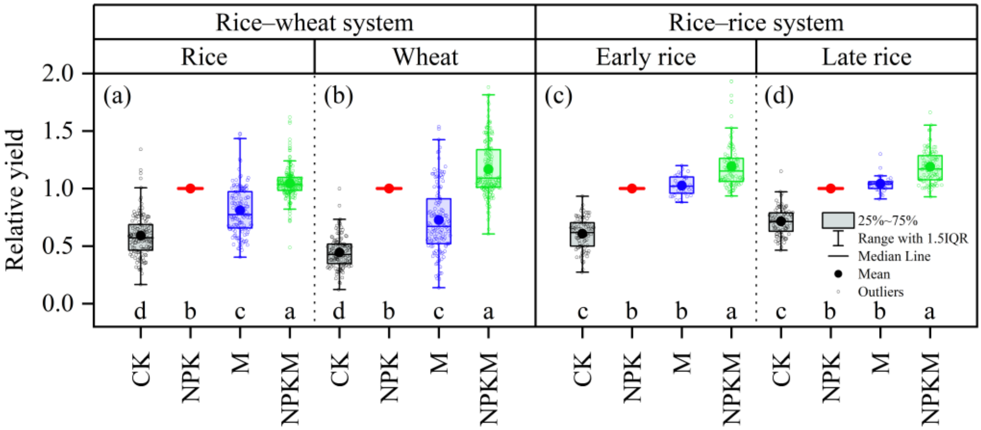


Figure 3-2: Relative crop grain yields with different fertilisation treatments in the rice–wheat system (a–b) and rice–rice system (c–d). CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, application of manure; NPKM, a combination of NPK and M.

Table 3-1: 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.

3.2. Relationship between SOC stock and relative grain yield

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

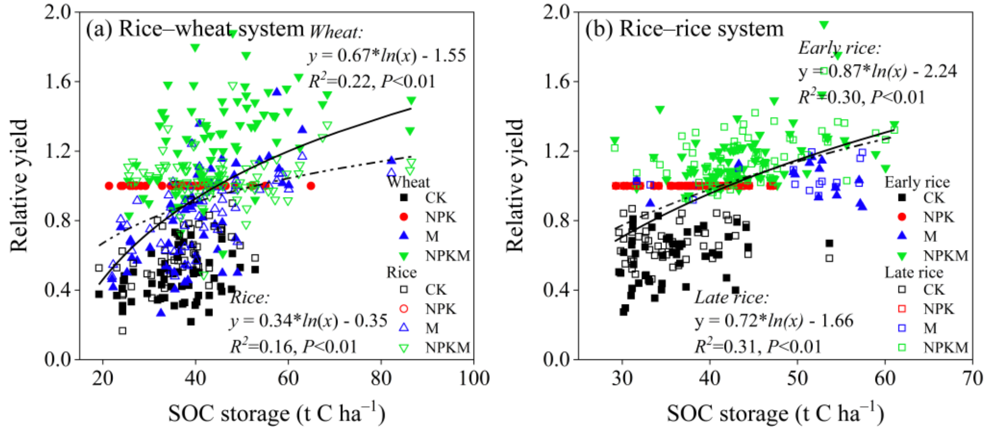


Figure 3-3: The relationships between SOC stock (0–20 cm) and relative crop grain yields in both the rice–wheat system (a) and rice–rice system (b). CK, no fertiliser application; NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, application of manure; NPKM, a combination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

3.3. Factors influencing relative grain yield

Structural equation modelling of the relative grain yield with explanatory variables is presented in Figure 3-4. 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) (Figure 3-4a), while in the rice–rice system, SOC alone had both direct (0.17) and indirect (0.08) positive effects on relative grain yield (Figure 3-4b).

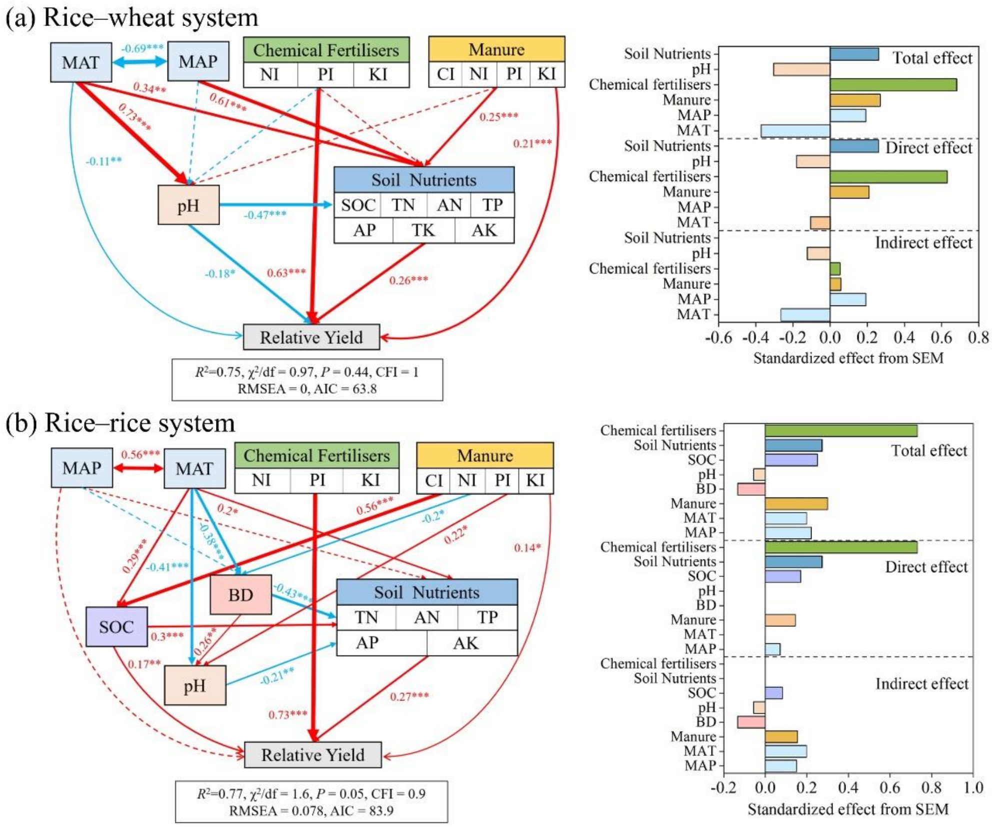


Figure 3-4: Structural equation modelling (SEM) analysis of the relative grain yields with explanatory variables (climate, fertiliser input and soil properties) in the rice–wheat system (a) and rice–rice system (b). The red and blue lines represent positive and negative effects, respectively. The line 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 stock (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.

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 (Figure 3-2). Moreover, the NPKM treatment produced comparable or even higher grain yield stability and sustainability compared to mineral-only fertilisation (Table 3-1), 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 3-S3), thereby improving nutrient availability for plant uptake (Table 3-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., 2017b). 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., 2021c; 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 3-S5).

Our results indicated a positive influence of manure amendment on SOC, subsequently benefiting crop yield in the rice–rice system (Figure 3-4b). 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., 2021b). 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 (Figure 3-4a), while chemical fertiliser, manure amendment, soil nutrients, and SOC had significant direct effects on crop yield in the rice–rice system (Figure 3-4b). 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 (Figure 3-4b). 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., 2017b; Luo et al., 2018), there was a negative impact of pH on crop yield in the two cropping systems (Figure 3-4). Although relatively high model performance was achieved using the selected explanatory variables for the two cropping systems (Figure 3-4), 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., 2023a), 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 (Figure 3-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 SOC 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., 2016a). 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 (Figure 3-4b). 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) (Figure 3-3) 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 (Figure 3-4b), 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 SOC sequestration

Our study has demonstrated that further increasing SOC levels can increase crop yield under both rice–wheat and rice–rice systems (Figure 3-3). 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 stock (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 stock (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.

6. Supplementary material

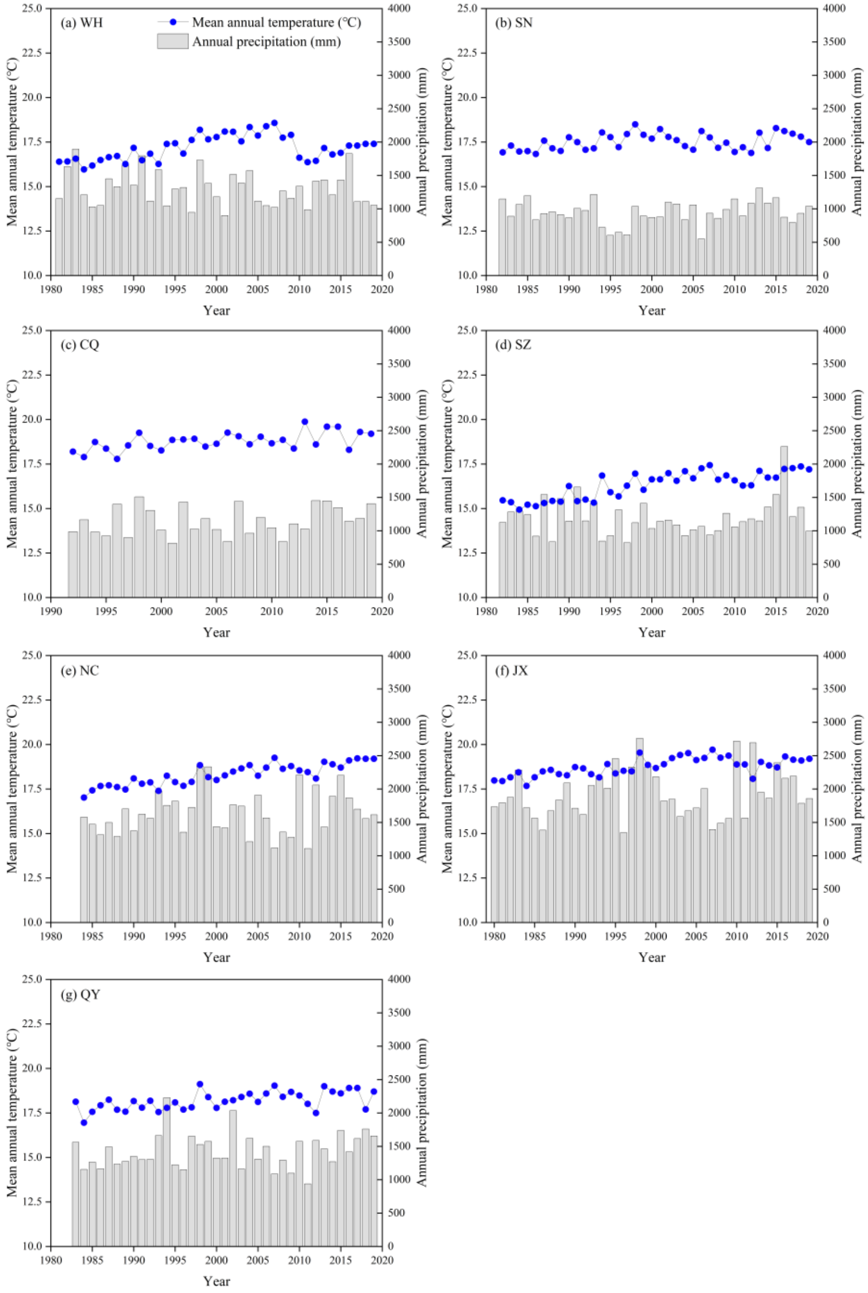


Figure 3-S1: The dynamic changes of mean annual temperature and annual precipitation over the experimental period at different long-term experimental sites.

Table 3-S1: Location, weather condition and soil properties at the beginning of the study period at the seven long-term experimental sites. Adapted from (Wang et al., 2023).

Site[a]	Initial year	Location		Climate			Soil properties (0–20 cm)						
		Longitude	Latitude	Altitude (a.s.l.)	MAT	MAP	Soil type[b]	SOM	TN	TP (P_2O_5)	TK (K_2O)	pH	BD
				m	ºC	mm		g kg^{-1}					g cm^{-3}
WH	1981	30°28'	114°25'	20	16.7	1300	Luvisol	27.4	1.80	1.00	30.22	6.3	1.03
SN	1982	30°34'	105°37'	284	17.3	993	Cambisol	15.9	1.09	0.59	22.32	8.6	NA
CQ	1991	29°48'	106°24'	266	18.3	1293	Cambisol	24.2	1.25	0.67	21.1	7.7	1.38
SZ	1980	31°32'	120°04'	4	15.7	1100	Anthrosol	24.2	1.43	0.43	23.7	6.8	1.26
NC	1984	28°57'	115°94'	25	17.5	1600	Luvisol	25.6	1.36	0.49	NA	6.5	1.19
JX	1981	28°15'	116°20'	30	18.1	1537	Cambisol	28.1	1.49	1.11	12.5	6.9	1.19
QY	1982	26°45'	111°52'	120	18.1	1408	Cambisol	19.8	1.5	0.48	14.2	6.0	NA

[a] WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang.

[b] World Reference Base for soil resources (WRB).

MAT, annual temperature; MAP, annual precipitation; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TK, total potassium; BD, bulk density.

Table 3-S2: Inorganic nitrogen (N), phosphorus (P), potassium (K) fertilisers and manure application rates in each cropping season under different fertilisation treatments at the seven long-term experimental sites. Adapted from (Wang et al., 2023).

Site	Crop	Replicates	Chemical fertilisation ($kg\ ha^{-1}$)[a]						Manure[a]	
			NPK			M/NPKM			Types	Amount ($t\ ha^{-1}$)
			N	P_2O_5	K_2O	N	P_2O_5	K_2O		
WH	Rice	3	90	45	90	90	45	90	Pig manure	11.3 (18.8)
	Wheat	3	60	30	60	60	30	60	Pig manure	11.3 (18.8)
SN	Rice	2, 4[b]	120	60	60	120	60	60	Pig manure	15
	Wheat	2, 4[b]	120	60	60	120	60	60	Pig manure	15
CQ[c]	Rice	1	150	75/60	75/60	150 (225)	75/60 (113/90)	75/60 (113/90)	-	-
	Wheat	1	150/135	75/60	75/60	150/135 (225/202)	75/60 (113/90)	75/60 (113/90)	Cattle manure	22.5
SZ	Rice	2	164	56	138	150	56	138	Pig manure	11.4
	Wheat	2	150	56	138	150	56	138	Rapeseed cake	11.4
NC	Early rice	3	150	60	150	150	60	150	Astragalus sinicus	25 (35)
	Late rice	3	180	60	150	180	60	150	Fresh pig manure	18.5 (26)
JX	Early rice	3	90	45	75	90	45	75	Astragalus sinicus	22.5
	Late rice	3	90	45	75	90	45	75	Pig manure	22.5
QY	Early rice	2, 3[b]	73	56	34	145	112.6	67.6	Cattle manure	22.5
	Late rice	2, 3[b]	73	56	73	145	112.6	145	Cattle manure	22.5

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang.

NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, application of manure; NPKM, a combination of NPK and M.

-, No fertilizer.

a Numbers out and in of brackets represent fertiliser application rate with low and high level of chemical fertilisers or manure.

b Numbers before and after comma represent the number of replicates for CK, M and NPK, NPKM treatments, respectively.

c Numbers before and after / represent the fertiliser application rate in year of 1991–1996 and 1997–2022.

Table 3-S3: Initial and current soil properties under different fertilisation treatments in two rice-based cropping systems at the seven long-term experimental sites.

Rotation system	Sites	Treatments	SOC ($g\ kg^{-1}$)		AN ($mg\ kg^{-1}$)		AP ($mg\ kg^{-1}$)		AK ($mg\ kg^{-1}$)		pH		BD ($g\ cm^{-3}$)	
			Initial	Current	Initial	Current	Initial	Current	Initial	Current	Initial	Current	Initial	Current
Rice–wheat system	WH	CK	15.9	12.4	150.7	112.2	5.0	8.2	98.5	105.6	6.3	6.6	1.03	1.47
		NPK		14.8		134.4		18.3		117.7		6.6		1.51
		M		19.8		190.4		143.6		137.3		6.6		1.54
		NPKM		19.7		189.0		151.3		205.9		6.7		1.56
	SN	CK	9.2	10.8	66.3	74.7	3.9	2.9	108.0	143.0	8.6	8.0	1.30#	1.14
		NPK		9.9		74.0		50.3		127.3		7.9		1.08
		M		11.1		80.0		5.5		129.4		8.0		1.16
		NPKM		13.3		106.2		82.2		146.2		7.9		1.08
	CQ	CK	14.0	13.0	93.0	78.8	4.3	2.6	88.0	102.0	7.7	8.0	1.38	1.34
		NPK		16.3		117.7		24.2		134.5		7.5		1.34
		M		16.6		125.3		8.6		171.3		7.8		1.22
		NPKM		16.9		131.0		34.2		141.0		7.5		1.27
	SZ	CK	14.0	15.2	138*	117.8	8.4	3.5	85.0	96.3	6.8	NA	1.26	1.32
		NPK		17.2		148.3		10.8		83.3		NA		1.21
		M		18.1		143.0		9.8		80.6		NA		1.24
		NPKM		19.0		162.3		28.9		78.8		NA		1.21
Rice–rice system	NC	CK	14.9	13.0	81.6	89.1	20.8	11.0	35.0	38.9	6.5	5.5	1.19	1.26
		NPK		16.6		134.2		52.7		69.9		5.1		1.23
		NPKM		21.9		173.4		100.2		61.2		5.5		0.99
	JX	CK	16.3	18.4	150.4	213.9	9.5	3.8	97.8	48.0	6.9	5.5	1.19	1.17
		NPK		18.4		190.5		5.8		50.7		5.5		1.19
		NPKM		22.7		253.7		63.3		60.0		5.6		1.16
	QY	CK	12.2	12.0	158.0	117.7	9.6	10.8	65.9	NA	6.0	6.4	NA	1.30
		NPK		15.2		131.4		29.7		NA		6.3		1.23
		M		21.2		171.0		12.3		NA		6.3		1.13
		NPKM		19.6		168.4		47.8		NA		6.4		1.12

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.
[*] Measured in 1999; [#] Measured in 1990; NA, not available.

Table 3-S4: Average nutrients (N, P and K) content of crops under different fertilisation treatments in two rice-based cropping systems at the seven long-term experimental sites.

Rotation system	Sites	Treatments	N content (%)		P content (%)		K content (%)	
			Rice/Early rice	Wheat/Late rice	Rice/Early rice	Wheat/Late rice	Rice/Early rice	Wheat/Late rice
Rice–wheat system	WH	CK	1.06	1.96	0.56	0.67	0.34	0.45
		NPK	1.15	1.92	0.57	0.81	0.39	0.48
		M	1.10	1.94	0.55	0.88	0.37	0.48
		NPKM	1.31	2.09	0.56	0.90	0.41	0.51
	SN	CK	1.30	2.25	0.22	0.29	0.31	0.52
		NPK	1.31	2.17	0.30	0.38	0.37	0.62
		M	1.21	2.14	0.27	0.29	0.30	0.53
		NPKM	1.36	2.44	0.30	0.40	0.35	0.64
	CQ	CK	1.39	1.72	0.21	0.25	0.24	0.41
		NPK	1.49	2.10	0.30	0.36	0.28	0.48
		M	1.32	1.71	0.25	0.28	0.26	0.43
		NPKM	1.49	2.17	0.30	0.35	0.29	0.48
	SZ	CK	1.18	1.50	0.31	0.34	0.32	0.30
		NPK	1.21	1.64	0.37	0.42	0.33	0.33
		M	1.14	1.50	0.37	0.44	0.32	0.32
		NPKM	1.21	1.72	0.36	0.44	0.33	0.32
Rice–rice system	NC	CK	1.04	0.99	0.52	0.45	0.37	0.37
		NPK	1.36	1.38	0.63	0.54	0.39	0.41
		NPKM	1.35	1.28	0.61	0.52	0.41	0.39
	JX	CK	0.98	1.02	0.45	0.47	0.35	0.37
		NPK	1.06	1.10	0.52	0.54	0.36	0.38

	NPKM	1.11	1.15	0.63	0.66	0.38	0.39
QY	CK	NA	1.19	NA	0.36	NA	0.43
	NPK	NA	1.24	NA	0.42	NA	0.45
	M	NA	1.24	NA	0.30	NA	0.34
	NPKM	NA	1.21	NA	0.37	NA	0.42

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.

NA, not available.

Table 3-S5: N input from NPK treatment and M treatment in two rice-based cropping systems at the seven long-term experimental sites.

Rotation system	Sites	NPK		M	
		Rice/Early rice season	Wheat/Late rice season	Rice/Early rice season	Wheat/Late rice season
Rice–wheat system	WH	90	60	117	117
	SN	120	120	69	69
	CQ	150	150/135*	0	180/221
	SZ	164	150	52	52
Rice–rice system	NC	150	180	NA	NA
	JX	90	90	NA	NA
	QY	72.5	72.5	72.5	72.5

WH, Wuhan; SN, Suining; CQ, Chongqing; SZ, Suzhou; NC, Nanchang; JX, Jinxian; QY, Qiyang.

NPK, application of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application.

* Numbers before and after / represent the fertiliser application rate in year of 1991–1996 and 1997–2022.

NA, not available, M treatment only conducted at QY site in rice–rice system.

Chapter 4

Strategies to reduce CH_4 and N_2O emissions whilst maintaining crop yield in rice–wheat system under climate change using SPACSYS model

Abstract

Context: Climate change is projected to threaten food security and stimulate greenhouse gas emissions. Hence, adaptation measures without sacrificing food production are required.

Objective: To assess possible consequences of rice–wheat system under climate change and to propose possible practices for mitigation.

Methods: The Soil-Plant-Atmosphere Continuum SYStem (SPACSYS) model was tested using datasets from long-term experiment (1991–2019) assessing the impact of different fertilisation on crop production, crop nitrogen (N) content, soil organic carbon (SOC) stock, methane (CH_4) and nitrous oxide (N_2O) emissions in a Cambisol under rice–wheat system. The validated SPACSYS was then used to investigate the possible mitigation strategies from 2024 to 2100 under climate change scenarios (SSP1–2.6 and SSP5–8.5) and the baseline scenario and mitigation management scenarios, i.e., (i) reduced N application rate by 20 % (RNA), (ii) the introduction of mid-season drainage (MSD) and (iii) integrated management combining RNA with MSD (IM).

Results and conclusions: Results showed that SPACSYS performed effectively in simulating yield and N content in grain and straw, SOC stock and CH_4 and N_2O emissions. Scenarios analysis elucidated that RNA would not decrease grain yields for either rice or wheat under the two climate change scenarios. Compared to the baseline scenario, low level of climate change scenario considering the CO_2 fertilisation effects (SSP1–2.6_CO_2) may benefit wheat yield (28 %) and had no effects on rice yield. In contrast, under the SSP5–8.5 scenario, whether CO_2 fertilisation effects are considered or not, both rice and wheat yield could face great loss (i.e., 11.8–29.9 % for rice, 8.3–19.4 % for wheat). The winter wheat would not be suitable for planting in the distant future (2070–2100) due to the incomplete vernalisation caused by warming. The switching from winter wheat to spring wheat from 2070 onward could avoid the yield loss by 8.3–19.4 %. Climate change could decrease SOC sequestration rate. Under future climate change scenarios, IM could significantly decrease CH_4 emissions by 56 % and N_2O emissions by 24 %, as such reducing the net global warming potential by 69 % compared to no adaptation. Our simulations suggest that under climate change, crop switching in rice–wheat system combining integrated mitigation practices is possible to mitigate global warming and maintain crop production.

Significance: Our results underscore the significance of integrated adaptation of agricultural systems to climate change.

Keywords: Climate change; crop yield; SOC; GHG; Mitigation; SPACSYS

1. Introduction

Rice is a staple food for nearly half of the world's population. Although flooded rice planting systems contributed to a large carbon store resulting from the anaerobic condition (Liu et al., 2021), it accounts for the largest greenhouse gas (GHG) emissions among all the cereal cropping systems due to the high methane (CH_4) emissions (Carlson et al., 2017). Globally, CH_4 and nitrous oxide (N_2O) emissions from paddies have been estimated as 6.3 t CO_2-eq ha^{-1} yr^{-1} (FAO, 2018) and 0.28 t CO_2-eq ha^{-1} yr^{-1} (Carlson et al., 2017), contributes about 18 % and 11 % to the total anthropogenic CH_4 and N_2O emissions (IPCC, 2014; FAO, 2020). Furthermore, climate change, mainly caused by GHG emissions, characterized by increased temperature and atmospheric CO_2 concentration, shifted precipitation patterns, frequent extreme weather events (Shivanna, 2022), is projected to aggravate GHG emissions from agriculture (Liu et al., 2018a; Liu et al., 2020b; Smith et al., 2013) and threaten agricultural productivity (Challinor, 2014; Han et al., 2024). Although many initiatives have been proposed to limit global warming to well below 2℃, the air temperature is expected to rise about 3.2℃ by 2100 (Raftery et al., 2017). Therefore, it is critical to optimise agricultural managements designed to mitigate global warming without compromising crop production in paddy fields (Bossio et al., 2020; Liao et al., 2021). The single rice–winter wheat rotation system is one of the major cropping systems in China, contributing to 9.5 % of the total grain production. However, the related GHG emissions account for 15 % of the total GHG emissions from rice fields (Gao et al., 2018). As such, it is necessary to explore the potential mitigations for GHG emissions in the rice–wheat system.

Process-based agricultural models, capable of considering the complex interactions between multiple environmental factors and various agronomic practices, are powerful for evaluating the impacts of climate change on agricultural systems and proposing GHG mitigation practices in future climate. A wide range of models have been developed and applied to simulate crop grain yields, SOC stock and GHG emissions in rice cropping systems, including DAYCENT (Guo et al., 2023), DNDC (Guo et al., 2024a), WHCNS (Liang et al., 2022), DSSAT (Baishya et al., 2023), CERES (Timsina and Humphreys, 2006), APSIM (Gaydon et al., 2017). Moreover, the potential risk with different management practices and climatic conditions has been assessed with various models. For instance, studies predicted a decreasing trend in SOC content without straw incorporation in paddies in South Korea (Ku et al., 2019), a substantial rice yield loss across China (Liu et al., 2020c) and an enhanced GHG intensity of rice production from global paddies (van Groenigen et al., 2012) under climate change. As such, based on the model approach, adaptive measures and suggestions to improve crop yields and simultaneously mitigating global warming have been recommended. For instance, Wang et al. (2022) highlighted the necessity of increasing C input in enhancing SOC stock under future climatic conditions and Zhou et al. (2023) suggested that the highest crop productivity and lowest CH_4 emissions can be obtained simultaneously by optimising the sowing window for 20 rice field stations across Hubei Province, China. Similarly, Zhao et al. (2020)

recommended a reduced N fertiliser application rate combined with moistening irrigation (soil was saturated with water but not covered with a layer of water) for reducing GHG emissions while maintaining grain yields in rice–wheat systems. Although there have been many studies using models to evaluate the response of agricultural systems to field management practices under future climatic conditions, few studies have systematically evaluated the net GHG emissions that combining SOC sequestration with GHG emissions, while considering crop yields.

The Soil-Plant-Atmosphere Continuum SYStem model (shorten as 'SPACSYS') (Wu et al., 2007, 2015) is one of the widely used agricultural models. The model has been proved to be effective in simulating crop growth and development, nitrogen (N) uptake, SOC sequestration, soil water dynamics and GHG emissions (Wang et al., 2019; Liu et al., 2020a). It has been widely used to explore the influence of climate change on agricultural systems under various agricultural management practices including N fertiliser application, organic amendment, irrigation and tillage (Liang et al., 2018; Liu et al., 2018b; Zhang et al., 2018; Hassall et al., 2022; Wu et al., 2022b; Wang et al., 2024a). It has also been used to optimise planting dates and N fertiliser management practices under various soil and climatic conditions (Abalos et al., 2016; Liu et al., 2020a; Wu et al., 2020). The new version of the model (Ver. 6.00) allows to simulate arable systems, bioenergy crops and intensive and extensive grazing systems on grasslands (Wu et al., 2022a; Wang et al., 2024b). Its special features are the biological-based denitrification component that can distinguish different nitrogenous gases emissions (N_2O, NO and N_2) (Wu et al., 2015) and the detailed three-dimensional root growth sub-modules that can simulate water and nutrients uptake by plants accurately (Bingham and Wu, 2011). However, the model lacks processes related to soil microbial mediation of carbon-cycle (e.g. microbial necromass recycling, active and dormant microbial dynamics) (Chandel et al., 2023). In general, SPACSYS is considered as a promising tool for identifying sustainable management practices for climate change adaptation.

In this study, the SPACSYS was calibrated and validated using datasets from an experiment on the rice–wheat system with long-term different fertilisation measures. The validated model was further applied to assess possible consequences under future climate change scenarios (i.e., SSP1–2.6 and SSP5–8.5) for the system and to propose possible agricultural management practices (i.e., chemical N fertilisers and irrigation management) for adaptation and mitigation in Southwest China.

2. Materials and methods

2.1. Study site and experimental design

In the present study, dataset was collected from the long-term experiment (1991–2019) at the National Monitoring Station for Purple Soil Fertility (29°48'N, 106°24'E) in Beibei, Chongqing, China. The area has a subtropical climate with a mean annual temperature of 19.2°C and mean annual precipitation of 1133 mm between 1991 and 2020 (Figure 4-1). The soil is classified as Rhodic Cambisol based on "World

Reference Base for soil resources" soil classification and its basic physicochemical characteristics (measured in 1991) were presented in Table 4-1.

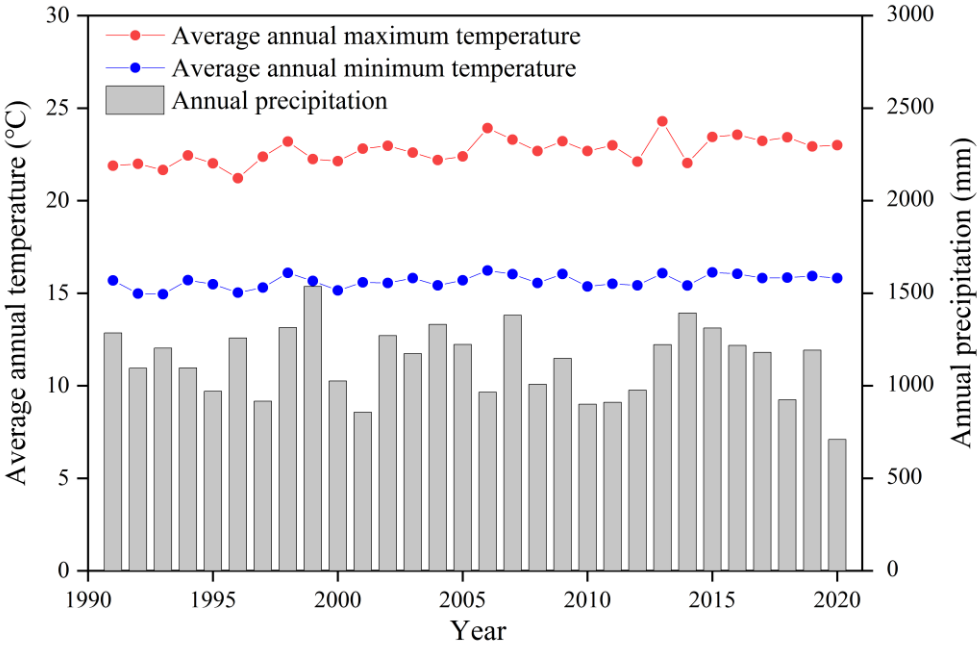


Figure 4-1: Average annual temperature and precipitation at the experimental site from 1991 to 2020.

Table 4-1: The initial soil basic physicochemical characteristics (measured in 1991) at the long-term experimental site.

Soil layer (cm)	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	pH (H_2O)	BD (g cm^{-3})
0–20	24.2	1.25	0.67	21.1	93	4.3	88	7.7	1.38
20–40	23.9	1.35	0.52	20.2	95	4.7	85	7.7	-

SOM: total soil organic matter; TN: total nitrogen; TP: total phosphorus; TK: total potassium; AN: available nitrogen; AP: available phosphorus; AK: available potassium; BD: Soil bulk density.
- No values.

The cropping system is single rice–winter wheat rotation system. Each year, rice is transplanted in mid-May and harvested in late August, whereas winter wheat sown in early November and harvested in early May next year. The changes in crop varieties during the experimental periods are shown in Table 4-S1. Four treatments were considered in this experiment, i.e., no fertiliser application (CK), application of chemical N, P and K fertilisers (NPK), application of manure (M) and a combined application of NPK and M (NPKM). Detailed information about the experiment has been reported previously (Wang et al., 2020a). The N fertiliser was applied in the form of urea in two split doses for both rice and wheat, i.e., 60 % of total application amount for a crop as basal fertiliser (before rice transplanted or wheat sown), and the rest applied at between the 3rd and 4th leaf expansion for wheat and between 2 and 3 weeks after transplantation for rice. The P and K fertilisers were applied as basal fertilisers only. Fresh pig manure was applied at 22.5 t ha^{-1} once a year as basal fertiliser before wheat sown for M and NPKM treatments. From 1996, the M treatment was changed into rice straw return at 7.5 t dry matter ha^{-1} (1996–2013) or 4.5 t ha^{-1} (2014–2017) and then switched back to the application of fresh pig manure from 2018. Table 4-2 shows the fertiliser application rates used during the experiment for N (urea), P (calcium superphosphate), K (potassium chloride) fertilisers as well as for manure. Wheat was rain-fed and rice was flooded with a waterlogging depth of 5–8 cm till 3 weeks before harvest and then the field was drained. Pesticide and herbicide were applied followed the local conventional practices. Historical (1991–2020) daily weather data were downloaded from the National Meteorological Information Center (http://data.cma.cn/).

Table 4-2: Fertiliser application rate for each crop at the experimental site during 1991–2019.

Treatments[1]	Rice (kg ha^{-1})			Wheat (kg ha^{-1})			
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	Manure/Straw[2]
CK	0	0	0	0	0	0	0
NPK[3]	150 (135)	75 (60)	75 (60)	150	75 (60)	75 (60)	0
M[4]	0	0	0	0	0	0	22500/ 4500–7500
NPKM	150 (135)	75 (60)	75 (60)	150	75 (60)	75 (60)	22500

[1] CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application; NPKM, a combination of NPK and M applications.

[2] The average N, P and K content for manure and straw are 0.56, 0.48, 1.31 %, and 0.70, 0.12, 2.59 %, respectively.

[3] Numbers out and in of brackets represent fertiliser application rate in year of 1991–1996 and 1997–2019.

[4] The application of manure changed to straw retention during 1996–2016.

2.2. Measurements

Soil samples were collected from the 0–20 cm topsoil (with 4 replicates) after rice harvest. The SOC content was measured with the wet oxidation method (Snyder and Trofymow, 1984) and converted to SOC stock (t C ha^{-1}):

$$SOC = SOC_C \times BD \times 20 \times 0.1 \quad (4\text{-}1)$$

where SOC_C is the soil C content (g kg^{-1}), BD is the soil bulk density, and 0.1 is a conversion coefficient.

The CH_4 and N_2O emission fluxes in CK and NPK treatments were measured (with 3 replicates) every 3–5 days during the rice season and every 7–10 days during the rest of the period from May 2014 to April 2015 using the static closed chamber method (60 cm × 30 cm × 110 cm). Gas samples were collected between 9:00 and 12:00 a.m. at 0, 10, 20 and 30 min after chambers were closed and analysed using a gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan) immediately after collection.

The crop grain and straw were manually collected at harvest and then air-dried and weighed. Crop grain and straw samples were oven-dried at 105°C for 30 min and then heated at 70°C to constant weight to determine crop N content with the method of Kjeldahl. The yield stability and sustainability of rice and wheat under different scenarios were evaluated by considering the coefficient of variation (CV) and the sustainable yield index (SYI), respectively (Han et al., 2020), which are calculated as follows:

$$CV = SD / Y_{mean} * 100\ \% \qquad (4\text{-}2)$$

$$SYI = (Y_{mean} - SD) / Y_{max} \qquad (4\text{-}3)$$

where Y_{mean} and Y_{max} (kg ha^{-1}) are the mean and maximum values of grain yield for a given crop during the study period in each simulation scenario, and SD is the standard deviation of the grain yield for a given crop.

2.3. The SPACSYS model

The SPACSYS model (Ver 6.00) is a field scale, weather-driven, process-based and flexible time step (up to daily) dynamic simulation model (Wu et al., 2007; Wu and Shepherd, 2011; Wu et al., 2015; Wu et al., 2022a). It simulates processes in plant development and growth, soil heat and water transformation, soil C and N dynamics. The actual growth of plant is determined by the potential growth and the limitation of leaf N, P concentration and soil water content in the root zone. The SOM pool is divided into four sub-pools, fresh organic material, humus, dissolved SOM and microbial biomass. The new version of SPACSYS includes a methanogenesis sub-model that considers the anaerobic oxidation of SOM under anaerobic conditions. Dry and wet N deposition was considered by the model.

2.4. Model calibration and validation

The model was initially run with parameters obtained from previous results (Bingham and Wu, 2011; Liu et al., 2020a). Observations from NPK and M treatments were used to calibrate the parameters related to crop and soil processes. The calibrated parameters are shown in Table 4-S2. The calibrated model was validated with the data from CK and NPKM treatments.

2.5. Simulation scenarios

To explore possible practices to mitigate GHG emissions under future climatic conditions in paddy fields, different field management practices with various climate scenarios were investigated. The daily bias-corrected weather data of the two future climate change scenarios (SSP1–2.6 and SSP5–8.5) for 2024–2100 and the baseline scenario spans the historical time period 1938–2014 with the UKESM1-0-LL model were downloaded from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) (https://esgfnode.llnl.gov/projects/cmip6/). The dataset of the baseline scenario was then cycled to 2100 for model simulation. The UKESM1-0-LL model is developed by the UK Earth System Modelling project, it performs well with the observations in the historical simulation periods (Sellar et al., 2019). Shared Socioeconomic Pathway (SSP) 1–2.6 and 5–8.5 represent two distinct pathways: SSP1–2.6 represents sustainable development with lower GHG emissions and SSP5–8.5 represents energy intensive and fossil-fueled development with higher GHG emissions (O'Neill et al., 2016). The downloaded data was then downscaled to the location based on geographical information with the R 'raster' package. A summary of different weather elements and CO_2 concentrations under each climate change scenario are shown in Table 4-3.

Local traditional management practices for simulation scenarios refer to the application of chemical N, P and K fertilisers with N application rate at 285 kg N ha^{-1} yr^{-1} (150 and 135 kg N ha^{-1} yr^{-1} for rice and wheat, respectively), and water managements of continuous flooding during rice season and rain-fed irrigation during wheat season in rice–wheat cropping system. We assume that the straw returning rate is 30 %, representing the stubble remaining at harvest. Three mitigation management scenarios were considered: reduced N application rate by 20 % (RNA), the introduction of mid-season drainage (MSD) during the rice growing period and integrated management combining RNA with MSD (IM). Therefore, 11 possible scenarios were generated considering a combination of climate scenarios and mitigation management practices (Table 4-4). For all the scenarios, we set initial soil properties the same values as the observations. Crop cultivars and the sowing/transplanting dates were assumed to be identical to those of 2018 (Table 4-S1). However, winter wheat requires a period of low temperature in winter for vernalisation, under the intensive climate change scenario, the increasing temperature in winter could hamper winter wheat development (when the development index of winter wheat from model output stops at 2, indicating that the crop cannot enter reproductive growth and the photosynthetic products will continue to accumulate in vegetative organs), we then changed winter wheat to spring wheat, which does not require vernalisation and is more suitable for planting under future climatic conditions.

The annual net global warming potential (GWP_N, kg CO_2-eq ha^{-1} yr^{-1}) is calculated (IPCC, 2021):

$$GWP_N = CH_4 \times 16/12 \times 27 + N_2O \times 44/28 \times 273 - SOC_r \times 44/12 \quad (4\text{-}4)$$

$$SOC_r = SOC_n - SOC_{(n-1)} \quad (4\text{-}5)$$

where CH_4 and N_2O are the annual cumulative CH_4 (kg C ha^{-1} yr^{-1}) and N_2O emissions (kg N ha^{-1} yr^{-1}), respectively, and SOC_r is the annual SOC sequestration rate (kg C ha^{-1} yr^{-1}), SOC_n and $SOC_{(n-1)}$ are the SOC stock in the year n and (n-1), respectively. The values 27 and 273 are the global warming potential of CH_4 and N_2O on a 100-year horizon given by IPCC (2021), 16/12, 44/28 and 44/12 are the conversion factors to get the corresponding CO_2-eq value.

Table 4-3: Characteristics of different meteorological elements for each climate change and baseline scenario.

	Annual mean maximum temperature (°C)		Annual mean minimum temperature (°C)		Annual precipitation (mm)		Annual mean global radiation (MJ m^{-2})		CO_2 concentration range (ppm)
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Baseline	21.5	0.6	15.2	0.5	1149.1	207.8	11.4	0.6	400
SSP1−2.6	24.6	0.7	18.1	0.6	1233.2	245.4	12.7	0.7	425.4−476
SSP5−8.5	27.0	2.4	20.4	2.3	1241.6	238.7	12.4	0.7	427.8−1148

Baseline, historical climate (1938–2014, constant CO_2 concentration at 400 ppm); SSP1–2.6, strict limits on GHG emissions; SSP 5–8.5, no limits on GHG emissions; SD, standard deviation.

Table 4-4: Designed scenarios combining climate change scenarios with mitigation management scenarios.

Scenarios abbreviation	Climate change scenarios	Mitigation management scenarios
Baseline	Downloaded historical data	Local traditional management practices*
SSP1–2.6	SSP1–2.6 with a constant CO_2 concentration	Local traditional management practices
SSP1–2.6_CO_2	SSP1–2.6 with CO_2 fertilisation	Local traditional management practices
SSP1–2.6_CO_2_RNA	SSP1–2.6 with CO_2 fertilisation	Reduced N application rate (20 % less N than Baseline)
SSP1–2.6_CO_2_MSD	SSP1–2.6 with CO_2 fertilisation	Mid-Season Drainage (continuous flooding with mid-season drainage in rice growing season)
SSP1–2.6_CO_2_IM	SSP1–2.6 with CO_2 fertilisation	Integrated management (combining RNA with MSD)
SSP5–8.5	SSP5–8.5 with a constant CO_2 concentration	Local traditional management practices
SSP5–8.5_CO_2	SSP5–8.5 with CO_2 fertilisation	Local traditional management practices
SSP5–8.5_CO_2_RNA	SSP5–8.5 with CO_2 fertilisation	Reduced N application rate (20 % less N than Baseline)
SSP5–8.5_CO_2_MSD	SSP5–8.5 with CO_2 fertilisation	Mid-season drainage (continuous flooding with mid-season drainage in rice growing season)
SSP5–8.5_CO_2_IM	SSP5–8.5 with CO_2 fertilisation	Integrated management (combining RNA with MSD)

* Local traditional management practices refer to the application of chemical N, P and K fertilisers with N application rate at 285 kg N ha^{-1} yr^{-1} (150 and 135 kg N ha^{-1} yr^{-1} for rice and wheat, respectively), and water managements of continuous flooding during rice season and rain-fed irrigation during wheat season in rice–wheat cropping system. The straw returning rate is 30 %, representing the stubble remaining at harvest.

2.6. Statistical analysis

Four statistical metrics were used to assess the model's performance, i.e., the coefficient of determination (R^2, 0 to 1), the normalised root mean square error (NRMSE), modelling efficiency (EF, –∞ to 1) and the index of agreement (d, 0 to 1). R^2 represents the proportion of the variance in measurements explained by the model; NRMSE indicates the percentage deviation from the range of observations; EF compares the modelling efficiency to the efficiency of describing the data as measured averages and d gives the degree to which the deviation toward 0 (Willmott, 1982; Moriasi *et al.*, 2007; Yang *et al.*, 2014; Tesfaye et al., 2021). They are calculated as follows:

$$R^2 = \left(\frac{\left(\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})\right)}{\sqrt{\sum_{i=1}^{n}(Oi - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}} \right)^2 \tag{4-6}$$

$$NRMSE = \frac{1}{(O_{max} - O_{min})}\sqrt{\frac{\sum_{i=1}^{n}(Si - Oi)^2}{n}} \tag{4-7}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(Si - Oi)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2} \tag{4-8}$$

$$d = 1 - \sum_{i=1}^{n}(S_i - O_i)^2 / \sum_{i=1}^{n}(|(S_i - \bar{O})| + |(O_i - \bar{O})|)^2 \tag{4-9}$$

where S_i and O_i are simulations and observations for the ith sampling point, respectively; $\bar{S}$ and $\bar{O}$ are the averages of all simulations and observations; O_{max} and O_{min} are the maximum and minimum values of the observations; and n is the sample size and "| |" is an absolute calculation.

One-way ANOVA analysis followed by the Duncan's test at the 0.05 level ($P < 0.05$) was used to determine the significant difference of the effects of climate and mitigation management scenarios on crop yields, CH_4 and N_2O emissions and GWP_N. The ANOVA have been performed using SPSS 22.0 (SPSS, Inc., 2017, Chicago, USA).

3. Results

3.1. Model calibration and validation

Statistical indicators for model performance at both the calibration and validation stages are shown in Table 4-5. The values showed that the SPACSYS model performed relatively well in simulating crop grain and straw yields, crop N uptake, SOC stock, and CH_4 and N_2O emission fluxes in the rice–wheat system. Specifically, simulated crop grain and straw yields along with their N contents matched well with the observed data for each treatment over the whole period (Figure 4-2). The simulation performance of wheat was better than that of rice, as shown by lower NRMSE (Table 4-5). Modelled SOC stock in the top 20 cm of soil was well consistent with the measured data, with modelled and observed average SOC sequestration rates ranged from 57 to 308 kg C ha^{-1} yr^{-1} and 24 to 421 kg C ha^{-1} yr^{-1}, respectively (Figure 4-3). The EF ranged between 0.12 and 0.53, the d ranged between 0.68 and 0.79

(Table 4-5). The model fairly captured the pattern and magnitude of observed daily CH_4 and N_2O fluxes (Figure 4-4). The simulated peak for CH_4 flux in summer 2014 (3.49 kg C ha^{-1} day^{-1}) agreed well with the observed (3.30 kg C ha^{-1} day^{-1}), however, the model did not capture the N_2O emission peak in the winter wheat growing season (Figure 4-4). The model performance in simulating daily CH_4 and N_2O fluxes was effective, with EF ranged from 0.14 to 0.63 and d ranged from 0.59 to 0.89 (Table 4-5).

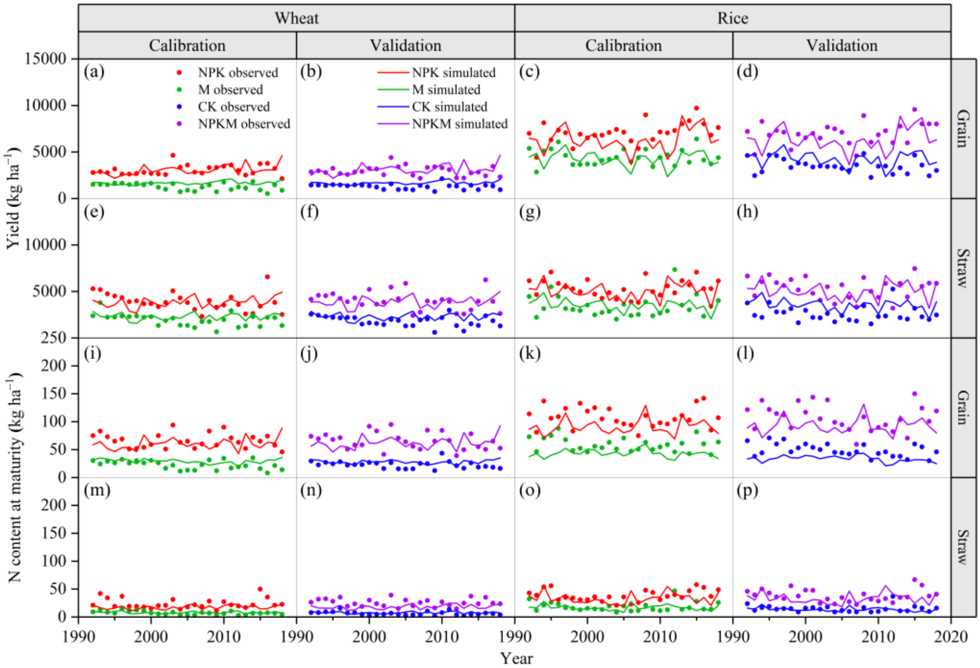


Figure 4-2: Observed and simulated crop yield and N content from 1991 to 2019. CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application; NPKM, a combination of NPK and M applications.

Table 4-5: Statistical analysis describing the performance of the SPACSYS model for the simulations of crop yield, crop N content, SOC stock, daily CH_4 and N_2O emissions in the rice–wheat rotation system.

Crop	Variable (kg ha^{-1} for crops)	Calibration					Validation				
		n	R^2	NRMSE	EF	d	n	R^2	NRMSE	EF	d
Wheat	Grain yield	54	0.46**	20 %	0.35	0.75	54	0.58**	18 %	0.48	0.84
	Straw biomass	54	0.38**	21 %	0.29	0.72	54	0.49**	17 %	0.48	0.79
	Nitrogen content in grain at maturity	54	0.54**	20 %	0.48	0.79	54	0.64**	17 %	0.64	0.88
	Nitrogen content in straw at maturity	54	0.43**	18 %	0.34	0.70	54	0.62**	21 %	0.48	0.78
Rice	Grain yield	54	0.38**	20 %	0.32	0.77	54	0.54**	19 %	0.54	0.83
	Straw biomass	54	0.22**	25 %	0.17	0.65	54	0.37**	23 %	0.33	0.72
	Nitrogen content in grain at maturity	54	0.63**	24 %	0.30	0.81	54	0.67**	21 %	0.46	0.85
	Nitrogen content in straw at maturity	54	0.39**	23 %	0.29	0.76	54	0.42**	21 %	0.33	0.78
SOC stock (t C ha^{-1})		30	0.21**	24 %	0.12	0.68	30	0.62**	18 %	0.53	0.79
Daily CH_4 emissions (g C m^{-2} day^{-1})		69	0.64**	16 %	0.63	0.89	69	0.56**	20 %	0.38	0.85
Daily N_2O emissions (g N m^{-2} day^{-1})		69	0.52**	13 %	0.26	0.69	69	0.17*	17 %	0.14	0.59

R^2, the correlation of determination; NRMSE, the normalised root mean square error; EF, the modelling efficiency; d, the index of agreement. ** *P*<0.01.

[1] The unit of RMSE is same as of the measured traits.

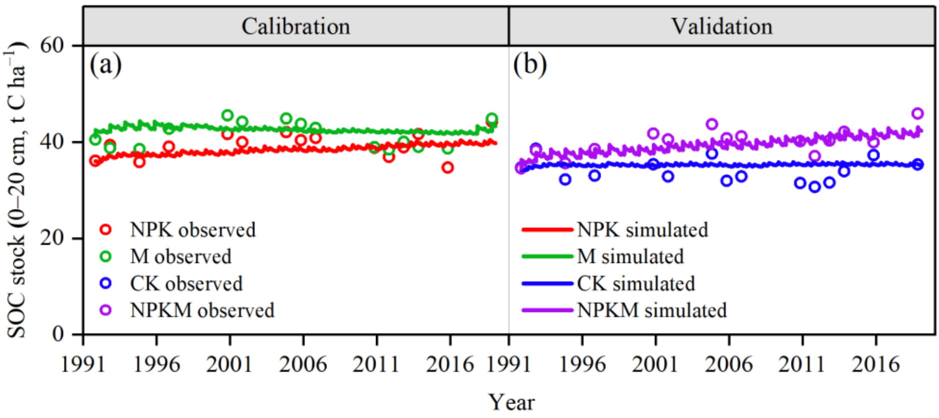


Figure 4-3: Observed and simulated SOC stock in the top 20 cm of soil depth in the rice–wheat rotation system from 1991 to 2019. CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application; NPKM, a combination of NPK and M applications.

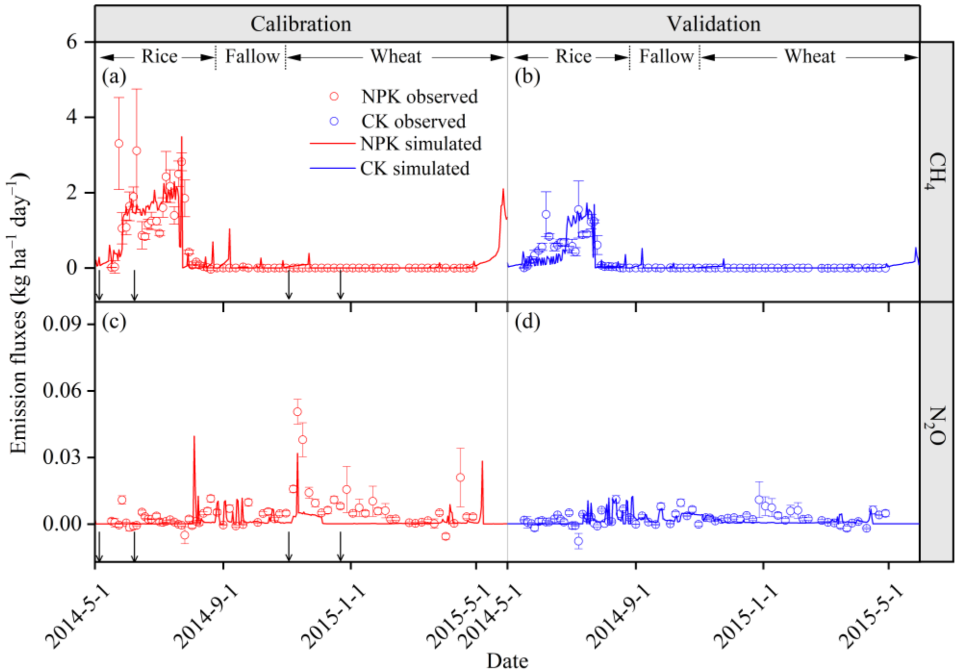


Figure 4-4: Observed and simulated CH_4 and N_2O emission fluxes for model calibration and validation at the experimental site in the rice–wheat rotation system between May 1, 2014, and May 31, 2015. Solid downward arrows indicate N fertiliser application events. CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers.

3.2. Crop grain yields under different climate change and mitigation management scenarios

The influence of climate change scenarios, mitigation management scenarios and their combination on crop yields are shown in Figure 4-5a, b (conventional cropping system) and Figure 4-5c, d (adaptive cropping system). Under the conventional cropping system (single rice–winter wheat), the climate in the SSP1–2.6 scenario considering the CO_2 fertilisation effects could significantly increase wheat yields by 28 %, while rice yields would not change compared to the baseline scenario ($P<0.05$) (Figure 4-5a, b). However, the climate in the SSP5–8.5 scenario (considering the CO_2 fertilisation effects or considering a constant CO_2 concentration) could significantly decrease rice yields by 11.8–29.9 % and wheat yield by 8.3–19.4 % ($P<0.05$) (Figure 4-5a, b). The decrease in wheat yields is significantly due to the incomplete vernalisation of winter wheat in warmer winter after 2070, suggesting it would be particularly unsuitable for planting winter wheat under the SSP5–8.5 scenario (Figure 4-S1). Therefore, the winter wheat was replaced by spring wheat from 2070 onward in the rice–wheat cropping system, referred as the adaptive cropping system. The results showed that under the adaptative cropping system, the wheat yield loss caused by warming in the conventional cropping system could be completely avoided (Figure 4-5d). On the contrary, wheat yield could increase by up to 21.9 % compared to the baseline scenario (Figure 4-5d). A 20 % reduction in N application would not significantly decrease grain yields for either rice or wheat ($P<0.05$) under the two climate change scenarios (Figure 4-5). The yield stability and sustainability of rice and wheat under the SSP5–8.5 climate change scenario could be lower than those under the SSP1–2.6 climate change scenario (Figure 4-S2). Rice had a higher stability and sustainability than wheat (Figure 4-S2).

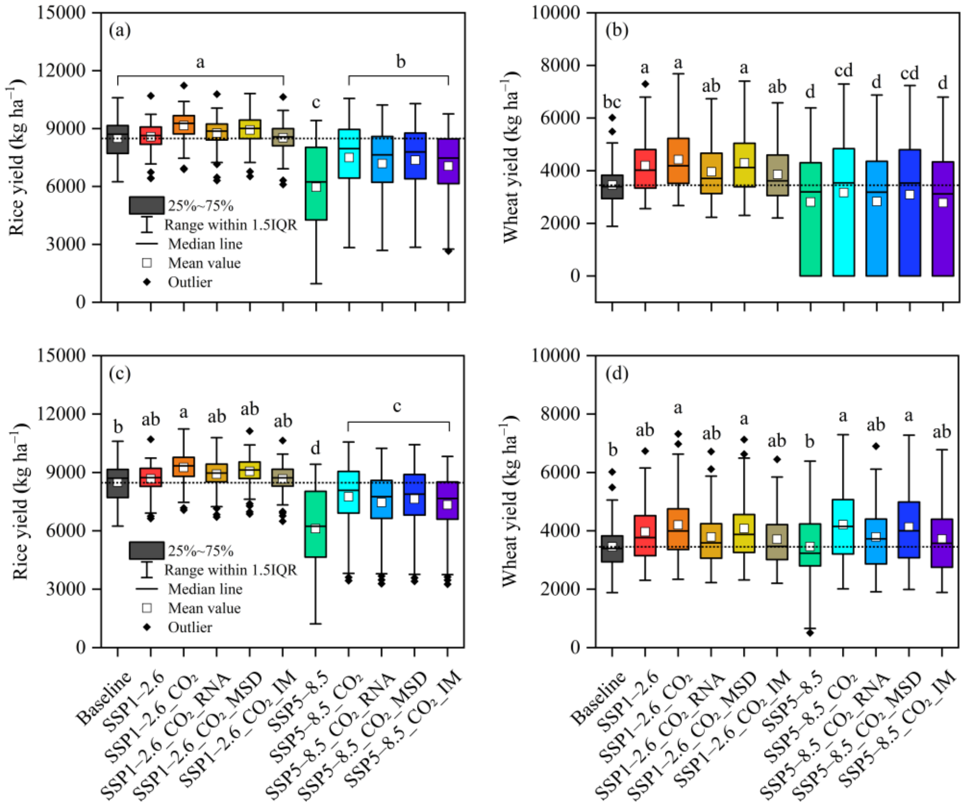


Figure 4-5: Rice and wheat yields in conventional cropping system (a, b) and adaptive cropping system (c, d) under different climate change and mitigation management scenarios from 2024 to 2100. For each boxplot, the central line is the median, the square is the mean value, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the outliers. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

3.3. SOC stock under different climate change and mitigation management scenarios

The dynamics of SOC stock in the top 20 cm of soil under various scenarios is shown in Figure 4-6. The SOC stock is projected to increase over the simulation period under all scenarios except for SSP5–8.5 with a constant CO_2 concentration, under which the stock could decline from 2080 onward. However, the average increase rates of SOC stock under both SSP1−2.6 (215–256 kg C ha^{-1} yr^{-1}) and SSP5−8.5 (175–197 kg C ha^{-1} yr^{-1}) are lower than that under the baseline scenario (263 kg C ha^{-1} yr^{-1}), suggesting a negative impacts of climate change on SOC sequestration (Table 4-S3).

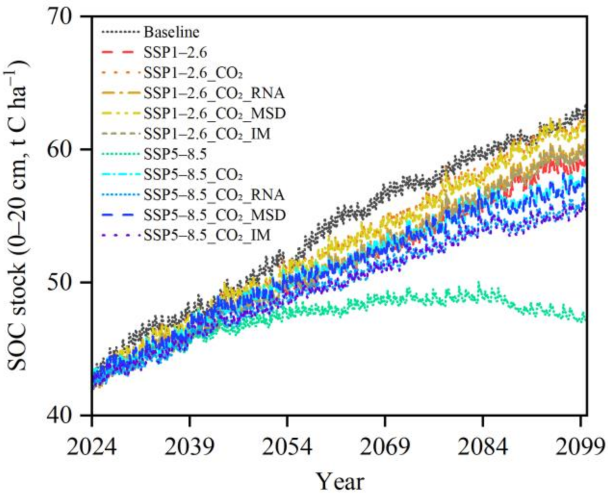


Figure 4-6: SOC stock in the top 20 cm of soil depth in adaptive cropping system under different climate change and mitigation management scenarios from 2024 to 2100. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

3.4. CH_4, N_2O emissions and GWP_N under different climate change and mitigation management scenarios

The influence of climate change scenarios, mitigation management scenarios and their combination on CH_4, N_2O emissions and net global warming potential (GWP_N) are shown in Figure 4-7 and Figure 4-8. Switching the irrigation method from continuous flooding to mid-season drainage (MSD) could significantly reduce CH_4 emissions by 45 % under SSP1−2.6 and 47 % ($P<0.05$) under SSP5−8.5 (Figure 4-7a). Additionally, integrated management combining RNA with MSD (IM) could further reduce CH_4 emissions by 55 % under SSP1−2.6 and 57 % ($P<0.05$) under SSP5−8.5 (Figure 4-7a). Reducing N application rate by 20 % (RNA) could significantly lower N_2O emissions by 23 % under SSP1−2.6 and 25 % under SSP5−8.5 ($P<0.05$) (Figure 4-7b). As a result, the GWP_N for the IM scenarios could decrease by 70 % and 67 % under the two climate change scenarios compared with no adaptation (Figure 4-8).

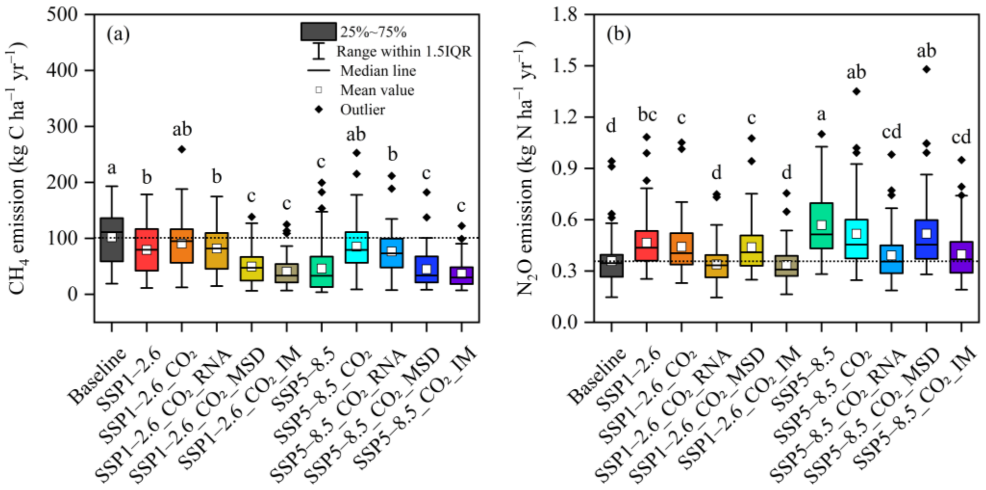


Figure 4-7: CH_4 (a) and N_2O emissions (b) in adaptive cropping system under different climate change and mitigation management scenarios from 2024 to 2100. For each boxplot, the central line is the median, the square is the mean value, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the outliers. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

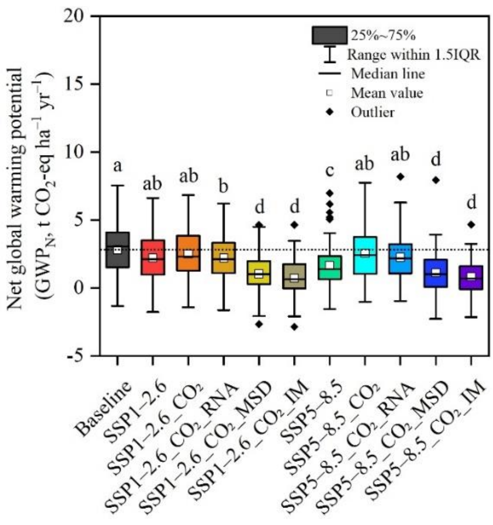


Figure 4-8: Net global warming potential (GWP_N) in adaptive cropping system under different climate change and mitigation management scenarios from 2024 to 2100. For each boxplot, the central line is the median, the square is the mean value, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the outliers. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

4. Discussion

4.1. Model performance

The statistical metrics indicated that the SPACSYS model robustly simulated soil-plant interactions in the rice–wheat system (Table 4-5). The model performed particularly well in considering the impacts of different fertiliser types on the system. For example, it effectively reproduced the downward trend in SOC dynamics under the M treatment from 1996 to 2017 due to the conversion from manure application to straw retention (Figure 4-3). However, the model underestimated rice grain yield and N content in rice grains for both NPK and NPKM treatments, particularly failing to capture high yields in some years (Figure 4-2). This discrepancy could be attributed to the model's simplified partitioning of absorbed N in different organs. In the model, the partitioning coefficients are determined by crop development index (obtained from accumulated temperatures from crop sowing/transplanting), this may not capture the actual dynamic changes during crop growth (Liu et al., 2020a; Wu et al., 2016, 2020). The model failed to capture the N_2O emission peaks during the wheat growing season (Figure 4-4c), likely due to 1) the inaccurate simulation of soil water content or soil temperature because the N_2O process is highly dependent on soil moisture and soil temperature (Smith et al., 2008), which was unavailable in this experiment for model validation; 2) other pathways producing N_2O emissions that are not included in the model, e.g. dissimilatory nitrate reduction to ammonium and anaerobic ammonium oxidation (Hu et al., 2015). Additionally, the CH_4 emissions are highly dependent on soil water and temperature conditions (Le Mer and Roger, 2001), the lack of the information in this study could influence the modelling of GHG emissions under future climatic conditions. In future study, the model should be 1) validated with more detailed field measurements to project more reliable results; 2) developed regarding dynamic changes in nutrient partitioning to different organs and other pathways of N_2O production.

4.2. Climate change impacts on crop yields

Climate warming has a huge impact on crop production through shifting phenological development of crops and changing the spatial distribution pattern of crops (Bai and Xiao, 2020; Fatima et al., 2020). Many studies have revealed the potential risk of crop production to climate change (Basche et al., 2016; Wing et al., 2021; Zhu et al., 2022b). For example, a recent study showed that under the most severe climate change scenario, yield of globally important staple cereal crops would decrease by 7–23 % (Rezaei et al., 2023). The economic benefit loss of six crops in the United States in 2070 will reach 31 % under RCP 8.5 without adaptation in crop cultivation (Rising and Devineni, 2020). Similarly, our results highlighted the potential risk of both rice and winter wheat yields under the intensive climate change scenario (SSP5–8.5) (Figure 4-5 and Figure 4-S3). The projected rice yield loss would be nearly 30 % without considering CO_2 fertilisation effect (Figure 4-5). This aligns with previous result of a 33.8 % loss for late rice (Zhang et al., 2023). Consistent with Wang et al. (2024b), the CO_2 fertilisation effect would not be sufficient to fully compensate for the negative effect of warming on rice yield under the SSP5–8.5 scenario (Figure 4-5).

One consequence of global warming is the spatial cropping pattern change in agriculture (Liang et al., 2021; Guo et al., 2024a). Rising and Devineni (2020) has indicated that half of the economic benefit losses of crops can be avoided through crop reallocation. In our study, rice production could face serious threat during 2050–2100 under the intensive climate change scenario (SSP5–8.5) (Figure 4-5 and Figure 4-S3). This implies that there might be a possible northward shift for rice cultivation to avoid damaging to crop yields in the future. Previous study has found that the northern limit of Chinese paddies has moved toward higher latitudes due to climate warming from 1984 to 2013 (Liang et al., 2021). Moreover, our results showed that winter wheat might not be suitable for rice–wheat system in Southwest China during 2070–2100 under the intensive climate change scenario (SSP5–8.5) (Figure 4-S3). This can be mainly explained by the incomplete vernalisation process due to the increasing temperatures during vegetative stage in wheat season. Other researchers have also raised concerns about the vulnerability of winter wheat yields to climate warming (Wang et al., 2015; Wu et al., 2017). Winter wheat requires a period of low temperatures to initiate the transition from vegetative growth to reproductive development (vernalisation), without vernalisation process, crops will continue to grow vegetatively (Chouard, 1960; Deng et al., 2015). Previous studies have demonstrated that the effective maximum temperature for vernalisation of winter wheat is usually below 18°C depends on different cultivars (Brooking, 1996; Porter and Gawith, 1999). However, in our study, the maximum temperature is basically higher than 20°C during overwintering period (from early December to mid-February) under the SSP5–8.5 scenario during 2070–2100 (Figure 4-S4). Therefore, based on our simulations, we recommend converting the cropping pattern from single rice–winter wheat to single rice–spring wheat in the distant future (2070–2100), in order to build agricultural resilience towards global warming across the studied region (Figure 4-5 and Figure 4-S3). Other studies have shown similar results. For example, using CMIP5 models to project optimal crop patterns, Rising and Devineni (2020) reported an upward trend for winter wheat from the south along the Mississippi under RCP 8.5 in the United States. The area for winter wheat suitability could be reduced due to drought risk under a climate with a mean temperature increased by 2°C in eastern England (Brignall and Rounsevel, 1995). Climate change would reduce the suitable areas for traditional crops in southern Europe due to water shortage and the increase in extreme weather events (Jørgen and Marco, 2002). This implies that agricultural policies toward encouraging the conversion of farming systems is necessary in the future. Overall, our findings highlight the need for the adjustment of cropping patterns and the development of breeding of climate-adapted genotypes to build agricultural resiliency and sustainability in the future.

4.3. GHG emissions mitigation under climate change

Our simulations suggest that comprehensive mitigation management strategies combining reduced N fertiliser with mid-season drainage can significantly reduce CH_4

and N_2O emissions while maintaining crop yield in paddies under climate change. Previous studies have also shown the similar results based on the current climate conditions (Tian et al., 2018; Wang et al., 2020b). It is well recognized that N fertiliser and irrigation regime are two important factors affecting crop yields and GHG emissions in paddies (Meijide et al., 2017; Zou et al., 2005b). N fertiliser application is the most important driver of soil N_2O emissions. The application rate of N fertiliser can be reduced to lower N_2O emissions with no or little yield penalty in agriculture (Zhong et al., 2016). Draining the flooded soils of rice paddies can reduce CH_4 emissions substantially. In this study, the magnitude of the CH_4 reduction (45–47 %) (Figure 4-7a) is in line with previous result (Liu et al., 2019c). However, mitigation measures for CH_4 emissions can lead to an increase of N_2O emissions in paddies due to the changes in water status. Study has indicated that the increase in N_2O emissions caused by mid-season drainage can offset 65 % of the benefits gained by CH_4 reduction (Li et al., 2004). As such, it is crucial to assess the global warming potential of CH_4 and N_2O emissions considering the trade-offs between them. Our results indicated that the integrated mitigation measures could reduce the net global warming potential by 69 % with limited risk for yield reduction under future climate change scenarios (Figures 4-5 and 4-8). Overall, our findings suggest that managing N fertilisation and irrigation regime are crucial for climate mitigation under future climate change.

4.4. Uncertainties and limitations

The uncertainty of the results may come from the methods used and assumptions made. First, we assumed that crop cultivars and crop sowing/transplanting dates remain unchanged under future climate change scenarios. However, studies have shown that improved crop cultivars and shifted sowing/transplanting dates are effective in mitigating the negative influence of climate change on crop production (Rezaei et al., 2018; Ding et al., 2020; Zhang et al., 2023). Second, the climate change scenarios used in this study are derived from single global climate model (GCM), this can only represent a narrow range of uncertainty in projected climate. As such, establishing an ensemble approach that integrating values from multiple GCMs is necessary. Third, process-based model can also introduce some uncertainties in the prediction results due to the specific model structure and parameters (Chapagain et al., 2022). Martre et al. (2015) has indicated that results from multi-model ensemble have higher accuracy and consistency than that of a single model. Therefore, the potential of improving the predictions through integrating two or more models should be investigated. Fourth, our study lacks measured soil water content and soil temperature for model's calibration and validation, this could introduce significant uncertainty in the results. Soil water content and soil temperature are the two important factors for CH_4 and N_2O emissions (Le Mer and Roger, 2001; Liu et al., 2017). As such, improving the simulation performance of the model with detailed information should be considered in future study.

5. Conclusion

In this study, we tested the SPACSYS model with the observed grain and straw yield, grain and straw N content, SOC stock, CH_4 and N_2O emissions under single rice–winter wheat rotation system from a long-term experimental field in Chongqing city. The validated model was applied to explore GHG mitigation practices without sacrificing crop production from paddy fields. Two climate change scenarios (SSP1–2.6 and SSP5–8.5) in addition to the baseline scenario and three mitigation management scenarios (reduced N application rate by 20 %, the introduction of mid-season drainage and integrated management) were established. Results showed that SPACSYS model effectively simulated the observed variables from the experimental fields. Simulation scenarios indicated that climate change has a positive impact on crop yields under the SSP1–2.6 scenario and a negative impact under the SSP5–8.5 scenario. In this last situation, converting winter wheat to spring wheat in the distant future (2070–2100) could avoid the wheat yield loss. Reduced N application rate by 20 % will not significantly decrease crop yield under the two climate change scenarios, but could decrease N_2O emissions. Mid-season drainage could significantly decrease CH_4 emissions under the two climate change scenarios. Our results suggest that crop switching combining integrated management (e.g. N reduction with mid-season drainage) can significantly mitigate global warming without sacrificing crop production from rice–wheat cropping system under climate change.

6. Supplementary material

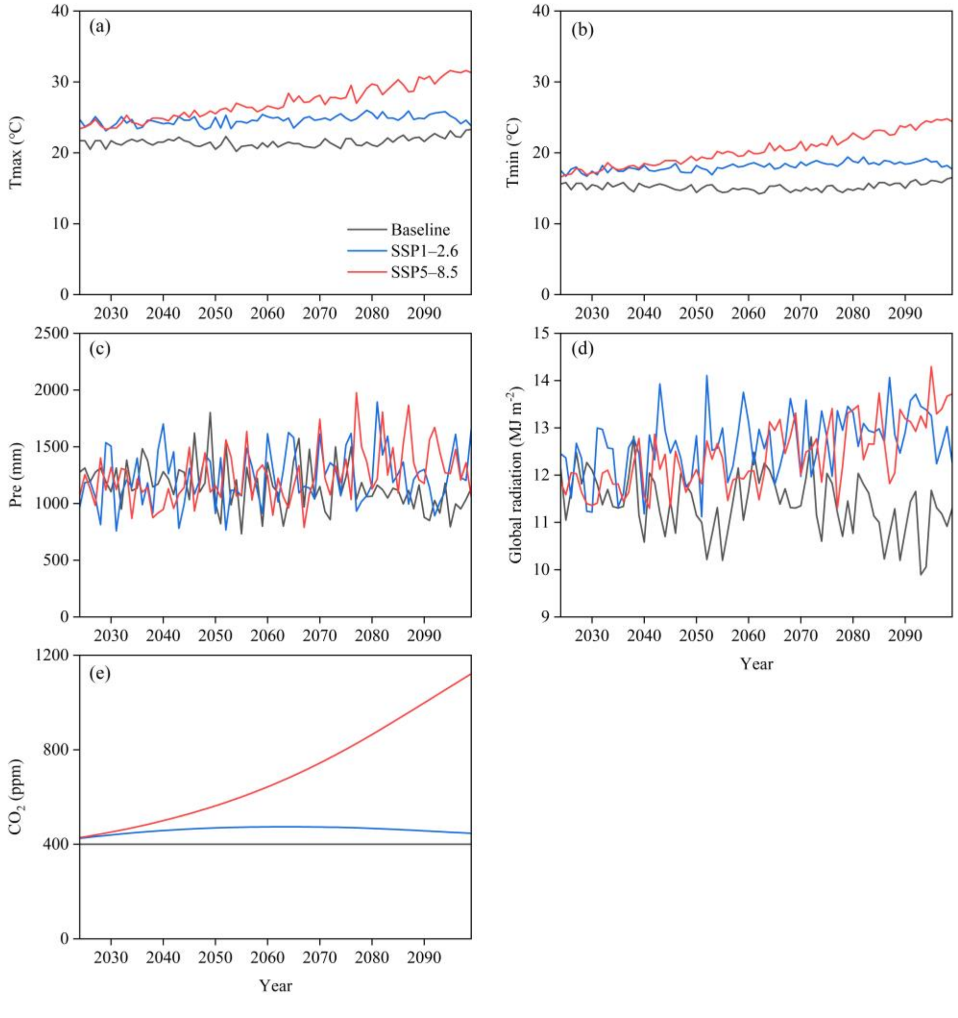


Figure 4-S1: Variations of mean annual maximum (Tmax) (a) and minimum (Tmin) temperatures (b), annual precipitation (Pre) (c), annual global radiation (d) and daily CO_2 concentration (e) under two future climate change scenarios (SSP1–2.6 and SSP 5–8.5) and the baseline scenario from 2024 to 2100.

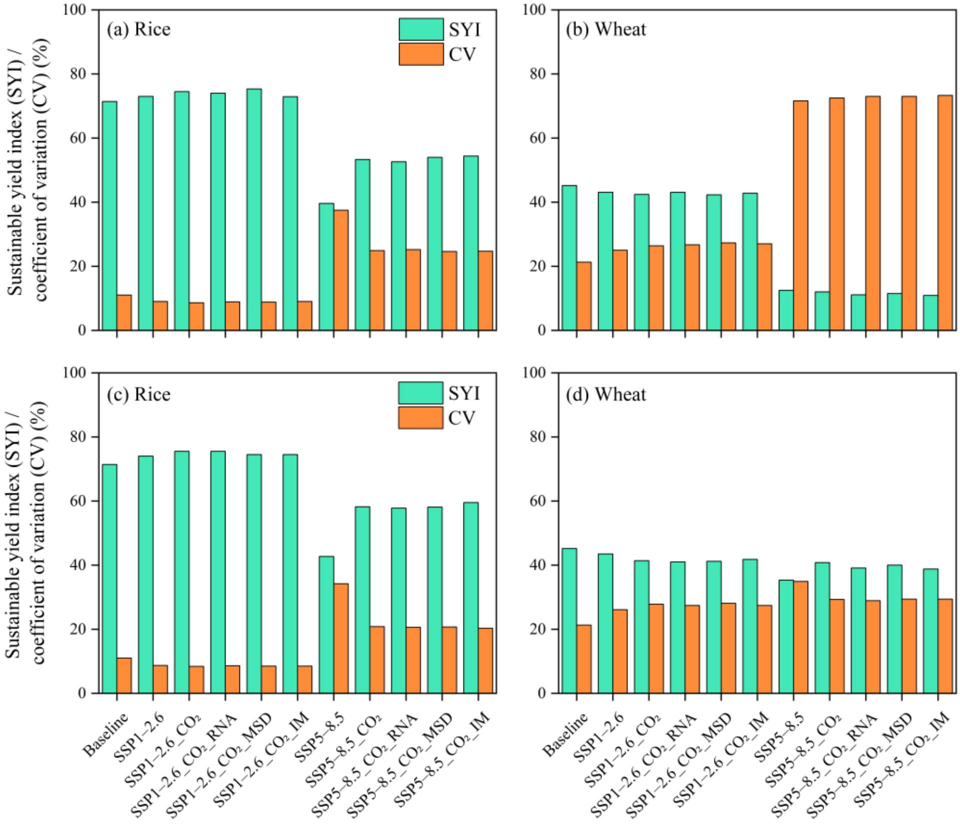


Figure 4-S2: Sustainable yield index (SYI) and coefficient of variation (CV) of rice and wheat yield in the conventional cropping system (a, b) and adaptive cropping system (c, d) under different climate change and mitigation management scenarios from 2024 to 2100. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

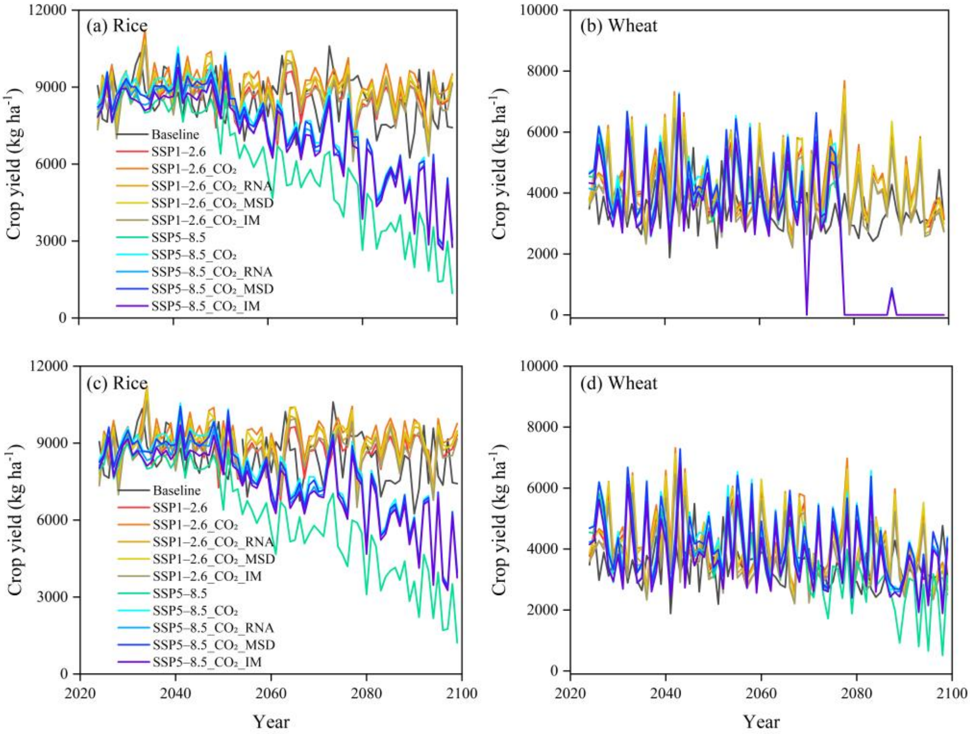


Figure 4-S3: Dynamic changes of rice and wheat yield in the conventional cropping system (a, b) and adaptive cropping system (c, d) under different climate change and mitigation management scenarios from 2024 to 2100. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

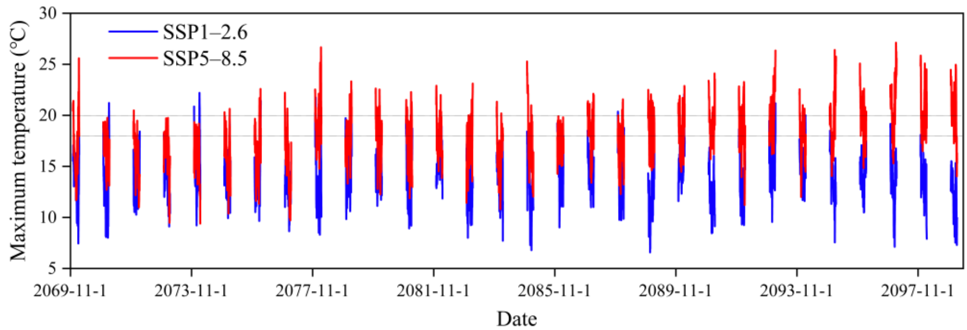


Figure 4-S4: Daily maximum temperature during overwintering period (from early December to mid-February) for wheat under two future climate change scenarios from 2069 to 2100.

Table 4-S1: Changes in crop varieties during 1992–2018 at the long-term experiment.

	Wheat			Rice					
Year	1992–2007	2008–2012	2013–2018	1992–1997	1998–2001	2002–2005	2006–2009	2010	2011–2018
Crop variety	Xinongmai-1	Mianyang-31	Chuanmai-45	Shanyou-63	IIYou-868	IIYou-7	IIYou-89	Chuanyou-9527	ZYou-272

Table 4-S2: Optimised parameters related to crop growth and development, soil carbon and nitrogen cycles in SPACSYS.

Parameter	Unit	Value	
Crop growth and development		Wheat	Rice
Accumulated temperatures required from sowing to emergence	°C d	50	75
Accumulated temperatures required from emergence to flowering	°C d	650–700	1550–1650
Accumulated temperatures required from emergence to flag leaf fully expansion	°C d	660–690	1450–1500
Accumulated temperatures required from flowering to maturity	°C d	730–790	960–1350
Critical photoperiod for vegetative stage below or over which plant development will not be affected by light	hr	11.5	10–16
Critical photoperiod for vegetative stage below or over which plant development will stop	hr	9.15	9.15–11.5
Coefficient in the photo period response function	hr	0.97	-0.201
Threshold temperature for vegetative stage	°C	3	10
Threshold temperature for reproductive stage	°C	10	15
Temperature below which photosynthesis ceases	°C	2	2
Temperature above which photosynthesis ceases	°C	40	40
Maximum temperature above which vernalisation response function is zero	°C	20	-
Maximum temperature below which vernalisation response function is zero	°C	-10	-
Optimum temperature at which vernalisation response function is maximised	°C	5	-

Leaf N concentration below which the photosynthesis ceases	g N g^{-1} DM	0.005	0.015
Leaf N concentration above which the effect on photosynthesis is in unity	g N g^{-1} DM	0.03	0.03
Base temperature at which temperature function is in unity for plant respiration	°C	30	30
Q10 value for plant respiration	-	3	2.5
Soil C and N cycles			
Coefficient in water function for decomposition, mineralization and nitrification	-	1	
Transformation fraction to humus from decomposed dissolved organic matter	-	0.1	
Transformation fraction to humus from decomposed fresh litter organic matter	-	0.15	
Potential decomposition rate for humus	d^{-1}	0.000032	
Critical C/N ratio favourable to immobilization	-	10	

Table 4-S3: Mean annual SOC sequestration rate under different simulation scenarios between 2024 and 2100.

Simulation scenarios	SOC sequestration rate (kg C ha^{-1} yr^{-1}) *	R^2	*P*
Baseline	263	0.99	<0.001
SSP1–2.6	215	0.99	<0.001
SSP1–2.6_CO_2	256	0.99	<0.001
SSP1–2.6_CO_2_RNA	234	0.99	<0.001
SSP1–2.6_CO_2_MSD	248	0.99	<0.001
SSP1–2.6_CO_2_IM	230	0.99	<0.001
SSP5–8.5	-	-	-
SSP5–8.5_CO_2	197	0.98	<0.001
SSP5–8.5_CO_2_RNA	179	0.98	<0.001
SSP5–8.5_CO_2_MSD	193	0.98	<0.001
SSP5–8.5_CO_2_IM	175	0.98	<0.001

* The mean annual SOC sequestration rate was obtained from the slope of the simple liner regression between SOC stock and year under different climate change and mitigation management scenarios; Baseline, historical climate (1938–2014, constant CO_2 concentration at 400 ppm); SSP1–2.6, strict limits on GHG emissions; SSP 5–8.5, no limits on GHG emissions; RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

Chapter 5

General discussion and conclusions

Part of it was extracted from: Shuhui Wang, Nan Sun, Xubo Zhang, Chunsheng Hu, Yuying Wang, Wei Xiong, Shuxiang Zhang, Gilles Colinet, Minggang Xu, Lianhai Wu. Assessing the impacts of climate change on crop yields, SOC sequestration and N_2O emissions in wheat–maize rotation system. Soil & Tillage Research, 2024, 240, 106088. https://doi.org/10.1016/j.still.2024.106088

1. General discussion

Since the pre-industrial period, GHG emissions (e.g. CO_2, CH_4 and N_2O) due to anthropogenic activities are key components responsible for climate change (IPCC, 2021). The land carbon sink in terrestrial ecosystem offsets about 30 % of the CO_2 emissions caused by human activities each year (Friedlingstein et al., 2020), plays a fundamental role in ecosystem service like climate regulation. Agricultural soils have great SOC sequestration potential (Beillouin et al., 2023), especially those with substantial yield gaps and large historic SOC losses (Amelung et al., 2020). While agricultural soils are also a major source of anthropogenic GHG emissions (USEPA, 2013). For example, N_2O emissions from fertilised soils and CH_4 emissions from paddy soils (Han et al., 2019). Therefore, optimising agricultural management practices for promoting SOC accumulation, mitigating GHG emissions, and enhancing agricultural resilience are needed in sustainable agriculture. In this study, we quantified the benefits of organic amendments in both SOC stock enhancement and crop yield improvement over the past 30–40 years of fertilisation in Chinese paddy fields. At the same time, the factors that driving changes in SOC and yield were investigated. The direct and indirect positive effects of SOC on crop yield was identified. Furthermore, using process-based modelling, the adaptation strategies in rice cropping systems were suggested to adapt to climate change. The results highlight the importance of implementing sustainable agricultural management practices to improve the resilience of agriculture in coping with climate change and proposing innovative pathways for climate change mitigation. The findings provide strong evidence to help farmers, environmentalists and decision-makers in safeguarding food production and mitigating global warming under future climate conditions.

1.1. Meeting the growing demand for crop production

Food security is facing various challenges like growing population (United Nations, 2017) and global environmental changes including climate change, environmental degradation and rapid urbanization (Humbal et al., 2023; Nguyen et al., 2023). It is therefore important to implement sustainable agricultural strategies to increase food production and protect the environment. Studies considering adaptation strategies to reduce climate change-related hazards mainly include nutrient and irrigation management, SOM management, crop cultivar changes, cropping system conversion and sowing dates shifts (Challinor et al., 2014; Hasegawa et al., 2022; Guo et al., 2024b).

During the past decades, synthetic N fertiliser plays a key role in boosting crop yields and has feed half of the global population (Erisman et al., 2008; Stewart and Roberts, 2012). However, it also resulted in great harm to the earth system as more than half of the N inputs are released into the environment through various pathways (Lassaletta et al., 2014). The current status of N biogeochemical flows among the nine planetary boundaries is under the high-risk zone (Richardson et al., 2023). As such, developing improved nutrient management practices for sustainable agriculture are urgently needed. Our results indicated that the reduction of N application rate by 20 % could significantly decrease N_2O emissions by 23–25 % without sacrificing yield production in rice–wheat cropping system under future climatic conditions (Figure 4-5 and Figure 4-7). Studies have reported the similar results, for example, Yao et al. (2024) suggested that the reductions in N fertiliser application by 25–27 % can achieve synergies between GHG emissions reductions and crop yield improvements in Chinese rice fields under future climate change scenarios. Liu et al. (2024) quantified that 49 % reduction in synthetic N fertiliser inputs can decrease reactive N losses by 52 % while maintaining production for Chinese staple crops.

Our results showed that crop production could face great loss under intensive climate change scenario (SSP5–8.5) (Figure 4-5a, b). While it is possible to avoid the wheat yield loss through switching winter wheat to spring wheat in years that the winter wheat cannot be vernalised (Figure 4-5d). This finding highlights the importance of considering suitability of crops for specific areas to adapt to future climate change. Vernalisation is essential for the transition from vegetative growth to flowering for some cereal crops, such as wheat and barley (Xu and Chong, 2018). Sayed Shourbalal et al. (2019) discovered that the use of plant growth regulators and cold stratification can alleviate the adverse effects of global warming on winter wheat production by controlling the vernalisation process. Many studies have suggested that considerable potential from changing the type of crop grown or cultivation systems to avoid the yield loss from climate change (Meng et al., 2014; Rising and Devineni, 2020; Guo et al., 2024b).

SOC is considered as a fundamental indicator of soil health due to its benefits on soil physical, chemical and biological properties (Lal, 2006). Consistent with previous studies (Pan et al., 2009; Lal, 2020b), our results indicated that increasing SOC stock in paddy fields can improve crop production (Figure 3-3). Previous study quantified that the benefit of SOC stock on crop production is one-fifth that of N fertilisation in global croplands (Ma et al., 2023). Thus, SOC-based strategy is a promising solution to reduce crop yield loss under future climatic conditions (Deng et al., 2023).

Adaptation measures such as the development of new cultivars and shifts in sowing dates can help overcome the adverse effects of climate warming and have made significant contributions to crop production over the last few decades in China (Zhang et al., 2013b). Therefore, efforts should be dedicated to cultivar improvement (i.e. high temperature resistance) to better adapt to warmer climate conditions in the future.

1.2. SOC-based strategy for climate change mitigation

As a nature-based climate solution, improving SOC stock in agroecosystems is crucial for achieving climate goals in international consensus such as the Paris Agreement (Buma et al., 2024). Increasing SOC stock has been considered as a promising approach to sustain agricultural productivity and ecosystem services (Lal, 2004, 2010a, 2014). The “4 per 1000” international initiative was launched to increase SOC stock by 4 ‰ per year as a compensation for the global anthropogenic GHG emissions in 2015. Minasny et al. (2017) concluded that the initiative was feasible under optimal management practices in global soils. However, the conclusion has been detailedly discussed and criticized (de Vries, 2018; VandenBygaart, 2018). The critical issues related to the accuracy of the calculation method for obtaining the increasing rate (4 ‰), the applicability of this rate to different land uses, soil types, and regions. In this study, our results demonstrated that the difference in magnitude of the SOC sequestration in different rice cropping systems mainly dependent on initial SOC levels (Figure 2-7), suggesting the varying SOC sequestration potential for different areas.

In addition to these limits, other aspects regarding the potential of the SOC sequestration on climate mitigation should be considered. First, SOC sequestration potential must take SOC saturation level into account (Martin et al., 2021; Gutierrez et al., 2023). Sommer and Bossio (2014) estimated that the mitigation potential by SOC sequestration is very limited, e.g. 1.9–3.9 % of the anthropogenic CO_2 emissions. Second, N limitation is a critical factor that should be considered to evaluate the potential of SOC sequestration in climate change mitigation (van Groenigen et al., 2017; Poulton et al., 2018). The increase in SOC requires corresponding amount of N inputs to balcancing stoichiometry (Batjes, 2014). Implementing the initiative would need additional 100 Tg N yr^{-1} in agricultural soils (van Groenigen et al., 2017), this is limited by the uneven distribution of global N surplus (Zhang et al., 2015) and runs counter to the achievement of the Sustainable Development Goals (SDGs) (Zhang et al., 2024a). Third, SOC sequestration in deep soils needs more attention in future research. As Lyu et al. (2021a) reported, the subsoil SOC may not be as difficult to decompose as previously thought. In fact, the subsoil SOC would be more sensitive to environmental or anthropogenic changes than the topsoil SOC. This may be attributed to the lower C input from crop residues in the subsoil and the lower stability of SOM at deep soil depths due to microbial N mining (Chen et al., 2014b). Fourth, implementing SOC-based strategy (e.g. manure amendment) may increase N or P surplus in soil, which in turn increase the risk of these nutrients losses to water (Kang et al., 2024), this should be taken into account in future study. Study has found that large N and P surpluses usually occurs in areas with high livestock densities (Svanbäck et al., 2019). The improved management and use of manure are critical for implementing the SOC-based strategy on a global scale.

Climate warming is projected to decrease SOC stock across the globe (Wang et al., 2022c). This study revealed that the SOC sequestration rate will decrease in paddy fields under future climatic conditions (Figure 4-6). Previous experimental studies have reported that increased SOC decomposition occurred in association with the increased microbial activity at higher temperatures, resulting in increased SOC loss from soils (Trumbore et al., 1996; Lin and Zhang, 2012). Organic farming is considered as a strategy for SOC sequestration in cropland (Gamage et al., 2023). Previous meta-analysis has demonstrated that organic farming significantly increases SOC stock at the local scale (Gattinger et al., 2012). However, this finding was not applicable to large scales. For example, study revealed that organic farming expansion to global scale may decrease SOC stock by 9 % in cropland, primarily due to the reduction of soil C input by 40 % from crop residues and animal manure as a result of N deficiency (Gaudaré et al., 2023). Cover crop and residue retention would be needed to sustain the SOC stock in organic farming (Gaudaré et al., 2023). Conservation agriculture, comprising no or minimum soil disturbance, retention of crop residues and crop diversification, has been regarded sustainable and environmentally friendly for crop cultivation (Hobbs et al., 2007). A recent study demonstrated that conservation agriculture not only increases SOC but also improves soil health and maintains crop production in a winter wheat–summer maize rotation system under climate warming (Teng et al., 2024). Similarly, study indicated that high-quality soils could enhance yield resilience to climate change compared with low-quality soils (Qiao et al., 2022). Therefore, the implementation of SOC-based climate mitigation strategies requires systematic and integrated agricultural management techniques to enhance the resilience of agriculture to the effects of climate warming.

1.3. Synergies between food security and climate change mitigation

Agroecosystems are facing increasingly serious natural hazards under climate change. Numerous studies have revealed that climate warming poses a threat to crop production and intensifies GHG emissions (Griffis et al., 2017; Li et al., 2019; Zhu et al., 2022b; Qian et al., 2023; Rezaei et al., 2023). Mitigation and adaptation strategies are urgently needed to ensure food security and protect the environment (Fawzy et al., 2020). However, studies have demonstrated that mitigation measures may bring trade-offs among crop production, GHG emissions and SOC sequestration (Wang et al., 2018b; Guenet et al., 2020). Therefore, maintaining or enhancing crop yield, increasing SOC stock and mitigating GHG emissions need to be balanced when sustainable land managements are introduced under future climate change.

Chemical N fertiliser and water management are the two most important factors influencing crop yield and GHG emissions from paddies (Qian et al., 2023). N fertiliser application is critical for achieving high rice yields, but it can also increase CH_4 emissions at low rates (Linquist et al., 2012b). Therefore, an appropriate N application rate can obtain a higher yield with lower GHG emissions. Our results showed that the reduction of current N application rate by 20 % could not decrease crop yield but could significantly decrease N_2O emissions by 24 % under future climatic conditions (Figure 4-7), indicating the synergies between food security and climate change mitigation. Previous studies have also revealed that proper agricultural management and cropping systems could achieve the synergies between them (Pittelkow et al., 2014; Lin et al., 2021). For example, study quantified that the replacement of chemical fertiliser by organic fertiliser (30–59 %) can significantly increase crop yield and decrease net GHG emissions in paddies (Shang et al., 2021). A recent meta-analysis and experiment indicated that N fertilisation strongly promotes CH_4 emissions in acidic soils (Tang et al., 2024). The addition of liming to acid soils can not only alleviate soil acidification but also decrease CH_4 and N_2O emissions from paddies (Wang et al., 2021d).

Irrigation methods in paddies can significantly influence CH_4 emissions. Water-saving irrigation (e.g. intermittent irrigation, alternate wetting and drying and mid-term drainage) can reduce the abundance of methanogens, increase soil E_h (redox potential), soil O_2 concentration and the abundance of methanotrophs, thereby significantly decrease CH_4 emissions. Study indicated that water-saving irrigation can reduce CH_4 emissions by 53 % compared with continuous flooding (Jiang et al., 2019). Our results revealed that the introduction of mid-season drainage in rice season could significantly decrease CH_4 emissions by 46 % without sacrificing crop yield and promoting N_2O emissions under future climatic conditions (Figure 4-7), emphasising the importance of water management on food security and climate change mitigation. Taken together, our findings suggest the need for integrated climate change solutions in addressing climate change. Other sustainable land managements that may contribute to the synergies between food security and climate change mitigation include agroforestry, minimum soil disturbance, organic fertilisation (Branca et al., 2013). Agroforestry can prevent water and soil erosion, improve soil health and soil productivity as well as C sequestration (Nair et al., 2021). The benefits of adopting mitigation strategies can vary considerably among geographic regions. For example, study indicated that the yield improvement is higher than GHG mitigation in dry areas (e.g. sub-Saharan Africa), while the two benefits are evenly balanced in humid areas (e.g. Asia) (Branca et al., 2013). In future study, optimal combinations of different mitigation strategies need to be identified to maximise the synergies between climate change mitigation and food security in global agricultural soils.

1.4. Implications for climate change mitigation policies

Previous study indicated that rice accounts for 48 % of the total GHG emissions in all cereal crops, as such GHG mitigation strategies should be focused on areas with the highest emission crops and higher cropping intensities (Carlson et al., 2017). Climate change mitigation policies should consider the possibility and effectiveness of adopting optimised agricultural management practices in site-specific regions. Non-continuous flooding is an important water management practice to mitigate GHG emissions from paddies, but not all rice fields are feasible for drainage because of climate or geography constraint (Linquist et al., 2014; Bo et al., 2022). More importantly, the associated yield performance should not be disregarded. In this study, the reduction of N application rate by 20 % or mid-season drainage could not decrease grain yield and significantly reduce GHG emissions (Figure 4-7). For countries where non-continuous flooding is rarely applied (e.g. Vietnam, Bangladesh, Indonesia, Philippines and Myanmar), considerable mitigation potential can be achieved through adopting optimised irrigation measures (Bo et al., 2022). Therefore, more ambitious goals should be implemented in these regions. For regions where triple-season rice is cultivated, multiple drainages might be the most cost-effective strategy. While for regions with single rice cultivation, nutrient management (e.g. biochar, off-season straw return) is the most efficient practice to reduce GHG emissions (Zhou et al., 2024). In terms of N_2O emissions, study indicated that 65 % of the global emissions can be mitigated on 20 % of the harvested area, suggesting the importance of a targeted policy on global hotspots with large N_2O mitigation potential (e.g. China, United States, India, Brazil) (Cui et al., 2021). Furthermore, policy-relevant decisions on mitigation practices should take into consideration the mitigation costs with systematic economic analysis. Efficient mitigation strategies that minimise the harm and maximise net benefits should be encouraged (Mendelsohn, 2000; Tilahun, 2021).

Although multiple drainage practice and off-season straw return can significantly decrease CH_4 emissions, the labor costs can increase accordingly (Wang et al., 2024c). Formulating region-specific incentives such as environmental subsidies and providing educational services and training can motivate farmers to adopt mitigation strategies. The integration of various methods (e.g. machine learning, meta-analysis, remote sensing and crop models) are expected to generate more reliable estimations (Zhuang et al., 2024). In future research, scientists should be encouraged to develop technology integration for exploring mitigation strategies. The achievement of global carbon-neutral agriculture requires global efforts, including farmers, agricultural entrepreneurs, environmentalists, scientists, policymakers, as well as average citizens. Collaboration across borders and disciplines is of great significance in promoting sustainable and low-carbon agriculture development.

2. General conclusions and recommendations

Based on datasets from seven long-term fertilisaion experiments (30–40 years) under two typical rice cropping systems (i.e. rice–wheat rotation and double rice rotation systems) located in middle and lower reaches of the Yangtze River Basin, this study quantified the characteristics of SOC sequestration and crop yield in response to different fertilisation treatments and explored their influencing factors using machine learning methods (e.g. random forest and structural equation modelling). Furthermore, combined with process-based model (SPACSYS), we assessed the consequences of summer rice–winter wheat cropping system in Southwest China under climate change and proposed adaptation strategies to mitigate global warming and maintain crop production in paddies. Results showed that NPKM treatment obtained the highest SOC stock, the largest SOC sequestration rate, the longest SOC sequestration duration, and the highest crop yield, yield stability and sustainability. Rice–wheat rotation system has a higher fertilisation-induced changes of the SOC stock compared with double rice system under both NPK and NPKM treatments, this result was mainly explained by the lower initial SOC stocks in rice–wheat rotation system. Crop yield increased logarithmically with increasing SOC stocks and no level off was found in two cropping systems. Manure application had both direct and indirect (through improvements in soil properties) positive effects on crop yield in both rotation systems. SOC had both direct and indirect (through improved availability of soil nutrients) positive effects on crop yield in double rice rotation system. Under climate change, crop yield in rice–winter wheat rotation system in Southwest China could increase or decrease depending on the level of climate warming. Under intensive climate warming, both winter wheat and rice yield could face great loss, the winter wheat could not be suitable for planting in distant future (from 2070 on) in this region due to the incomplete development of vernalization process in warmer climate. Switching from winter wheat to spring wheat could totally avoid the yield loss. Reducing the current N application rate by 20 % and introducing mid-season drainage in rice season could significantly reduce CH_4 and N_2O emissions in the future. Based on the results of this study, the following conclusions are proposed (Figure 5-1):

(1). Based on traditional fertilization, manure application contributes to SOC stock, SOC sequestration and crop grain yield over the past 30–40 years of fertilisation in paddies.
(2). The difference in SOC sequestration under different rice cropping systems is mainly dependent on soil properties, especially initial SOC content rather than C input.
(3). Increasing SOC stock contributes to crop production and yield stability and sustainability.
(4). Organic fertilisation may benefit both food security and climate mitigation.
(5). Low levels of climate change may benefit crop production while high levels of climate change could threaten crop production.
(6). Crop switching in rice–wheat system combining integrated mitigation practices is possible to mitigate global warming and maintain crop production.

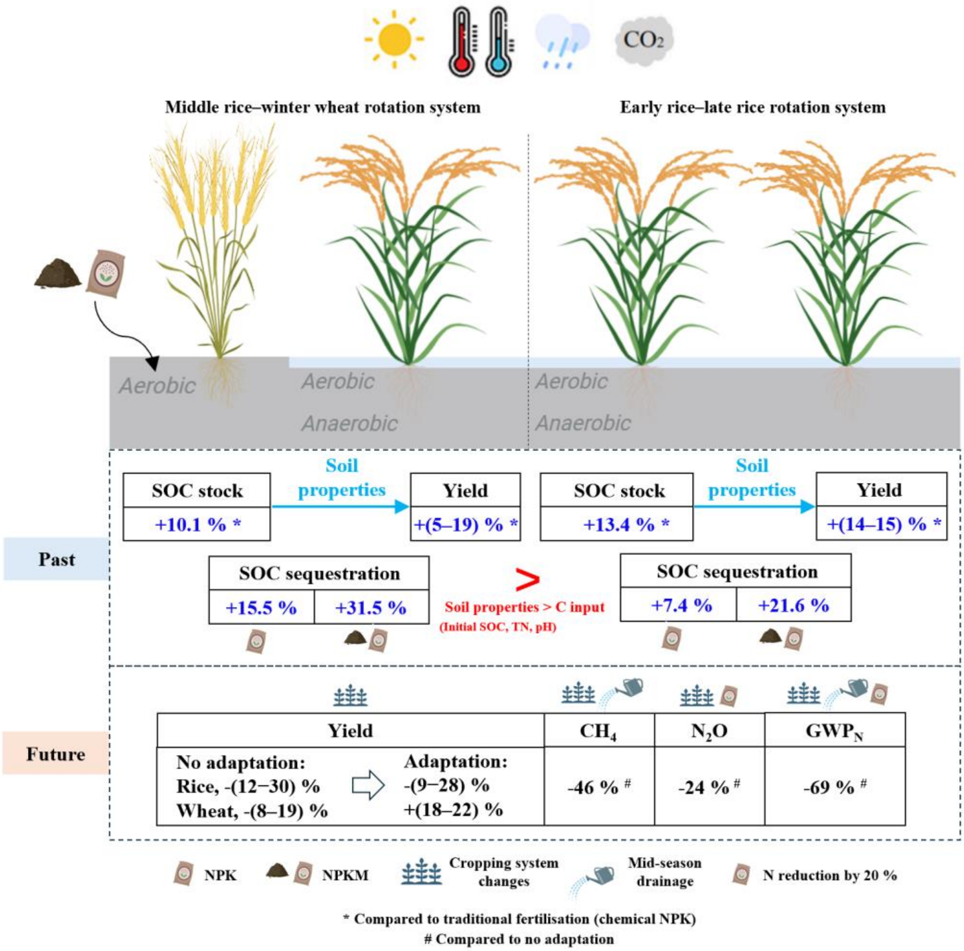


Figure 5-1: The conclusion of this study.

Our findings highlight the co-benefits between SOC sequestration and crop yield improvement from the application of manure in paddy fields. Furthermore, we assessed the risks facing rice–winter wheat system in Southwest China under future climate change scenarios and provided adaptation solutions for maintaining crop yield and mitigating global warming. As such, the following aspects are recommended for farmers and policy makers towards sustainable agriculture:

(1). Paddy fields with low initial SOC content should be given priority to applying organic fertiliser to increase SOC sequestration.

(2). Organic fertiliser should be applied on the basis of chemical fetilisers in paddy fields to benefit both SOC sequestration and crop production.

(3). Different technology combinations in paddies should be adopted to achieve synergies between climate change mitigation and crop production.

3. Uncertainties and perspectives

In this study, we evaluated the potential risk of the rice–wheat system under climate change and proposed mitigation strategies for maintaining crop yield and decreasing GHG emissions (Chapter 4). Our estimates have some uncertainties. First, the uncertainties arise from the selected crop model and climate model; Second, the calibration and validation of the model remain unclear. Third, we only considered the direct N_2O emissions from the rice–wheat system when calculating the net global warming potential of different scenarios, we do not take into account the indirect N_2O emissions (e.g. N leaching, N runoff, and ammonia volatilization); Fourth, we focused on the direct GHG emissions from the on-farm stage, the GHG emissions from the agri-materials stage were not considered, which include production, packaging, transportation and application of the main inputs (chemical fertilisers, irrigation, seeds, pesticides, diesel, and electricity). Our study only evaluated the impact of rice cropping system on the environment regarding climate change, other impacts such as eutrophication, environmental acidification, energy and water consumption, and land use should be considered in the future (Li et al., 2021c). At the same time, the economic benefits should be quantified. Based on this, the following aspects are suggested in further studies.

Firstly, uncertainty analysis should be conducted. Understanding the uncertainties in climate change impacts on agricultural systems can reflect the reliability of the projections and help to improve the accuracy of the results (Chapagain et al., 2022). A low uncertainty in the results is critical for the development of mitigation strategies. The major sources of uncertainty in climate–crop modelling approach are crop model, global climate model (GCM), climate change scenarios and the interactions between these three (Wang et al., 2020c). Spatial downscaling of the GCM climate data to generate site-specific climate data also introduces some uncertainty. Multi-model ensemble is an effective method to improve the accuracy and consistency of the results (Chen et al., 2013; Martre et al., 2015). Meanwhile, integrating data assimilation, machine learning and process-based crop models are promising for increasing the accuracy of model estimations (Zhuang et al., 2024).

Secondly, the sustainable agricultural management practices for maximising the yield benefit from increasing SOC stock can be optimised. Study revealed that Southeast Asia needs to narrow the yield gap (the difference between potential yield and current yield) to meet the domestic rice demand and to remain as a major net exporter in the context of climate change and yield stagnation (Yuan et al., 2022). Our results indicated that higher yields can be expected from further increases in SOC stock for both rice–wheat system and rice–rice system in Southeast China (Figure 3-3). Therefore, it is necessary to estimate the potential yield benefits from increasing SOC stock for narrowing the current yield gap (Figure 5-2). The study helps to achieve the synergy between SOC stock and different ecosystem services (e.g. yield production/SOC sequestration rate) through managing SOC levels. The study also provides insights for decision-makers to develop tailored strategies towards sustainable agriculture.

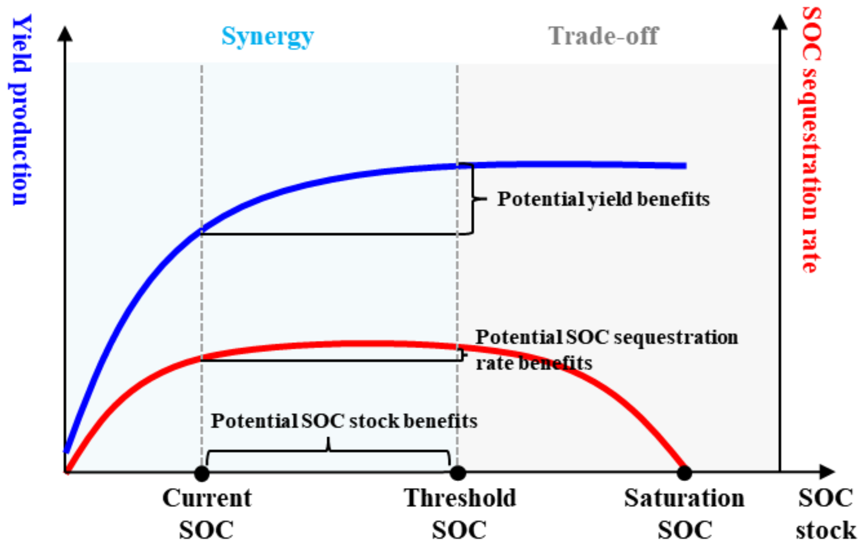


Figure 5-2: Synergy or trade-off between SOC stock and different ecosystem services.

Thirdly, the GHG emission mitigation potential at global and regional scales should be quantified. The quantification allows to identify the hotspots for GHG mitigation and implement targeted policies aimed at promoting low-carbon development. For example, study quantified that 65 % of the mitigation potential for N_2O emission could be obtained from 20 % of the global harvested area (Cui et al., 2021). In which the mitigation potential from reduction in N input is equivalent to 30 % of direct N_2O emissions from global cropland. In China, the CH_4 and N_2O emissions from South-central China, East China, and the Sichuan Basin account for 70 % of the total agricultural non-CO_2 GHG emissions (Gao et al., 2025b). Therefore, substantial GHG emission mitigation potential can be achieved through implementing GHG emission mitigation strategies on those GHG emission hotspots in China.

Fourthly, it is imperative to comprehensively evaluate the environmental impact of the crop production system under climate change by using cradle to gate life cycle assessment (LCA) combined with process-based modelling. LCA methodology has been increasingly used to assess the environmental impacts of agricultural systems and propose sustainable management practices (Jimmy et al., 2017; Harun et al., 2020; Li et al., 2021c). It considers all the environmental inputs and outputs within a defined system boundary from a life cycle perspective. Furthermore, LCA provides quantification of different environmental impacts regarding land use, resource consumption, and environmental pollution. A comprehensive environmental impact assessment can help to propose targeted environmental protection strategies and policies.

Further, technical pathways for agroecosystem to achieve a "win-win" situation for both economic benefit and environmental sustainability under climate change should be investigated. Efficient mitigation strategies that have the maximum net benefits should be encouraged in the future (Mendelsohn, 2000). A cost–benefit analysis that considers all input costs (the cost of agricultural materials and the associated labor cost) and yield profit is critical to developing economically viable mitigation strategies.

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Appendix

1. Publications

(1). **Shuhui Wang**, Nan Sun*, Zhijian Mu, Fa Wang, Xiaojun Shi, Chuang Liu, Shuxiang Zhang, Joost Wellens, Bernard Longdoz, Jeroen Meersmans, Gilles Colinet, Minggang Xu*, Lianhai Wu. Strategies to reduce CH_4 and N_2O emissions whilst maintaining crop yield in rice–wheat system under climate change using SPACSYS model. Agricultural Systems 2025, 226, 104337. https://doi.org/10.1016/j.agsy.2025.104337.

(2). **Shuhui Wang**, Nan Sun*, Xubo Zhang, Chunsheng Hu, Yuying Wang, Wei Xiong, Shuxiang Zhang, Gilles Colinet, Minggang Xu*, Lianhai Wu. Assessing the impacts of climate change on crop yields, SOC sequestration and N_2O emissions in wheat-maize rotation system. Soil & Tillage Research 2024, 240, 106088. https://doi.org/10.1016/j.still.2024.106088.

(3). **Shuhui Wang**, Nan Sun*, Shuxiang Zhang, Bernard Longdoz, Joost Wellens, Jeroen Meersmans, Gilles Colinet, Lianhai Wu, Minggang Xu*. Soil organic carbon storage impacts on crop yields in rice-based cropping systems under different long-term fertilisation. European Journal of Agronomy 2024, 161, 127357. https://doi.org/10.1016/j.eja.2024.127357.

(4). **Shuhui Wang**, Nan Sun*, Shuo Liang, Shuxiang Zhang*, Jeroen Meersmans, Gilles Colinet, Minggang Xu, Lianhai Wu. SOC sequestration affected by fertilization in rice-based cropping systems over the last four decades. Frontiers in Environmental Science 2023, 11, 1152439. https://doi.org/10.3389/fenvs.2023.1152439.

(5). **Shuhui Wang**, Wen Tao, Shuo Liang, Xubo Zhang*, Nan Sun*, Minggang Xu. The spatial characteristics of soil organic carbon sequestration and N_2O emission with long-term manure fertilization scenarios from dry Land in North China Plain. Scientia Agricultura Sinica 2022, 55(6): 1159-1171. https://doi.org/10.3864/j.issn.0578-1752.2022.06.009. (in Chinese)

(6). Shuo Liang, Nan Sun*, **Shuhui Wang**, Gilles Colinet, Bernard Longdoz, Jeroen Meersmans, Lianhai Wu, Minggang Xu*. Manure amendment acts as a recommended fertilization for improving carbon sequestration efficiency in soils of typical drylands of China. Frontiers in Environmental Science 2023, 11, 1173509. https://doi.org/10.3389/fenvs.2023.1173509.

2. Presentations

(1). Strategies to reduce CH_4 and N_2O emissions and maintain crop yields in the rice–wheat system under climate change (The Ninth Frontier Forum on Global Change Ecology-Towards Carbon Neutrality, Beijing, 20/09/2024, Poster presentation).

(2). SOC sequestration benefits crop production under long-term fertilisation in rice paddies (Chinese Society of Plant Nutrition and Fertilizer Science 2024 Annual Conference, Taiyuan, 10/08/2024, Oral presentation).

(3). SOC sequestration affected by fertilization in rice-based cropping systems over the last four decades in the Yangtze River catchment (The General Assembly 2023 of the European Geosciences Union, Vienna, 26/04/2023, Poster presentation).

(4). SOC sequestration affected by fertilization in rice-based cropping systems over the last four decades in the Yangtze River catchment (Soil Science Society of Belgium Thematic Day 2022, Brussel, 19/12/2022, Poster presentation).