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Balancing Non-CO_2 GHG Emissions and Soil Carbon Change in U.S. Rice Paddies: A Retrospective Meta-Analysis and Agricultural Modeling Study

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Key Points:

- U.S. rice paddy was a rapidly growing net GHG emission source (8.88 ± 2.65 Tg CO_2eq yr^{-1} in the 2010s) over the last six decades
- SOC sequestration could offset about 14.0% (1.45 ± 0.46 Tg CO_2eq yr^{-1}) of soil non-CO_2 GHG emissions in the 2010s
- Non-continuous irrigation exhibited the potential to mitigate around 39% of soil non-CO_2 GHG emissions than continuous irrigation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

U.S. rice paddies, critical for food security, are increasingly contributing to non-CO_2 greenhouse gas (GHG) emissions like methane (CH_4) and nitrous oxide (N_2O). Yet, the full assessment of GHG balance, considering trade-offs between soil organic carbon (SOC) change and non-CO_2 GHG emissions, is lacking. Integrating an improved agroecosystem model with a meta-analysis of multiple field studies, we found that U.S. rice paddies were the rapidly growing net GHG emission sources, increased 138% from 3.7 ± 1.2 Tg CO_2eq yr^{-1} in the 1960s to 8.9 ± 2.7 Tg CO_2eq yr^{-1} in the 2010s. CH_4, as the primary contributor, accounted for 10.1 ± 2.3 Tg CO_2eq yr^{-1} in the 2010s, alongside a notable rise in N_2O emissions by 0.21 ± 0.03 Tg CO_2eq yr^{-1}. SOC change could offset 14.0% (1.45 ± 0.46 Tg CO_2eq yr^{-1}) of the climate-warming effects of soil non-CO_2 GHG emissions in the 2010s. This escalation in net GHG emissions is linked to intensified land use, increased atmospheric CO_2, higher synthetic nitrogen fertilizer and manure application, and climate change. However, no/reduced tillage and non-continuous irrigation could reduce net soil GHG emissions by approximately 10% and non-CO_2 GHG emissions by about 39%, respectively. Despite the rise in net GHG emissions, the cost of achieving higher rice yields has decreased over time, with an average of 0.84 ± 0.18 kg CO_2eq ha^{-1} emitted per kilogram of rice produced in the 2010s. The study suggests the potential for significant GHG emission reductions to achieve climate-friendly rice production in the U.S. through optimizing the ratio of synthetic N to manure fertilizer, reducing tillage, and implementing intermittent irrigation.

Plain Language Summary

The rapid expansion and intensification of U.S. rice paddies play an increasingly vital role in ensuring food security, which also contributes to massive emission of anthropogenic non-CO_2 (CH_4 and N_2O) greenhouse gas (GHG). By using an improved agricultural ecosystem model and a meta-analysis of multiple field studies, we have quantified the magnitude and spatiotemporal variations of net GHG balance (trade-offs between SOC sequestration and non-CO_2 GHG emissions) in paddy soils and the underlying drivers. Our findings point out that U.S. rice paddy was a rapidly growing net GHG emission source, which increased 138% over the last six decades. SOC sequestration could offset about 14.0% of the climate-warming effects of soil non-CO_2 GHG emissions in the 2010s. Our study suggests that the optimization of the synthetic N fertilizer and manure ratio effectively curtail net GHG emissions per yield, especially when combined with no/reduced tillage and non-continuous irrigation. Our results underscore the importance of net CO_2 GHG mitigation in U.S. rice paddies for achieving net zero-emission and climate-friendly rice production.

1. Introduction

Rice paddy, a flooded agricultural system that grows rice (*Oryza sativa* L.), is a significant source of greenhouse gases (GHG) like CH_4 and N_2O (Gupta et al., 2021; Hussain et al., 2015; Linquist et al., 2018; Saunois et al., 2020; Tian et al., 2016). Around 30% and 11% of global agricultural CH_4 and N_2O are emitted from rice paddies (Gupta et al., 2021; Hussain et al., 2015; Saunois et al., 2020; Tian et al., 2020; Zhao et al., 2011). It is projected that by 2030, emissions of both non-CO_2 GHGs from global rice paddies could experience a rise of 35%–60% (Smith et al., 2007). This increase is attributed to a growing demand for rice production, expected to

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surge by 40% due to the expanding global population (Smith et al., 2007). These projections raise serious environmental concerns.

The United States is one of the top grain yield producers in the world and is among the top five countries for rice exports, with an expanding cultivation area (FAO, 2017). According to data from the USDA National Agriculture Statistics Service, approximately 80% of the rice produced in the U.S. is grown in the mid-South states (Arkansas, Louisiana, Texas, Mississippi, and Missouri), with the remaining 20% mainly produced in the Sacramento Valley in California. As the United States is expanding its rice paddy area, an urgent need is to quantify N_2O and CH_4 fluxes and improve our understanding of these gases from U.S. rice paddies to develop effective mitigation strategies.

Considerable efforts have been made to broadly quantify GHG emissions from rice systems and to assess the effects of agronomic management and biogeochemical variables on these emissions. These efforts have been driven by data mostly observed and measured in Asia which produces ~90% of the world's rice (Akiyama et al., 2005; Yan et al., 2005, 2009), and have been used to form guidelines to estimate GHG inventories for global rice paddies including those in the United States (Eggleston et al., 2006). However, overwhelmed by data from Asia, the lessons learned from previous studies on how to quantify GHG emissions and identify the major drivers of the emissions are unlikely to be valid for U.S. rice systems, which inherently differ from those typically found in Asia in terms of agronomic practices. Differences include but are not limited to improved water management due to laser leveling and reliable water supply, a greater degree of mechanization, direct seeded rather than transplanted, and others (Linquist et al., 2018).

Rice paddy also has a considerable potential to be harnessed at a large scale to sequester carbon through effective agricultural management practices (Canadell et al., 2021; Eswaran et al., 1993; Fargione et al., 2018; Smith et al., 2007, 2008; Tian et al., 2016; Wollenberg et al., 2016). Since the 1960s, the application of agricultural management practices in the U.S. croplands has constantly been strengthened. For example, rice cultivation area in the U.S. increased notably from 0.8 million ha. in the 1960s to 1.2 million ha. in the 1990s, and then slightly declined to 1.1 million ha. in the 2010s (FAO, 2017; McManamay et al., 2021). Synthetic N fertilizer use in U.S. croplands increased substantially from 2.5 Tg N $year^{-1}$ in 1960 to 11.8 Tg N $year^{-1}$ in 2015 (You et al., 2022). However, it is worth noting that the upward trend has subsequently shown signs of deceleration. Moreover, the proportion of U.S. croplands changing tillage (e.g., no tillage or reduced tillage instead of conventional tillage) practices increased significantly over the past three decades according to the tillage survey data from the National Crop Residue Management Survey (CRM) of the Conservation Technology Information Center (https://www.ctic.org/CRM). Nevertheless, for U.S. rice paddies, conventional tillage was still dominant, and the proportion was increasing over the study period. Manure application has continuously increased since 1900, resulting in over 1.2 Tg N yr^{-1} in manure usage after the 2000s (Bian et al., 2021). For rice production, manure application increased by 13.2% by the 2010s from about 1,227 Tons in the 1960s (Bian et al., 2021). However, extensive reviews about the impact of these changes on SOC change and non-CO_2 GHG emissions have not been conducted for the U.S. rice system. Due to possible trade-offs between SOC change and non-CO_2 GHG emissions under different agricultural management practices (Guenet et al., 2021; Runkle et al., 2018; Tian et al., 2011, 2015), simultaneous quantification of SOC change and non-CO_2 GHG emissions is crucial to accurately assess the overall climate abatement potential of mitigation measures. Furthermore, whether SOC change in U.S. rice paddies can offset non-CO_2 GHG emissions and how far we are from achieving carbon-neutral agriculture still need to be determined. Net soil GHG balance, defined as the sum of SOC change and emissions of N_2O and CH_4, can be used to measure the overall climate effect resulting from cumulative radiative forcing of non-CO_2 GHG emissions and CO_2 uptake (Robertson & Grace, 2004; Tian et al., 2015). Therefore, it is crucial to advance our understanding of the magnitude and spatiotemporal variations of net GHG balance in rice paddies soils, as well as the drivers of these changes. Such knowledge is essential for developing effective climate change mitigation strategies for rice cultivation without sacrificing grain production.

Given the complexity of net GHG emissions, a process-based model would be ideal for quantifying and evaluating potential mitigation options. By utilizing process-based terrestrial biosphere models that accurately depict crop growth processes and incorporate agricultural management practices along with detailed assessments of hydrological, biophysical, and biogeochemical processes, we can gain a better understanding of how management practices and environmental changes affect net soil GHG balance at regional scales (Bondeau et al., 2007; McDermid et al., 2017; You et al., 2022). However, model simulation performance is primarily limited by input data and process parameterization. Conversely, field experiments offer practical and dependable avenues for unraveling intricate correlations between shifts in net soil GHG balance and agricultural management practices amidst various environmental changes (Plaza-Bonilla et al., 2018). However, extending site-specific findings directly to extensive geographical areas increases the uncertainties due to the distinct environmental and management conditions at each site (Fer et al., 2021; Huang et al., 2022; Peng et al., 2011). Until recently, there has been insufficient data to quantify emissions from the U.S. rice system and evaluate the effects of significant practices over large regional scales. Therefore, combining the strengths of field observations and models while addressing their respective limitations may offer a promising approach to overcoming current bottlenecks.

Here we quantified the combined effects of multiple management practices and environmental changes on the magnitude and spatiotemporal variations of net soil GHG balance in U.S. rice paddies using a model-data integration approach. The model used here is the Dynamic Land Ecosystem Model v4.0 (DLEM v4.0), which is a highly integrated process-based terrestrial biosphere model that is capable of simultaneously depicting biosphere-atmosphere exchanges of CO_2, N_2O, and CH_4 as driven by multiple environmental forcings and management practices (You et al., 2022). A meta-analysis was conducted over U.S. and global rice paddies to compile field observations of SOC stock/change and non-CO_2 GHG (i.e., N_2O and CH_4) emissions under various management practices and environmental conditions. Global metadata was employed to enhance existing data concerning the effects of U.S. agricultural management practices and to facilitate parallel comparisons with U.S. results. We used the compiled data set to calibrate, validate, and corroborate model simulations. Our study aimed to achieve three objectives: (a) estimate the net soil GHG balance of U.S. rice paddies from 1960 to 2018, considering multiple environmental changes (e.g., synthetic N fertilization, manure, tillage, irrigation, climate conditions, historical land use, atmospheric CO_2 concentration, and N deposition); (b) quantify the contributions of different drivers to the spatial and temporal variations in net soil GHG balance across the country; and (c) estimate the temporal-spatial changes in the net GHG emission intensity of U.S. rice paddies, a measure of GHG emissions per unit rice production.

2. Materials and Methods

2.1. Data Sources for Meta-Analysis

We conducted a comprehensive literature search to identify peer-reviewed publications reporting in situ soil GHG emissions (CH_4, N_2O, and CO_2) from the U.S. and global rice paddies under different management practices and environmental conditions. Several databases, such as Google Scholar, Web of Science, and Scopus, were used to search literature. Search keywords included "rice field or rice paddies," "the United States or America or U.S. or USA," "soil organic carbon or SOC," "nitrous oxide or N_2O," "methane or CH_4," and "greenhouse gases or GHG." To ensure the quality of the compiled data set, we collected papers further refined by the following criteria: (a) measurements were made in experimental plots situated outdoors in actual field conditions rather than hydroponic trials or any other experiments conducted within indoor laboratory settings; (b) ancillary information such as cropping systems, experimental year and duration, and applied management practices (e.g., N fertilizer use rate, tillage type, and irrigation) were provided; and (c) replicated field experiments were performed.

A total of 322 site-year data representing 43 locations for U.S. rice paddies and 3,402 site-year data representing 1,113 locations for global rice paddies were collected (Figure 1 and Table S1 in Supporting Information S1). The data set for U.S. rice paddies included 74 observations of N_2O emissions, 322 observations of CH_4 emissions, and 225 observations of rice yield (Figure 1 and Table S1 in Supporting Information S1). Since there were few records of SOC stock/change experiments in U.S. rice paddies, we adopted 192 observations of SOC stock that were obtained from the WoSIS (Batjes et al., 2016, http://dx.doi.org/10.17027/isric-wdcsoils.20160003). The global data set included 724 records of N_2O emissions, 1,238 records of CH_4 emissions, 3,402 records of SOC stock (3,256 records of SOC change), and 1,006 records of rice yield (Figure 1), obtained from Bo et al. (2022) and Liu et al. (2021). Multiple management practices were involved in these observations, such as tillage type, N fertilization, irrigation, manure application, and cover cropping. The data collection methodologies employed across the studies were as follows: For greenhouse gas (GHG) emissions, most studies used chamber methods to measure emissions from rice paddies. Yield data were generally obtained through random sampling methods within the fields. Soil Organic Carbon (SOC) stock changes were determined by comparing SOC content at

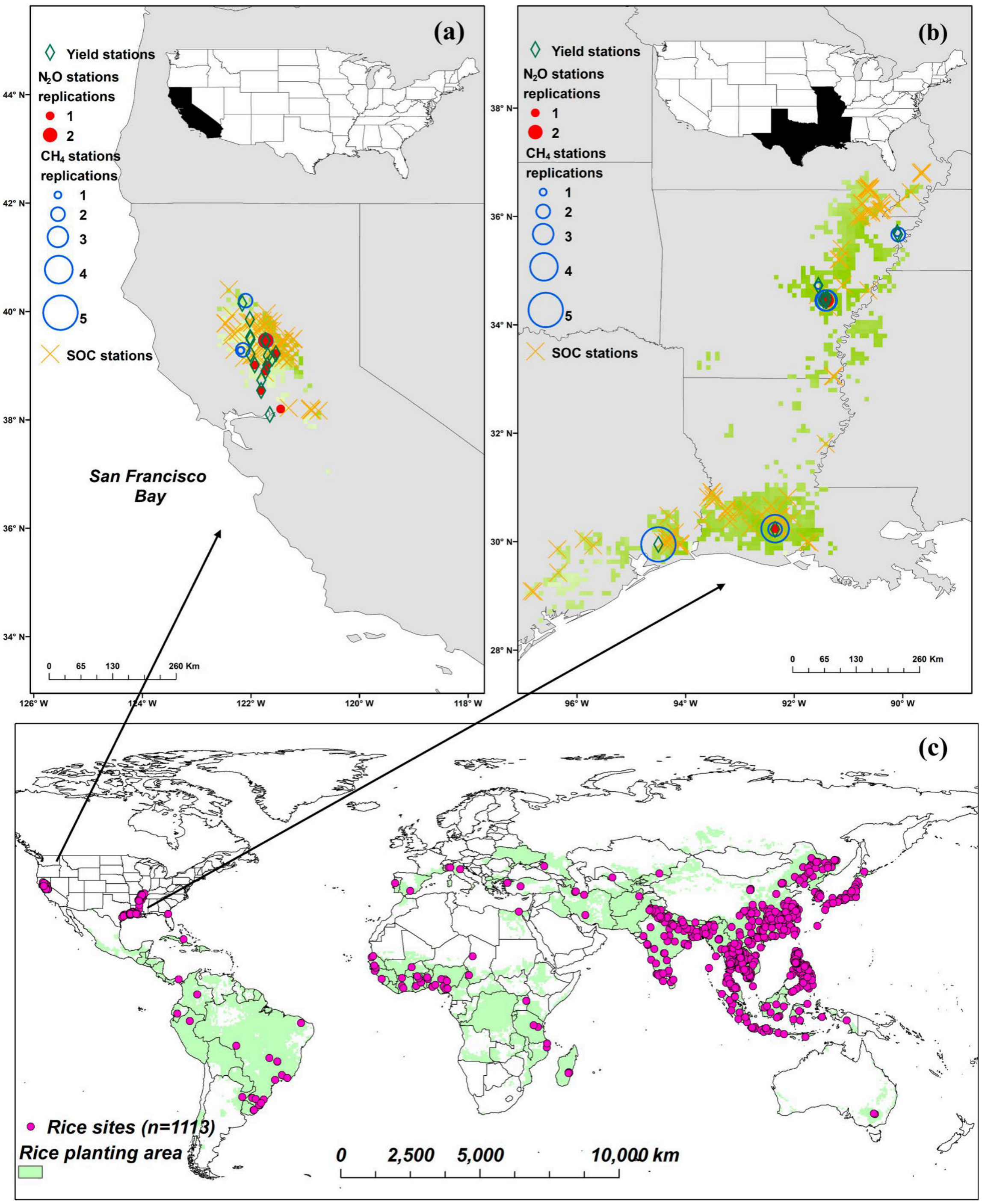

Figure 1. Spatial distribution of rice experimental sites in this study. (a and b) Represent rice experimental/observation sites in U.S. rice paddies used for model calibration, validation, and meta-analysis. (c) Represents global rice experimental/observation sites used for the meta-analysis. Rose circles include CH_4 flux, N_2O flux, SOC stock/change, and yield experimental stations, obtained from Bo et al. (2022) and Liu et al. (2021); the blue circle represents the CH_4 emissions experimental station; the red circle represents the N_2O emission experimental station, and fork shape means SOC observations obtained from Batjes et al. (2016) (http://dx.doi.org/10.17027/isric-wdcsoils.20160003). Point size represents the number of replications/observations at each site in (a) and (b). More details about sites in (a) and (b) are shown in Table S1 of the Supporting Information S1.

different time intervals, with measurements typically taken from the 0–20 cm soil layer. In addition, GetData Graph Digitizer software (https://getdata-graph-digitizer.software.informer.com/) was used to extract exact values when data was presented in graphical form.

2.2. Model Description

DLEM v4.0 is a comprehensive process-based terrestrial biosphere model that integrates major biophysical, biogeochemical, and hydrological processes to quantify daily, spatially explicit stocks and fluxes of carbon, water, and nutrients in terrestrial ecosystems and inland water systems at site, regional, and global scales (Pan et al., 2021; Tian et al., 2010, 2020; Yao et al., 2020; You et al., 2022; J. T. Zhang et al., 2018; J. Zhang et al., 2020). In addition to meeting cross-scale agricultural needs such as management guidance, climate change mitigation, and adaptation, DLEM v4.0 also includes dynamic representations of crop growth and development processes, such as crop-specific phenological development, carbon allocation, yield formation, and biological N fixation, as well as agricultural management practices such as N fertilization, irrigation, tillage, manure application, dynamic crop rotation, cover cropping, and genetic improvements (You et al., 2022). The detailed representation of crop growth and management practices in DLEM v4.0 allows for the simulation of crop yield, crop state variables, biogeochemical fluxes, and pools of carbon, N, and water related to agroecosystems across various spatial and temporal scales, driven by multiple environmental forces such as climate change, atmospheric CO_2 fertilization and N deposition, tropospheric ozone pollution, and land use and land cover change. For more information on the representation of crop growth and agricultural management practices in DLEM v4.0, please refer to You et al. (2022).

2.3. Model Forcing Data Set

To drive DLEM v4.0, four types of long-term spatial datasets at a resolution of 5 × 5 arc-min were developed: Natural environmental changes (daily climate conditions, monthly atmospheric CO_2, and monthly N deposition); Yearly agricultural management practices (annual N fertilizer use rate, crop rotation, tillage, irrigation, manure application, and crop phenology); Yearly land use and land cover change (LULC); and soil properties and other auxiliary data. Further details on this data set were provided in Text S1 of the Supporting Information S1.

2.4. Model Calibration, Validation, and Uncertainty Analysis

DLEM has been widely validated and applied in various regions, including China (e.g., Tian et al., 2011; J. T. Zhang et al., 2018; J. Zhang et al., 2020), the U.S. (e.g., Huang et al., 2020; Lu et al., 2021; You et al., 2022; Yu et al., 2018), and globally (e.g., Friedlingstein et al., 2020; Ren et al., 2020; Saunois et al., 2020; Tian et al., 2020; B. Zhang et al., 2016; H. Zhang et al., 2016). This includes specific studies focused on rice paddies, particularly in China (e.g., J. T. Zhang et al., 2018; J. Zhang et al., 2020) and East Asia (B. Zhang et al., 2016; H. Zhang et al., 2016), where CH_4 and N_2O fluxes from rice fields have been comprehensively verified. In our study, we have adapted and validated the latest version of DLEM (DLEM v4.0) (You et al., 2022), which includes updated farmland management measures like organic fertilizers and planting practices, to simulate SOC stock/change and emissions of N_2O and CH_4 specifically in U.S. rice paddies. This calibration and validation were performed using field observations compiled through meta-analysis. The model's performance was quantitatively evaluated using metrics such as the coefficient of determination (R^2), root mean square error (RMSE), and normalized root mean square error (NRMSE).

We have conducted a sensitivity and uncertainty analysis for DLEM to quantify uncertainties in the simulated regional SOC change rate and fluxes of N_2O and CH_4 in U.S. croplands (Tian et al., 2011; Xu, 2010; You et al., 2022). First, we used the Sobol method (Sobol, 1993) to perform a variance-based global sensitivity analysis to determine the relative importance of model parameters in simulating SOC change rate and emissions of N_2O and CH_4. We then identified parameters that significantly affected the simulation results and generated an ensemble of 100 parameter sets by randomly varying their values within 30% of their calibrated values using a Monte Carlo sampling scheme (Tian et al., 2011; You et al., 2022). Finally, we used the ensemble of parameter sets to drive DLEM v4.0 to simulate regional SOC change rate and emissions of N_2O and CH_4 from U.S. rice paddies.

2.5. Model Implementation and Experimental Design

The implementation of DLEM v4.0 consists of three main stages: an equilibrium run, a spin-up run, and a transient run. During the equilibrium run, 30-year average climate conditions from the 1900s to the 1920s and other environmental factors in 1900 were used (You et al., 2022). The equilibrium state was considered reached when changes in C, N, and water pools between two consecutive 50-year periods were less than 0.5 g C m^{-2} yr^{-1}, 0.5 g N m^{-2} yr^{-1}, and 0.5 mm yr^{-1}, respectively. To eliminate model fluctuations caused by the transition from

Table 1
Factorial Experiments to Quantify the Relative Contributions of Different Drivers to Changes in SOC, N_2O, and CH_4 Emissions From U.S. Rice Paddies

No.	Scenario	Nfer[a]	Tillage[b]	Irrigation[c]	Manure	Climate[d]	CO_2	Ndep	LULC
S0	Reference	1900	1900	1900	1900	1900	1900	1900	1900
S1	All Combined	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018
S2	Without N fertilization (Nfer)	1900	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018
S3	Without Tillage	1900–2018	1900	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018
S4	Without Irrigation	1900–2018	1900–2018	1900	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018
S5	Without Manure	1900–2018	1900–2018	1900–2018	1900	1900–2018	1900–2018	1900–2018	1900–2018
S6	Without Climate	1900–2018	1900–2018	1900–2018	1900–2018	1900	1900–2018	1900–2018	1900–2018
S7	Without CO_2	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900	1900–2018	1900–2018
S8	Without N deposition (Ndep)	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900–2018	1900	1900–2018
S9	Nfer + Tillage + Irrigation	1900–2018	1900–2018	1900–2018	1900	1900	1900	1900	1900
S10	Nfer + Tillage + Irrigation + LULC	1900–2018	1900–2018	1900–2018	1900	1900	1900	1900	1900–2018

[a]We assumed N fertilization rate before 1910 was kept constant at the 1,910 level. [b]We assumed tillage data before 1960 was kept constant at the 1,960 level. [c]We assumed irrigation data before 1950 was kept constant at the 1,950 level. [d]Climate data in 1900 was the 30-year average climate condition from the 1900s to the 1920s.

the equilibrium run to the transient run, the spin-up run was driven by detrended climate data from the 1900s to the 1920s. Finally, the transient run was driven by historical data from 1900 to 2018.

We conducted 11 simulation experiments (Table 1) to identify the distinct roles played by various drivers in influencing the net soil GHG balance of U.S. rice paddies during 1960–2018 (You et al., 2024). The factors considered for attribution included N fertilization, tillage, irrigation, manure application, climate change, atmospheric CO_2 concentration and N deposition, and LULC. To evaluate model fluctuations resulting from internal system dynamics, a reference run (S0) was carried out by maintaining all factors at the 1900 level (climate data in the 1900 level means the 30-year average climate condition from the 1900s to the 1920s). To determine the overall impact of all the factors on SOC change and N_2O and CH_4 emissions, an all-factors run (S1) was conducted using all historically varying input forcings during 1900–2018. The difference between S1 and S0 simulations was calculated to estimate the net changes in SOC change rate and emissions of N_2O and CH_4 driven by all factors. Furthermore, we performed 7 additional simulations (S2–S8) to examine the individual contributions of each factor to annual variations in SOC change rate and fluxes of N_2O and CH_4. In each simulation, one specific factor was kept at the 1900 level, while all other factors were varied over time, and the contribution of this factor was obtained by subtracting the simulation from the "All Combined" simulation (S1). Additionally, since LULC is often associated with changes in the overall input of management practices (e.g., manure and mineral fertilizer application) (S9), we calculated the contribution of LULC by maintaining all management factors at the 1900 level while varying other environmental factors (S10) (Lu et al., 2021). Thus, the difference between S9 and S10 was used to determine the contribution of LULC. More details were provided in You et al. (2024).

2.6. Global Warming Potential Calculation

The global warming potential (GWP) is a metric used to quantify the cumulative radiative forcing resulting from the emission of 1 kg of a trace gas compared to the emission of 1 kg of CO_2 (Myhre et al., 2013). In croplands, the GWP value of the net soil GHG balance is determined by calculating the sum of CO_2 equivalents from SOC change and emissions of N_2O and CH_4:

$$\mathrm{GWP} = F_{CO_2-C} \times \frac{44}{12} + F_{N_2O-N} \times \frac{44}{28} \times \mathrm{GWP}_{N_2O} + F_{CH_4-C} \times \frac{16}{12} \times \mathrm{GWP}_{CH_4} \tag{1}$$

$$F_{CO_2-C} = -\mathrm{SOCSR} \tag{2}$$

where F_{CO_2-C}, F_{N_2O-N}, and F_{CH_4-C} are annual fluxes of CO_2, N_2O, and CH_4, respectively; SOCSR was SOC change rate; molecular weight conversion fractions 44/12, 44/28, and 16/12 were used to convert the mass of CO_2-C, N_2O-N, and CH_4-C into CO_2, N_2O, and CH_4, respectively; GWP_{N_2O} and GWP_{CH_4} were GWP constants

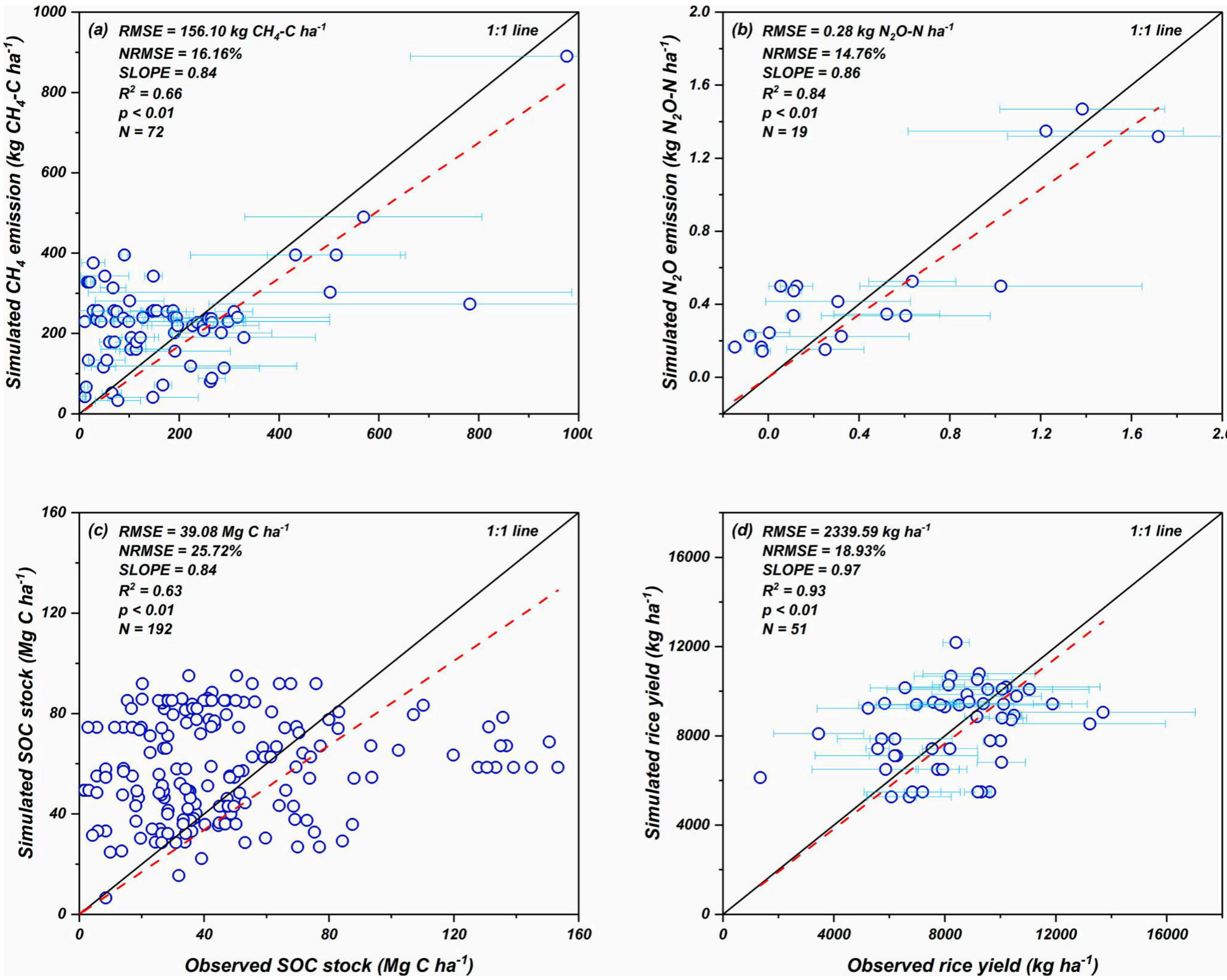

Figure 2. Site-scale comparisons of model estimates and field observations of CH_4 (a), N_2O (b), SOC stock (c), and rice yield (d) across different agricultural managements (e.g., fertilizer, irrigation, tillage, and others) in U.S. rice paddies. The dashed line is the regression of observed data and modeled results, and the solid line is the 1:1 line. Note that we outputted the simulation results at the corresponding observed period for validation.

indicating radiative forcing of N_2O and CH_4 in terms of their CO_2 equivalents, and this study used the GWP values integrated over a time horizon of 100 years for N_2O and CH_4, which were 273 and 27, respectively (IPCC, 2023).

3. Results

3.1. Spatiotemporal Changes of Net GHG Balance in U.S. Rice Paddies

A total of 322 site-year measurements from 43 U.S. rice paddy sites were utilized to calibrate, validate, and confirm model simulations in this study (see Figure 1). In general, DLEM v4.0 exhibited good performance in simulating yearly CH_4 and N_2O emissions as well as SOC stock/change in rice paddies when compared with field observations from meta-analysis. The RMSE (NRMSE) values between model simulations and observations were 156.1 kg CH_4-C ha^{-1} yr^{-1} (16.2%), 0.3 kg N_2O-N ha^{-1} yr^{-1} (14.8%), 39.1 Mg C ha^{-1} yr^{-1} (25.7%), and 2,339.6 kg ha^{-1} yr^{-1} (18.9%), respectively, while the corresponding R^2 values were 0.7, 0.8, 0.6, and 0.9, respectively (see Figure 2).

According to our estimates by DLEM v4.0, the annual soil non-CO_2 greenhouse gas (GHG) emissions from U.S. rice paddies experienced a notable increase over the years. In the 1960s, these emissions were approximately

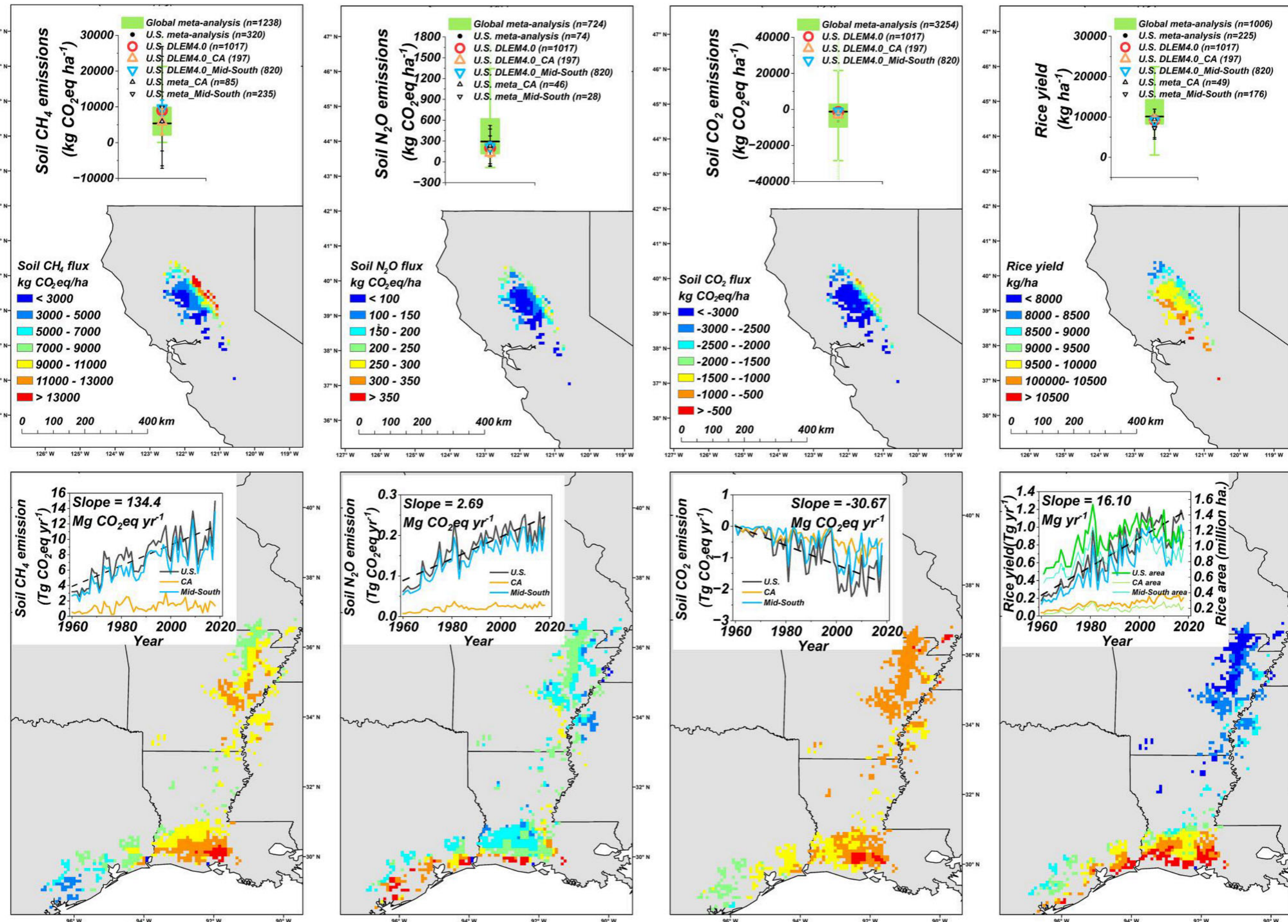

Figure 3. Spatial patterns of average annual soil CH_4 flux, N_2O flux, and CO_2 flux in rice paddies from 2010 to 2018. The insets in the top row depicted a comparison between observations and simulations of soil CH_4 flux, N_2O flux, CO_2 flux, and yield in global rice paddies (illustrated by the box), U.S. rice paddies (represented by the circle), California (triangle), and the Mid-South regions (inverted triangle). The insets in the bottom row showed annual changes in soil CH_4 flux, N_2O flux, CO_2 flux, yield, and cultivation area of rice paddies from 1960 to 2018. Note that negative values in soil fluxes represent uptake, positive values represent release, and negative SOC change rate indicates soil CO_2 flux.

3.9 ± 1.1 Tg CO_2eq yr^{-1}. By the 1990s, they had surged to 9.8 ± 1.1 Tg CO_2eq yr^{-1}, showing a significant growth rate of 181.1 Mg CO_2eq yr^{-1}. Subsequently, in the 2010s, the emissions reached a level of 10.3 ± 2.3 Tg CO_2eq yr^{-1}, demonstrating a slightly weaker upward trend with an increase of 57.4 Mg CO_2eq yr^{-1}. The annual soil CH_4 emissions originating from rice paddies represented a substantial portion, accounting for 97.9% (equivalent to 10.1 ± 2.3 Tg CO_2eq yr^{-1} or 8,792.2 ± 1,578.0 kg CO_2eq ha^{-1}) in the 2010s. This was accompanied by a growth rate of 134.4 Mg CO_2eq yr^{-1} (60.5 kg CO_2eq ha^{-1} yr^{-1}) since the 1960s (3.8 ± 1.1 Tg CO_2eq yr^{-1} or 5,838.3 ± 739.9 kg CO_2eq ha^{-1}) (Figure 3a). While soil N_2O emissions in paddies soil were initially modest in the 1960s (0.08 ± 0.02 Tg CO_2eq yr^{-1} or 134.2 ± 17.1 kg CO_2eq ha^{-1}), it displayed a substantial and noteworthy increase, reaching 0.2 ± 0.03 Tg CO_2eq yr^{-1} (198.7 ± 13.2 kg CO_2eq ha^{-1}) in the 2010s. This growth trend is particularly significant at a rate of 2.7 Mg CO_2eq yr^{-1} (1.3 kg CO_2eq ha^{-1} yr^{-1}) (Figure 3b).

The simulations aligned closely with the findings from our meta-analysis, showing similar results for CH_4 emission (8,792.2 ± 1,578.0 kg CO_2eq ha^{-1} vs. 8,809.3 ± 1,507.4 kg CO_2eq ha^{-1}) and N_2O emissions (198.7 ± 13.2 kg CO_2eq ha^{-1} vs. 208.0 ± 264.1 kg CO_2eq ha^{-1}) over the same period. Notably, the annual soil CH_4 emission from U.S. rice paddies surpassed the meta-analysis global average (7,787.6 ± 10,771.4 kg CO_2eq ha^{-1}). Conversely, the soil N_2O emissions in the 2010s from U.S. rice paddies were lower than the global average (521.6 ± 729.5 kg CO_2eq ha^{-1}). The distribution of CH_4 flux resulting from rice cultivation exhibited remarkable polarization, with a high CH_4 emission of approximately 7,200 kg CO_2eq ha^{-1} observed in the majority of the

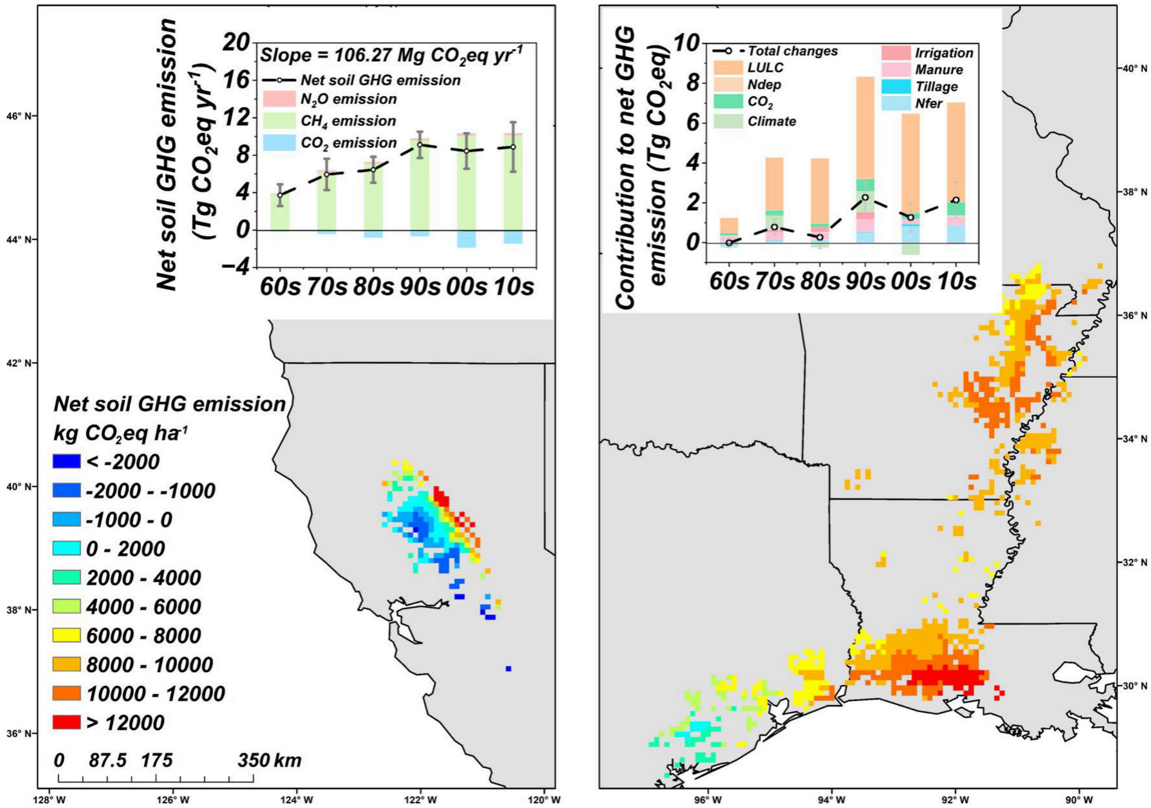

Figure 4. Spatial pattern of average net soil GHG balance of U.S. rice paddies in the 2010s. To Inset on the left represents the decadal average GWP of three gases; the inset on the right shows factorial contributions of multiple agricultural management practices and environmental forcing to changes in the net GHG balance of U.S. rice paddies from the 1960s to the 2010s. *Nfer* represents nitrogen fertilizer use; *Ndep* represents atmospheric nitrogen deposition; *LULC* represents land use and land cover change (reflecting both cropland abandonment and expansion, as well as interannual crop rotation changes); and CO_2 represents atmospheric carbon dioxide concentration. Note that the sum of factorial contributions of individual drivers (i.e., stacked bars) does not equal net changes in the net GHG balance (i.e., black line) due to interaction effects. Note that error bars in insets represent ±1 standard deviation of the net GHG balance in each decade.

mid-South States, particularly in the Mississippi Delta Arkansas region, as well as in the northern part of the Sacramento Valley region in California (Figure 3a). In contrast, other areas, such as Texas, displayed lower rates, measuring less than 5,400 kg CO_2eq ha^{-1}. Similarly, the spatial pattern of N_2O emissions showed limited variation across the mid-South States, with emissions higher than 128.7 kg CO_2eq ha^{-1} (Figure 3b). In contrast, the simulations indicated low N_2O emissions for the Sacramento Valley region.

The soil stock in U.S. rice paddies measured 200.8 ± 3.6 Mg CO_2eq ha^{-1} in the 2010s, surpassing the global average of 162.0 ± 84.9 Mg CO_2eq ha^{-1} based on meta-analysis. This outcome stems from U.S. rice paddies exhibiting a significant capacity to sequester about 0.16 ± 0.11 Tg CO_2eq yr^{-1} (equivalent to 166.5 ± 189.4 kg CO_2eq ha^{-1} yr^{-1}) from the 1960s to the 1.45 ± 0.46 Tg CO_2eq yr^{-1} (equivalent to 1,305.8 ± 460.2 kg CO_2eq ha^{-1} yr^{-1}) in the 2010s, accounting for approximately 14.0% of soil non-CO_2 GHG emissions. This soil CO_2 uptake demonstrated an average growth rate of 30.5 Mg CO_2eq yr^{-1} (equivalent to 24.4 kg CO_2eq ha^{-1} yr^{-1}) from 1960 to 2018 (Figure 3c). The majority of U.S. rice paddies acted as carbon sinks, with relatively higher rates of SOC change (>290 kg CO_2eq ha^{-1} yr^{-1}) observed in the Sacramento Valley region and lower rates (<150 kg CO_2eq ha^{-1} yr^{-1}) across the mid-South States (Figure 3c). Conversely, the global rice paddies exhibited a carbon source, with an average emission of 6,828.8 ± 37,238.8 kg CO_2eq ha^{-1} yr^{-1} of soil CO_2 throughout the study period.

The U.S. rice paddy thus showed a rapidly increasing in net soil GHG emissions at a growth trend of 161.3 Mg CO_2eq yr^{-1} (36.0 kg CO_2eq ha^{-1} yr^{-1}) from the 1960s (3.7 ± 1.2 Tg CO_2eq yr^{-1} or 5,615.0 ± 736.3 kg CO_2eq ha^{-1}) to the 1990s, and then leveled off to 8.9 ± 2.7 Tg CO_2eq yr^{-1} (7,405.1 ± 1,665.1 kg CO_2eq ha^{-1}) by the 2010s (Figure 4). The distribution of net soil GHG balance showed considerable spatial heterogeneity, with hotspots in the north of the Sacramento Valley region and the Mississippi

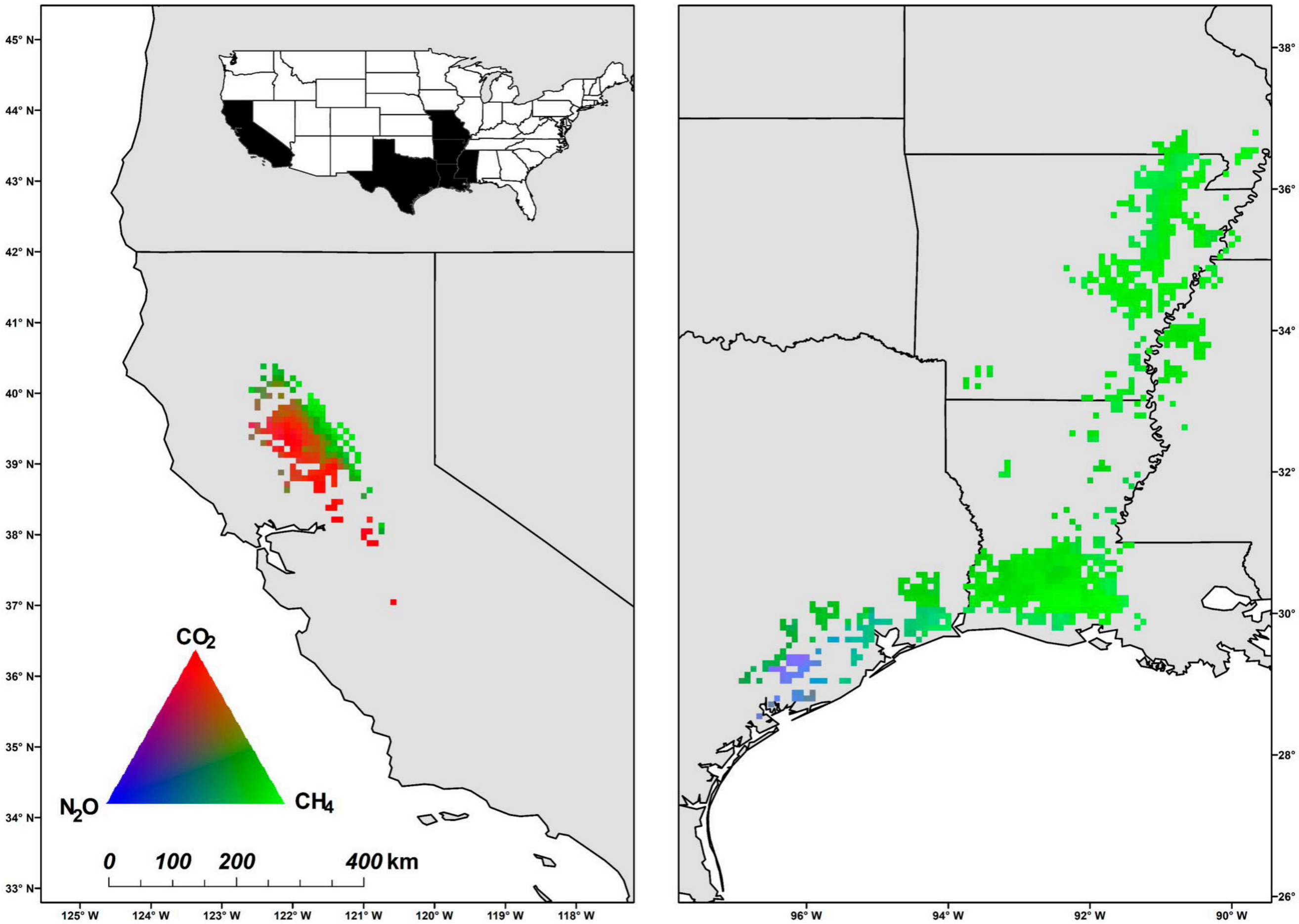

Figure 5. Spatial distributions of the relative contribution of SOC change and emissions of N_2O and CH_4 to net soil GHG balance of U.S. rice paddies in the 2010s. Note: The grid annual mean relative contributions of the three driver categories in the soil layer were used to derive the RGB (Red-Green-Blue) combinations to visualize the spatial patterns of the influential intensity of different driver categories. We defined the single dominant driver category of each pixel as the variable with a relative contribution larger than 60%. If the maximum relative contribution of any driver category is below this threshold, the dominant driver category of that pixel is defined as the combination of the two driver categories with larger relative contributions among the three driver categories.

Delta region where peak net soil GHG emissions were estimated to be higher than 8,000 kg CO_2eq ha^{-1} (Figure 4). In contrast, some U.S. rice paddies (primarily located in the southeast of the Sacramento Valley region) acted as a net sink of GHGs during the study period (representing <5% of U.S. rice paddies area), suggesting that sequestered SOC in these regions completely offset non-CO_2 GHG emissions (Figure 4).

We further analyzed the spatial distribution of the relative contribution of SOC change and N_2O and CH_4 emissions to the net GHG balance of U.S. rice paddies (Figure 5). Over the study period, soil CH_4 emissions played a dominant role in controlling the net GHG balance of most rice paddies (e.g., most of the Mississippi Delta and the north of the Sacramento Valley region), while SOC change and CH_4 emissions synergistically controlled the net GHG balance in the southwest of mid-South States (mainly in Texas). Meanwhile, the proportion of regions dominated by SOC change that increased over time in most of the Sacramento Valley region is noteworthy and indicates an increasing role of SOC change in controlling the net GHG balance across U.S. rice paddies (Figure 5).

3.2. Factorial Contributions of Multi-Driver Changes to Net GHG Balance in U.S. Rice Paddies

We further quantified the factorial contributions of key drivers, including multiple agricultural management practices and environmental forcings, to changes in the net soil GHG balance of U.S. rice paddies from 1960 to 2018 by setting up a series of simulation experiments (Table 1). Simulation results during the study period showed that the increase in rice cultivation area unquestionably was the dominant factor for driving the net GHG emission

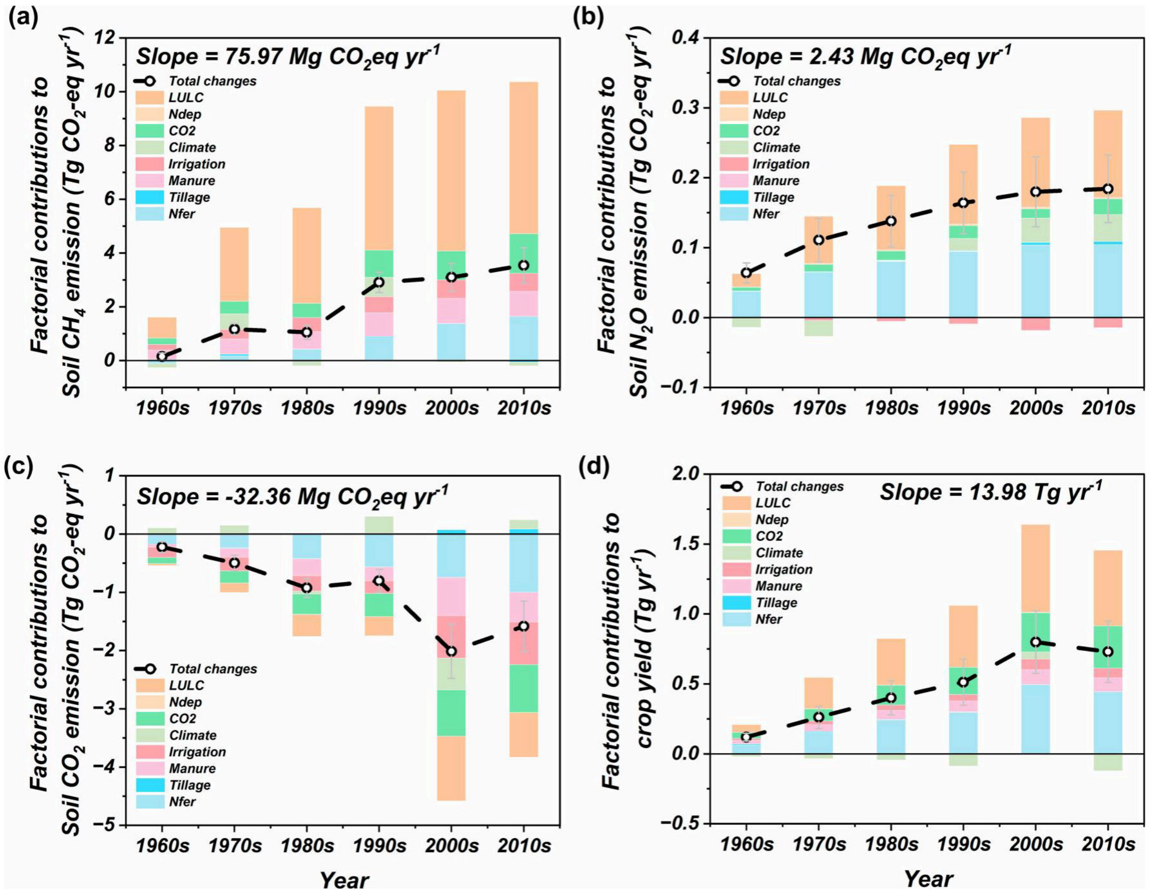

Figure 6. Factorial contributions of multiple agricultural management practices and environmental factors to changes in U.S. rice paddies' net GHG emission and crop yield from the 1960s to the 2010s. *Nfer* represents nitrogen fertilizer use; *Ndep* represents atmospheric nitrogen deposition; *LULC* represents land use and land cover change (reflecting both cropland abandonment and expansion, as well as interannual crop rotation changes); and CO_2 represents atmospheric carbon dioxide concentration. Note that the sum of factorial contributions of individual drivers (i.e., stacked bars) does not equal net changes in the net GHG balance (i.e., black line) due to interaction effects. Note that error bars in insets represent ±1 standard deviation of the net GHG balance in each decade.

exacerbation of U.S. rice paddies, with 5.5 times more than that in the 1960s (Figure 4). Except that, the rapid increase of synthetic N fertilizer application was the next dominant factor, which could still induce a sink of 0.23 Tg CO_2eq yr^{-1} in the 1960s, contributing to a net GHG emission of 0.75 Tg CO_2eq yr^{-1} on average in the 2010s with a rising trend of 21.5 Mg CO_2eq yr^{-1}. These changes accounted for roughly 34.9% of the total net GHG alterations (Figure 4). Within this context, N fertilizer played a substantial role in influencing the changes in soil CH_4 emission of about 46.4% (equivalent to 1.6 Tg CO_2eq yr^{-1}) in the 2010s (Figure 6), consistent with findings from similar studies in U.S. rice paddies (50.6% in observations), but higher than the global average (33.9% in observations) based on the meta-analysis in this study (Figure 7a). This contribution exhibited a growth trend of 37.2 Mg CO_2eq yr^{-1} over the study period (Figure 6a). Moreover, N fertilizer also notably influenced soil N_2O emissions, contributing from about 0.04 Tg CO_2eq yr^{-1} (representing 58.3% of the emissions) in the 1960s to 0.10 Tg CO_2eq yr^{-1} (representing 56.6% of the emissions) during the 2010s. This contribution exhibited a considerable increasing trend of 1.36 Mg CO_2eq yr^{-1} throughout the study period (Figure 6b), surpassing the meta-analysis results for both U.S. rice paddies (23.1% in observations) and the globe average (48.1% in observations) (Figure 7b). Despite these intensified GHG emissions, N fertilizer positively affected SOC change simultaneously, which induced a carbon sink of 0.15 Tg CO_2eq yr^{-1} in the 1960s with a growth rate of 17.0 Mg CO_2eq yr^{-1}. This contribution accounted for 63.2% (equivalent to 1.0 Tg CO_2eq yr^{-1}) of changes in SOC change in U.S. rice paddies during the 2010s (Figure 6c), surpassing the global average (29.8% in observations) as indicated in Figure 7c.

Increasing manure application was another impact factor for driving changes in the net GHG balance of U.S. rice paddies. On average, manure application contributed approximately 0.30 Tg CO_2eq yr^{-1} in the 1960s and

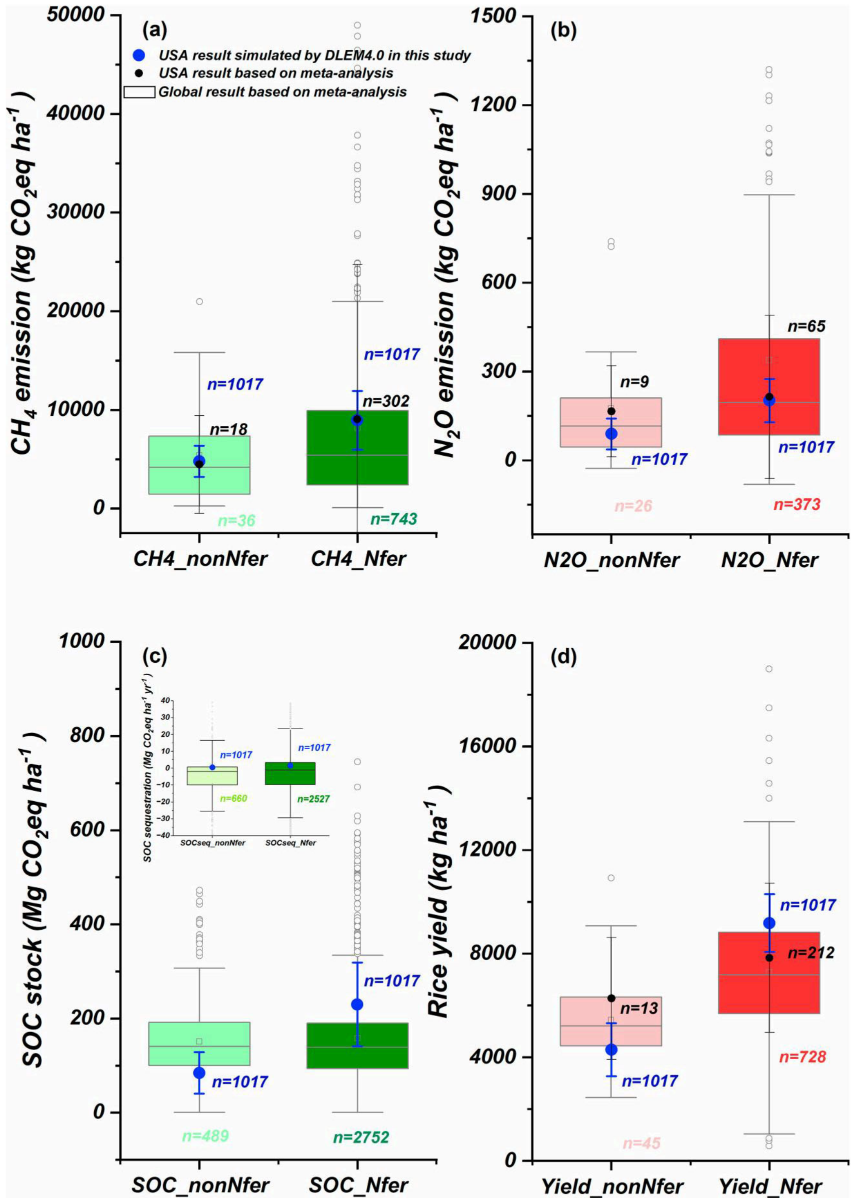

Figure 7. Effects of synthetic nitrogen fertilizer (*Nfer*) application to CH_4 emissions (a), N_2O emissions (b), SOC stock/change (c), and rice yield (d) in U.S. rice paddies over the study period based on simulation and meta-analysis. Inset in (c) represents the effect of *Nfer* to SOC change. *nonNfer* and *Nfer* represent without and with nitrogen fertilizer use, respectively; *n* is the number of data records.

then this contribution increased to 0.42 Tg CO_2eq yr^{-1} during the 2010s, showing a weak growth trend and accounting for 19.5% of changes in net GHG emissions (see Figure 4). As the most important organic soil amendment, manure played a crucial role in enhancing SOC change. Its contribution increased significantly from 0.05 Tg CO_2eq yr^{-1} (24.2%) in the 1960s to 0.51 Tg CO_2eq yr^{-1} (32.2%) in the 2010s, with a gradually increasing trend of 10.8 Mg CO_2eq yr^{-1} (Figure 6c). However, it is worth noting that manure application also contributed to a notable CH_4 emission from 0.35 Tg CO_2eq yr^{-1} in the 1960s to 0.93 Tg CO_2eq yr^{-1} (representing 26.2% of the emissions) in the 2010s (Figure 6a). On a global scale, the contribution of manure application to SOC change and CH_4 emission was even more remarkable, accounting for 94.6% and 44.9%, respectively, based on meta-analysis (Figures 8a and 8c). Interestingly, while manure induced only a slight increase in soil N_2O emissions in U.S. rice paddies (Figure 6b), it reduced soil N_2O emissions by 14.1% in global rice paddies.

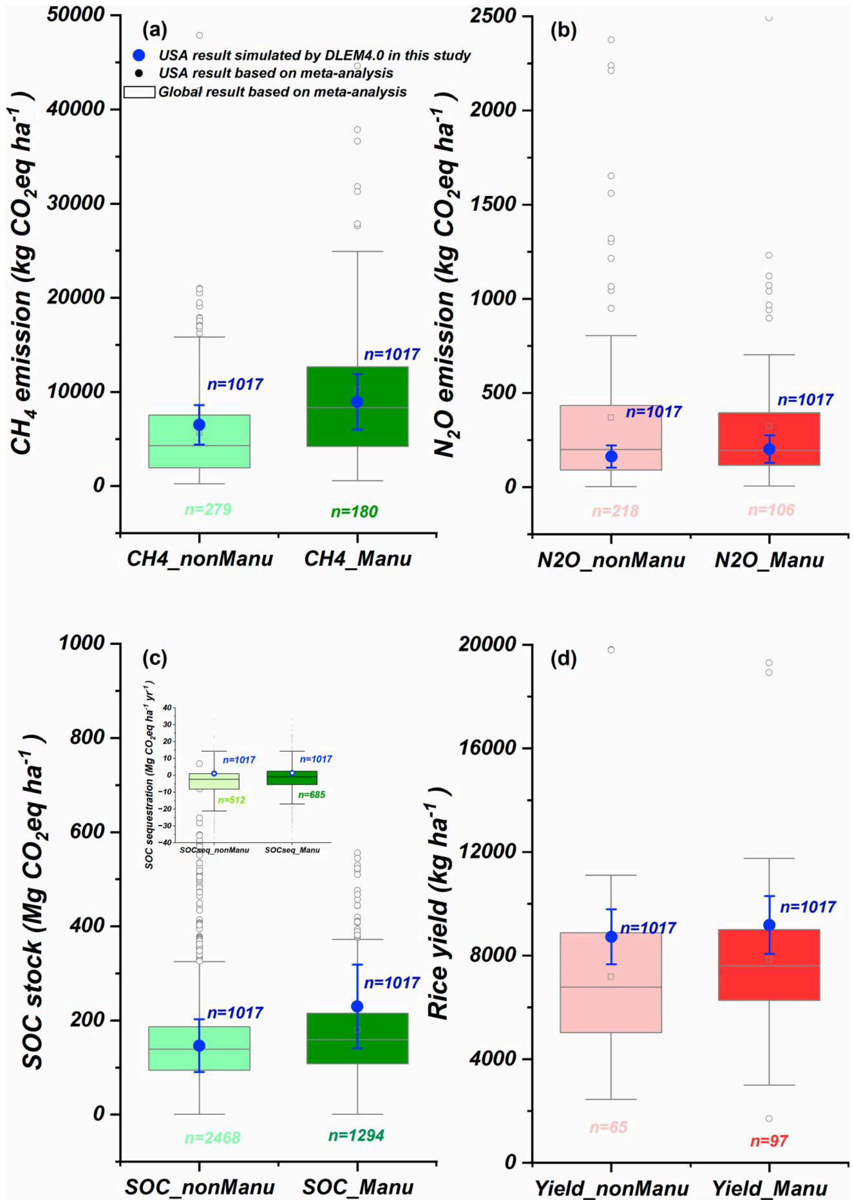

Figure 8. Effects of manure application to CH_4 emissions (a), N_2O emissions (b), SOC stock/change (c), and rice yield (d) in U.S. rice paddies over the study period based on simulation and meta-analysis. Inset in (c) represents the effect of manure on SOC change. *nonManu* and *Manu* represent without or with manure input, respectively; *n* is the number of data records.

The tillage practice changes for U.S. rice paddies decreased net soil GHG emissions from 0.08 Tg CO_2eq yr^{-1} in the 2000s to 0.03 Tg CO_2eq yr^{-1} in the 2010s (Figure 4). As a result, the relative contribution of tillage practice changes to net GHG emission changes steadily decreased from 6.0% in the 2000s to 1.2% in the 2010s. Within this context, tillage practice changes were associated with a significant decrease of 18.4% (0.04 Tg CO_2eq yr^{-1}) in soil CH_4 emission changes during the 1960s (Figure 6a). However, this effect diminished notably in subsequent years, leading to a remarkable reduction in emissions. By the 2010s, tillage practice changes even facilitated a positive transformation, causing a change of 1.8% (0.06 Tg CO_2eq yr^{-1}) in soil CH_4 emission changes. Regarding soil N_2O emission, tillage-induced changes increased slightly to 0.004 Tg CO_2eq yr^{-1} in the 2010s, contributing to 2.3% of soil N_2O emission changes (Figure 6b). However, one concerning consequence of increasing the proportion of conventional tillage practices was the continuous aggravation of SOC loss, resulting in 0.08 Tg CO_2-eq yr^{-1} (6.1%) in soil CO_2 emission in the 2010s (Figure 6c). On the other hand, compared to conventional tillage, adopting no/reduced tillage methods induced a significant increase of 12.8% in soil CH_4 emission changes in the

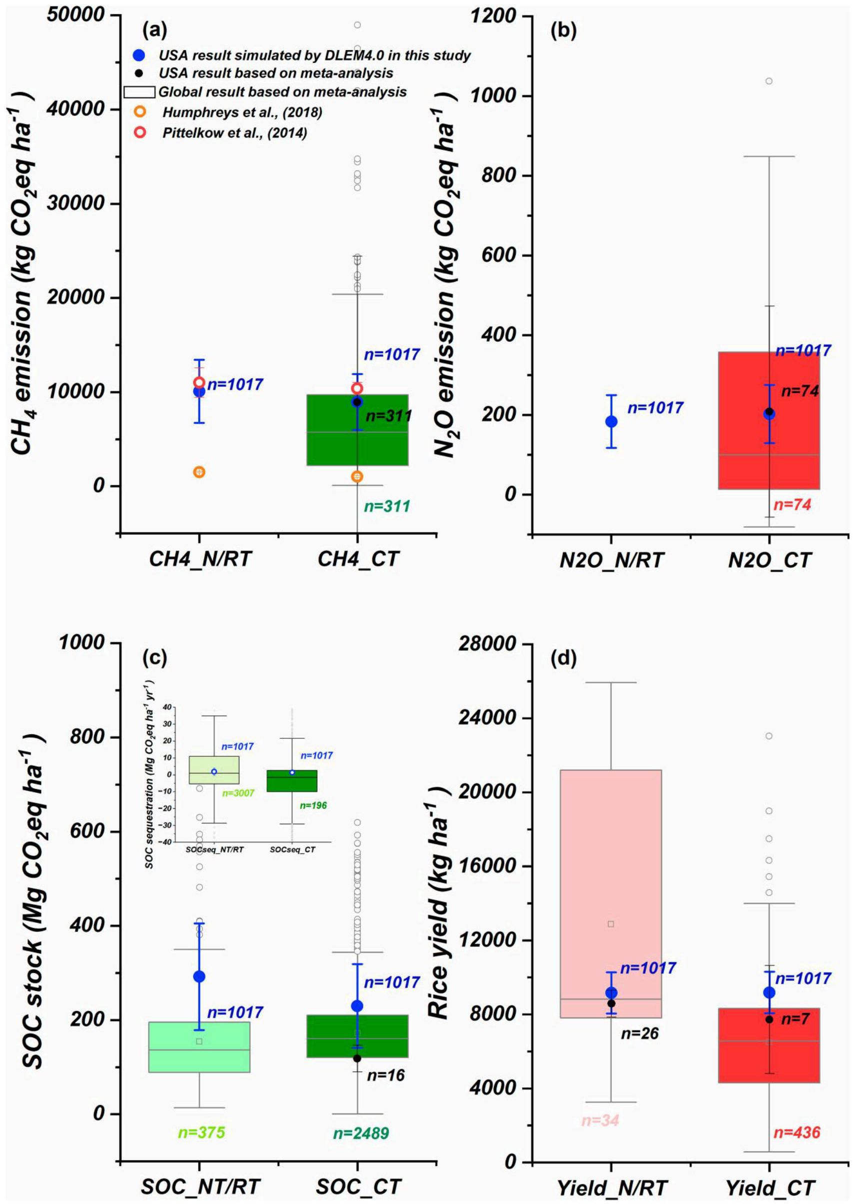

Figure 9. Effects of tillage practices on CH_4 emissions (a), N_2O emissions (b), SOC stock/change (c), and rice yield (d) in U. S. rice paddies over the study period based on simulation and meta-analysis. Inset in (c) represents the effect of tillage practices on SOC change. *NT/RT* and *CT* represent no tillage or reduced tillage and conventional tillage, respectively; *n* is the number of data records.

U.S. rice paddies. This value fell within the range of 6.1%–45.2% obtained from control trials in Humphreys et al. (2018) and Pittelkow et al. (2014) (Figure 9a). Nevertheless, in U.S. rice paddies, adopting no/reduced tillage resulted in a substantial decrease of 9.2% in soil N_2O emissions while simultaneously boosting SOC change by an impressive 27.0% when compared to the conventional tillage practices (Figures 9b and 9c). This boost of SOC change induced by no/reduced tillage in global rice paddies was more notable, by 1.5 times.

The importance of irrigation in determining the net soil GHG balance of U.S. rice paddies cannot be overstated. During the 1990s, irrigation strategy change (including area and method) contributed approximately 0.37 Tg CO_2eq yr^{-1} on average, with a slight growth rate of 11.0 Mg CO_2eq yr^{-1} (Figure 4). However, due to the decreasing adoption of continuous irrigation practices, the changes induced net GHG emissions of U.S. rice paddies significantly reduced, resulting in sequestering approximately 0.07 Tg CO_2eq yr^{-1} in the 2010s (Figure 4). This strategy change had a notable impact on soil CH_4 emission changes in U.S. rice paddies, steadily

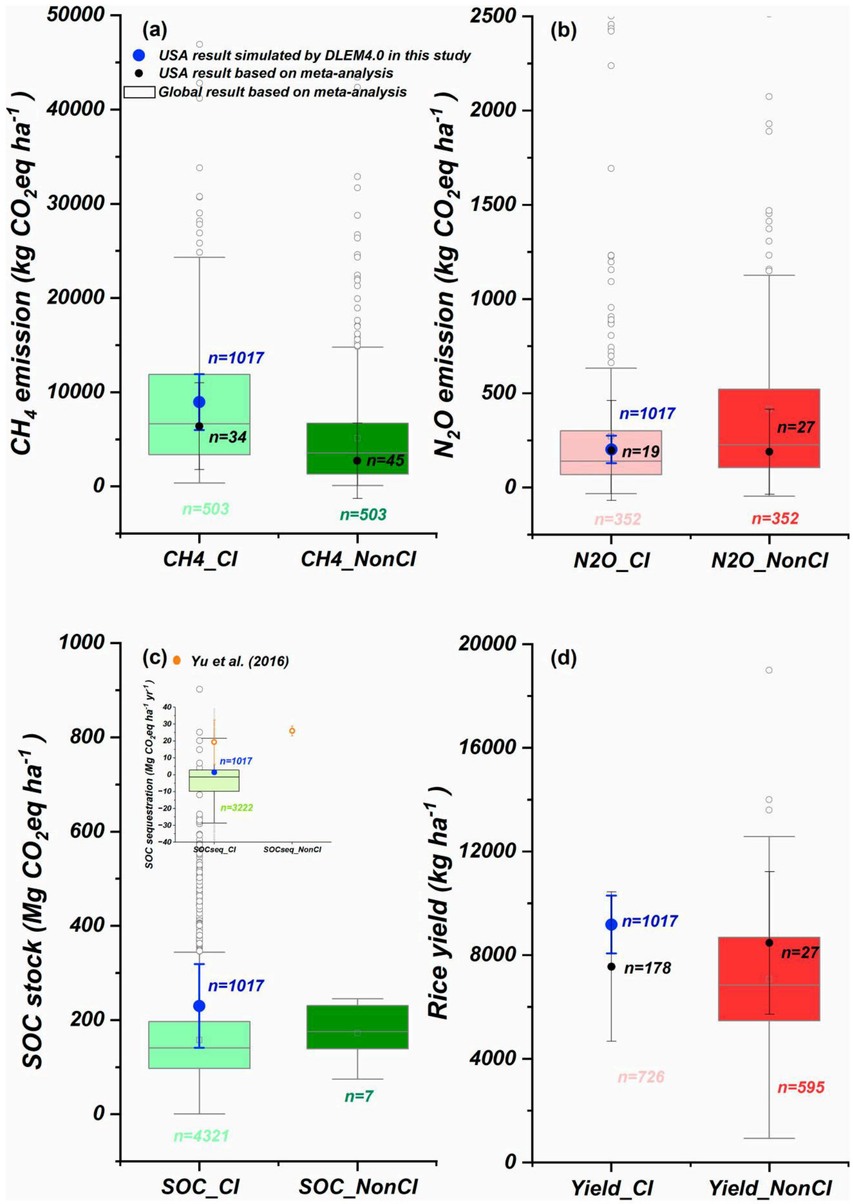

Figure 10. Effects of irrigation on CH_4 emissions (a), N_2O emissions (b), SOC stock/change (c), and rice yield (d) in U.S. rice paddies over the study period based on simulation and meta-analysis. Inset in (c) represents the effect of irrigation on SOC change. *nonCI* and *CI* represent no continuous irrigation and continuous irrigation, respectively.

increasing from 0.20 Tg CO_2eq yr^{-1} in the 1960s to 0.68 Tg CO_2eq yr^{-1} in the 2010s, roughly explained 19.1% of soil CH_4 emission changes (Figure 6a). A meta-analysis conducted in this study revealed that non-continuous irrigation in U.S. rice paddies led to a substantial reduction of 57.3% (equivalent to 3,668.7 kg CO_2eq ha^{-1}) in soil CH_4 emissions compared to continuous irrigation (6,405.8 ± 4,608.4 kg CO_2eq yr^{-1}) (Figure 10a). Furthermore, on a global scale, the adoption of non-continuous irrigation practices resulted in a similarly significant decrease of 40.7% (5,057.0 kg CO_2eq ha^{-1}) in soil CH_4 emissions (Figure 10a). In contrast, irrigation strategy change played a crucial role in curbing soil N_2O emission changes in U.S. rice paddies, leading to a notable reduction of 7.8% (equivalent to 0.014 Tg CO_2eq yr^{-1}) during the 2010s (Figure 6b). Globally, non-continuous irrigation practices aggravated soil N_2O emission by an average of 53.4% (equivalent to 144.6 kg CO_2eq ha^{-1}) relative to continuous irrigation, as illustrated in Figure 10b. On the whole, non-continuous irrigation exhibited the potential to mitigate around 39.2% of soil non-CO_2 GHG emissions on the global average. Over the study period, irrigation strategy change had a notably enhanced effect on SOC change in U.S. rice paddies, contributing to 0.73 Tg CO_2eq yr^{-1} in the 2010s, accounting for 46.4% of the total changes in SOC change (Figure 6c). Other driving factors, such as LULC, CO_2 concentration, and climate change increased net GHG emission at an average rate of 5.0 Tg CO_2eq yr^{-1} (233.6%), 0.67 Tg CO_2eq yr^{-1} (31.4%), and 0.06 Tg CO_2eq yr^{-1} (3.0%) in the 2010s, respectively (Figure 4). It is noteworthy that climate change led to a 3.8% decrease (equivalent to 0.13 Tg CO_2eq yr^{-1}) in soil CH_4 emissions, while simultaneously causing a 20.7% increase (equivalent to 0.38 Tg CO_2eq yr^{-1}) in soil N_2O emissions and a 10.2% increase (equivalent to 1.2 Tg CO_2eq yr^{-1}) in soil CO_2 emissions during the 2010s.

3.3. Spatiotemporal Changes of Net GHG Emissions Intensity in U.S. Rice Paddies

The enhancement of agricultural management practices across U.S. croplands resulted in a significant increase in rice production from 0.27 ± 0.06 Tg yr^{-1} (4,027.2 ± 463.4 kg ha^{-1} yr^{-1}) in the 1960s to 0.98 ± 0.31 Tg yr^{-1} (8,951.9 ± 1,570.4 kg ha^{-1} yr^{-1}) in the 2010s. This growth equated to a rise of 14.0 Mg yr^{-1} (107.5 kg ha^{-1} yr^{-1}) over the study period (Figure 3d). While slightly lower than the global average (11,339.8 ± 4,314.7 kg CO_2eq ha^{-1}), these changes underscored the positive impact of various factors on rice production. In this context, the augmentation of N fertilizer application, the increase in atmospheric CO_2 concentration, the incorporation of manure, and the expansion of irrigation area contributed to these rice production changes by 0.44 (60.7%), 0.30 (41.5%), 0.10 (13.5%), and 0.07 (9.5%) Tg ha^{-1} yr^{-1}, respectively (Figure 6d). However, the influence of climate change somewhat hindered these production changes by 0.12 (16.5%) Tg ha^{-1} yr^{-1}. These trends were consistent with both the U.S. and global averages based on the meta-analysis. For instance, N fertilizer led to a 20.0% increase in rice yield in U.S. rice paddies and a 25.2% increase on the global average (Figure 7d). Furthermore, manure input enhanced rice yield by 8.5% on the global average (Figure 8d). Comparatively, non-continuous irrigation, as opposed to continuous irrigation, improved U.S. rice yield by 12.1% according to the meta-analysis findings (Figure 10d).

Achieving increased U.S. rice yields over the past six decades has come with a trade-off of boosting soil GHG emissions. On average, producing a kilogram of grain in the 1960s emitted 1.27 ± 0.38 kg CO_2eq of net soil GHGs. Nonetheless, this intensity exhibited a substantial reduction to 0.84 ± 0.18 kg CO_2eq kg^{-1} in the 2010s, highlighting a remarkable trend of decline at 0.013 kg CO_2eq kg^{-1} yr^{-1}. This trend signifies an increasingly efficient rice production process in emitting fewer GHGs. It is crucial to emphasize the mounting concern regarding the intensity of N fertilizer, which escalated from 0.29 kg CO_2eq kg^{-1} in the 1970s to 1.13 kg CO_2eq kg^{-1} in the 2010s (Figure S1 in Supporting Information S1). Conversely, the net GHG intensity of manure exhibited a significant reduction, indicating a notably improved emission generation efficiency. The majority of U.S. rice paddies functioned as net sources of GHGs, as depicted in Figure 11. Regions exhibiting net soil GHG emissions intensities higher than 0.8 kg CO_2eq kg^{-1} were predominantly situated in the northeast of the mid-South States, encompassing Arkansas, Louisiana, Mississippi, and Missouri. Conversely, Texas displayed comparatively lower net soil GHG emissions intensities, with lower than 0.6 kg CO_2eq kg^{-1}, as indicated in Figure 11. However, certain U.S. rice paddies, primarily located in the southeast of the Sacramento Valley region, acted as minor net sinks of GHGs during the production of a kilogram of grain in the 2010s (Figure 11).

4. Discussion

4.1. Comparison With Previous Studies

We compared our estimates of SOC stock/change and emissions of N_2O and CH_4 in U.S. rice paddies and similar estimates from various regions (Table 2). Our estimate of CH_4 emissions, 0.28 ± 0.06 Tg C yr^{-1} or 224.6 ± 40.2 kg C ha^{-1} yr^{-1} in the 2010s, was closely aligned with earlier assessments in an annual emissions rate of approximately ∼0.25 Tg C yr^{-1} or ∼226.2 kg C ha^{-1} yr^{-1} (EPA, 2015; Huang et al., 1998; Linquist et al., 2018; Sass & Fisher, 1997; Sass et al., 1999; Tian et al., 2015). Our estimated N_2O emissions in U.S. rice paddies amounted to 0.42 ± 0.04 kg N ha^{-1} yr^{-1} in the 2010s, which was lower than values reported in prior studies (ranging from 1.2 to 8.4 kg N ha^{-1} yr^{-1}, Linquist et al., 2018; Mummey et al., 1998), but comparable to the outcomes of the meta-analysis in this study (0.48 ± 0.62 kg N ha^{-1} yr^{-1}). Over the last six decades, our estimated average SOC density in U.S. rice paddies during the 2010s stood at 54.8 ± 1.0 Mg C ha^{-1} yr^{-1}, aligning with the reported ranges from WoSIS and previous studies (Rogers, Brye, Norman et al., 2014; Rogers, Brye, Smartt et al., 2014; Ruark et al., 2010; Vasques et al., 2010; Zhong & Xu, 2014).

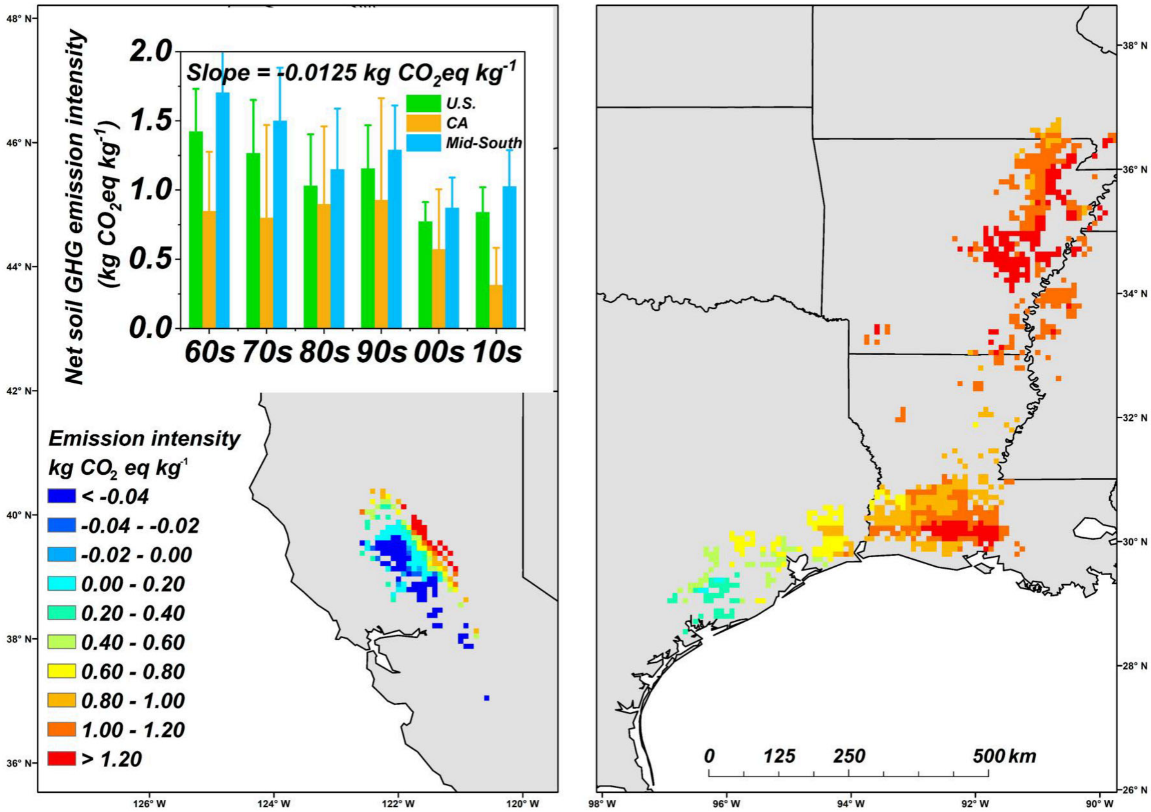

Figure 11. Spatial pattern of average annual net soil GHG emission intensity of U.S. rice paddies in the 2010s. Inset represents U.S. rice paddies' decadal average net soil GHG emission intensity. Note that error bars in insets represent the ±1 standard deviation of the net GHG emission intensity each decade.

On the whole, our estimates of SOC stock and emissions of N_2O and CH_4 in U.S. rice paddies showed similar magnitudes and trends to those of other regional estimates. However, disparities persist, likely attributable to uncertainties in input data and variations in estimation methodologies. For example, the records of N_2O emissions from rice fields in the meta-analysis were generally slightly higher (12.5%) than those indicated by the model. This difference could stem from the inclusion of N_2O emissions induced by non-continuous irrigation in some experiments, whereas our model considers only conventional continuous irrigation. Furthermore, certain experiments captured emissions solely during the growing season and disregarded emissions during the fallow period, a significant peak of N_2O emissions (Linquist et al., 2018), whereas the model results provide a comprehensive annual emission total. By integrating the model with empirical data, we can gain a more accurate comprehension of how agricultural management practices and environmental alterations influence the net soil GHG balance on a continual regional scale (Bondeau et al., 2007; McDermid et al., 2017; You et al., 2022). Thus, this study's approach of integrating the model and data offers a reasonable method for estimating the net soil GHG balance in U.S. rice paddies.

4.2. Impacts of Natural Environmental Changes on Net GHG Balance

Changes in natural environmental factors, encompassing climatic conditions, the rise in atmospheric CO_2 concentration, and heightened atmospheric N deposition, exerted significant contributions to the increase of net GHG emissions within U.S. rice paddies across the study period (Figure 4). Despite notable interannual variability, there exists a positive correlation between soil GHG emission and climate warming at a specific temperature threshold, as evidenced by various studies (e.g., Aben et al., 2017; Griffis et al., 2017). This threshold generally corresponds to increased activity among soil microorganisms, leading to a heightened pace of soil organic matter degradation and release of inorganic nitrogen (Avrahami & Conrad, 2003; Boonjung & Fukai, 1996; Carey et al., 2016; Laborte et al., 2012; Pärn et al., 2018; Weier et al., 1993; Yvon-Durocher et al., 2014; H. Zhang et al., 2016), ultimately exacerbating the flux of soil CH_4, N_2O, and CO_2. Precipitation can directly change soil moisture levels, thereby influencing anaerobic conditions and (de)nitrification by affecting soil oxygen content,

Table 2
Comparisons of SOC Density and N_2O and CH_4 Emissions From Other Studies

Fluxes	Reported value	Reported region	Time period	Approaches	References*
SOC density (Mg C ha^{-1} yr^{-1})	20.82	Arkansas	2011–2012	Experiment	Rogers, Brye, Norman et al. (2014) and Rogers, Brye, Smartt et al. (2014)
	44.21	Florida	2003–2005	Observation	Vasques et al. (2010)
	31.36	Louisiana	2001–2010	STATSGO database	Zhong and Xu (2014)
	33.55	California	2006–2008	Experiment	Ruark et al. (2010)
	51.57 ± 46.86	Entire U.S. rice paddies	1960–2012	WoSIS	WoSIS
	54.76 ± 0.98	Entire U.S. rice paddies	1981–2018	Process-based model	This study
N_2O (kg N ha^{-1} yr^{-1})	7.6 ~ 8.4	Entire U.S. rice paddies	/	The NGAS model	Mummey et al. (1998)
	1.29 ~ 2.57	Entire U.S. rice paddies	1980–2013	Meta-analysis	Linquist et al. (2018)
	0.48 ± 0.62	Entire U.S. rice paddies	Until to 2019	Meta-analysis	This study
	0.42 ± 0.04	Entire U.S. rice paddies	1980–2016	Process-based model	This study
CH_4 (kg C ha^{-1} yr^{-1})	261.0 ~ 394.0	Entire U.S. rice paddies	1980–2013	Meta-analysis	Linquist et al. (2018)
	249.9 ± 121.5	Texas	1991–1995	Meta-analysis	Huang et al. (1998)
	263.3 ± 134.1	Texas	1991–1995	Semi-empirical model	Huang et al. (1998)
	226.2 ± 101.0	Texas	1989–1993	Meta-analysis	Sass et al. (1999)
	244.7 ± 425.2	Entire U.S. rice paddies	Until to 2019	Meta-analysis	This study
	224.6 ± 40.2	Entire U.S. rice paddies	1980–2018	Process-based model	This study
CH_4 (Tg C yr^{-1})	0.04 ~ 0.47	U.S. rice paddies	/	IPCC Guidelines	Sass et al. (1999)
	0.3	North America croplands	1979–2018	Process-based model	Tian et al. (2015)
	0.276	U.S. rice paddies	1990	IPCC Guidelines	EPA (2015)
	0.267	U.S. rice paddies	2005	IPCC Guidelines	EPA (2015)
	0.255	U.S. rice paddies	2011	IPCC Guidelines	EPA (2015)
	0.279	U.S. rice paddies	2012	IPCC Guidelines	EPA (2015)
	0.249	U.S. rice paddies	2013	IPCC Guidelines	EPA (2015)
	0.28 ± 0.06	Entire U.S. rice paddies	2010s	Process-based model	This study

Note. Some stations only recorded N_2O emissions during the growth period of rice. In this paper, the annual emissions of these stations were estimated according to the ratio of emissions during the growth period and the fallow period in Linquist et al. (2018).

which in turn contributes to the production and emission of CH_4 and N_2O (Butterbach-Bahl et al., 2013; Turner et al., 2015; L. Zhang et al., 2010). The oxidation rate of CH_4 in the soil has a critical water content value, which determines its maximum oxidation rate. If the soil moisture content goes above this critical value, the oxidation capacity of CH_4 significantly reduces, leading to a considerable increase in CH_4 emissions (Gupta et al., 2021; Oh et al., 2020; Saunois et al., 2020; Tian et al., 2016). Concerning N_2O emissions, the highest levels occur during alternating soil wetting and drying when soil moisture content (water-filled porosity, WFPS) falls within the range of 45%–75% (Ciarlo et al., 2008; Kuang et al., 2019; H. Liu et al., 2022). Soil water content levels above or below these thresholds can reduce soil oxygen status, which indirectly affects (de)nitrification and soil microorganism activity (Butterbach-Bahl et al., 2013; Turner et al., 2015), ultimately leading to decreased N_2O emission rates (Dalal et al., 2003; Khalil & Baggs, 2005). Moreover, it is noteworthy that the population status, quantity, and activity of CH_4-producing, CH_4-oxidizing, and (de)nitrification bacteria are significantly impacted by not only the status but also fluctuations in soil water content, thereby profoundly influencing CH_4 and N_2O emissions. For instance, during the initial stages of rice drying, CH_4 emissions do not decrease as soil water content drops; instead, a peak emission occurs (Bo et al., 2022; Majumdar et al., 2000). Similarly, during the early flooding stage, considerable N_2O emissions still occur in the soil (Bo et al., 2022). This is why our meta-analysis showed that rice paddies in the Sacramento Valley region in California, where rainfall is low and unevenly distributed, emitted 32% more N_2O but 40% less CH_4 than the Mid-South regions. Nevertheless, it is important to note that our model's configuration of the paddy flooding state before grain filling somewhat overlooks the rise in N_2O emissions due to frequent dry and wet soil fluctuations. Consequently, the model results do not fully reflect the higher N_2O emissions observed in California paddies. However, our simulation results still showed that the ongoing rise in climatic warming and variable precipitation patterns in U.S. rice paddies since 1960 (You et al., 2024) indicate a positive response of net GHG emissions to climate change, contributing to a 20.7% increase in soil N_2O emissions and a 10.2% rise in soil CO_2 release, alongside a 3.8% increase in soil CH_4 emissions during the 2010s. Similar positive responses have been documented in other studies (Guo et al., 2023; Liu et al., 2020). For example, a global meta-analysis by Liu et al. (2020) found that experimental warming of approximately 1.5°C in rice paddies accelerated SOC decomposition by 12.9% and stimulated N_2O emissions by 35.2%.

In our investigation, the enrichment of atmospheric CO_2 concentration has led to a 31.4% increase in net soil GHG emissions annually across global rice fields from the 1960s to the 2010s (Figure 4). Elevated CO_2 levels are known to promote belowground carbon production, which both improves organic carbon change and provides a heightened substrate for (de)nitrification and methanogens' activity (Allen et al., 2003; Jackson et al., 2009; Pregitzer et al., 2008; Zak et al., 2000). Similar to the findings of others (Bai et al., 2023; Shen et al., 2023), our study found that the enrichment of atmospheric CO_2 concentration improved SOC change by 51.8% but exacerbated soil CH_4 emissions by 41.5%. Field observations have corroborated these findings, demonstrating that rice fields subjected to free-air CO_2 enrichment experiments exhibited significantly higher CH_4 production and N_2O emissions compared to those under ambient conditions (Dijkstra et al., 2012; Inubushi et al., 2003). Chen et al. (2013) identified an increasing trend in CH_4 emissions from rice fields in China attributed to elevated atmospheric CO_2 concentrations. A meta-analysis of data on the effect of elevated CO_2 on CH_4 emissions highlighted that CO_2 enrichment could enhance CH_4 emissions in rice fields by 43.4% (van Groenigen et al., 2011).

During the study period, U.S. N deposition exhibited an upward trend, increasing at a rate of 0.04 kg N ha^{-1} yr^{-1} (You et al., 2024). The stimulative impact of N deposition on CH_4 emission in this study is notably constrained within environments characterized by high nitrogen fertilizer levels (Figure 6a). Similar findings of the positive impact of heightened N deposition on net GHG emissions have been documented in other studies (Xu et al., 2020; Yang et al., 2021). This effect arises from the increased availability of nitrogen, which can foster processes like nitrification and denitrification, consequently leading to heightened N_2O emissions. Additionally, nitrogen addition can bolster crop growth, providing more carbon substrate for microbial activity, thereby stimulating CH_4 emissions and SOC change (B. Zhang et al., 2016; H. Zhang et al., 2016).

4.3. Impacts of Agricultural Management Practices on Net GHG Balance

Numerous field investigations and meta-analyses have provided evidence that intensified agricultural management practices significantly exacerbate soil GHG emissions in croplands (Bai et al., 2019; Bo et al., 2022; Cui et al., 2013; Davidson, 2009; Dutta et al., 2023; Gupta et al., 2021; Lu et al., 2021; Reay et al., 2012). However, these practices also hold the potential to confer advantages for SOC change in croplands due to their substantial mitigation benefits, cost-effectiveness, and additional positive outcomes such as improved soil and water quality and preservation of biodiversity (Fargione et al., 2018; Li et al., 2022). For example, the increased application of synthetic N fertilizer not only directly supplements nitrogen, thereby contributing to N_2O emissions, but also stimulates higher litter input, increased root biomass, and greater root exudation, providing carbon substrates for methanogens and stimulating CH_4 production (B. Zhang et al., 2016; H. Zhang et al., 2016). In this study, it has been identified as the primary driver promoting non-CO_2 GHG emissions (with a 46.4% increase in CH_4 emissions and a 56.6% increase in N_2O emissions) and enhancing SOC change by 63.2% (Figures 6a and 6b). Similar findings have been reported in other studies (Crutzen et al., 2016; Cui et al., 2013; Galloway et al., 2008; Gao et al., 2018; Gerber et al., 2016; Grassini & Cassman, 2012; Li et al., 2022; Lu et al., 2021; Reay et al., 2012; Van Groenigen et al., 2010). Furthermore, excessive application of N fertilizer can lead to detrimental effects on soil structure, resulting in increased bulk density, reduced porosity, altered soil pH, and decreased or imbalanced nutrient content. This can also lead to a reduction in the number of beneficial microorganisms, ultimately resulting in a surge of N_2O and CH_4 emissions and a slowdown or even reversal of SOC change (Cui et al., 2021; Liu & Greaver, 2009; Zaehle et al., 2011; J. Zhang et al., 2020). For instance, the application of more than 200 kg ha^{-1} of N fertilizer induced a 90.4% increase in N_2O emissions in U.S. rice paddies and a 1.97-fold increase globally, while SOC change showed only a marginal increase compared to the 100–200 kg ha^{-1} N fertilizer application (see Figure S2 in Supporting Information S1). Optimizing N fertilizer use rates is an imminent need for achieving maximum benefits, enhancing SOC change, improving crop yields, and curbing non-CO_2 GHG emissions (Gerber et al., 2016; Xia et al., 2017). In addition to decreasing the amount of N fertilizer applied, changing the timing of N fertilizer application and deep fertilization can also improve N use efficiency and decrease GHG emissions (X. Chen et al., 2014; Cui et al., 2013; Ju et al., 2009; Xia et al., 2017).

The influence of manure change (increased by 13.2% by the 2010s based on about 1,227 Ton in the 1960s) was particularly pronounced in this study, especially concerning CH_4 production (which increased by 26.2%) and SOC change (rising by 32.2%). This effect can be attributed to the introduction of carbon-rich substrates through humus input, which in turn stimulates microbial growth, metabolic processes, and methane-producing microbial activity. Consequently, this leads to a substantial rise in SOC content and CH_4 production (Amon et al., 2001). The carbon-nitrogen ratio present in manure plays a role in shaping N_2O emissions by impacting microbial nitrogen processes, leading to an increase in (de)nitrification (Davidson, 2009). However, this contribution is considerably less significant compared to synthetic N fertilizer. For instance, in our study, manure only contributed to a 0.2% increase in soil N_2O emissions in U.S. rice paddies in the 2010s (see Figure 6b). In comparison to synthetic N fertilizer, manure stimulates microorganisms to assimilate more ammonium nitrogen into the active organic nitrogen pool in the soil. Our study revealed that in soils treated with both synthetic N fertilizer and manure, SOC stock was 9.2% higher than in soils treated with synthetic N fertilizer alone (see Figure S3 in Supporting Information S1). Moreover, it is important to note that regardless of whether synthetic N fertilizer or manure is applied, exceeding the carbon and nitrogen demands of crops and soil microorganisms can lead to a significant decline in the cumulative effect of SOC. For example, in the case of manure application, SOC density in soils with 100–200 kg N ha^{-1} increased by 14.2% compared to soils with less than 100 kg N ha^{-1} of manure application. However, the increase was only 1.4% when manure application levels exceeded 200 kg N ha^{-1} (Figure S3 in Supporting Information S1).

Our factorial analysis revealed that enhanced tillage practices significantly contributed to an increase in soil CO_2 release by 6.1%, a finding consistent with other studies conducted in the U.S. (Bai et al., 2019; Dutta et al., 2023). This effect can likely be attributed to the fact that tillage disrupts the soil, accelerating the rate of decomposition of soil organic matter (Bai et al., 2019; Mishra et al., 2010; Olson et al., 2014; Salinas-Garcia et al., 1997) and diminishing the biomass of fungi and earthworms (Briones & Schmidt, 2017; Lavelle et al., 1999). Consequently, this disruption leads to a reduction in the stabilization of SOC. Furthermore, the disturbance caused by tillage introduces more oxygen into the soil, temporarily altering the anaerobic environment. As a result, CH_4 emissions reduced by 1.8%, while N_2O emissions increased by 2.2% in the 2010s, as observed in this study (see Figures 6a and 6b). This insight is also reflected in one of our study's findings, illustrated in Figure 8. Comparing it to conventional tillage, the adoption of no-tillage or reduced tillage practices yielded an approximately 27% increase in SOC change. However, it also led to a 12.7% increase in CH_4 emissions and a 9.2% reduction in N_2O emissions.

Apart from fertilization, CH_4 emissions in rice paddies are primarily influenced by water management (Nayak et al., 2015; Shang et al., 2011; Wassmann et al., 2000; B. Zhang et al., 2016; H. Zhang et al., 2016). Conventional continuous irrigation practices intensified soil CH_4 emissions by around 19% in U.S. rice paddies during the 2010s (Figures 6a and 6b), aligning with similar findings from other studies (Bo et al., 2022; Gupta et al., 2021). A strategy like non-continuous irrigation (e.g., midseason drainage and intermittent irrigation) has been proposed to decrease CH_4 emissions (Cheng et al., 2015; Ma et al., 2013; Nayak et al., 2015; Wassmann et al., 2000; B. Zhang et al., 2016; H. Zhang et al., 2016; Zou et al., 2005) by promoting aerobic soil conditions and reducing CH_4 production from paddy fields by 36%–65% (Ma et al., 2013; Runkle et al., 2018; Zou et al., 2005). Our research revealed that non-continuous irrigation in U.S. rice paddies led to a substantial reduction of 51.8% in soil CH_4 emissions compared to continuous irrigation (Figure 10a). However, it is important to note that these measures often involve a trade-off between CH_4 and N_2O emissions (Ma et al., 2013; Wassmann et al., 2000; Zou et al., 2005). For instance, the reduction in CH_4 emissions through midseason drainage is partly offset by increased N_2O emissions, offsetting 49.2%–67.6% of CH_4 reduction (Zou et al., 2005). Our extensive meta-analysis revealed that this offset was 4.9% in global and 0.2% in U.S. rice paddies, respectively (Figures 10a and 10b). However, the impact of non-continuous irrigation can vary widely based on environmental and management factors, as previously documented (Carrijo et al., 2017; Jiang et al., 2019; Liu et al., 2019). Our research demonstrates that the disparity in CH_4 and N_2O emissions between continuous and non-continuous irrigation practices in rice fields becomes more pronounced with higher synthetic N fertilizer application rates. When the application of synthetic N fertilizer surpasses 200 kg ha^{-1}, the adoption of non-continuous irrigation concurrently leads to a reduction in CH_4 emissions by roughly 48% relative to continuous irrigation, while N_2O emissions experience a corresponding increase of approximately 80% (Figure S4 in Supporting Information S1). This effect of non-continuous irrigation translates to a 90% enhancement in CH_4 emissions mitigation and a substantial 4.2-fold escalation in N_2O emissions compared to scenarios with synthetic N fertilizer application below 100 kg ha^{-1}.

Overall, the adoption of non-continuous irrigation has led to a reduction in soil non-CO_2 GHG emissions by 39.2% globally and 50.6% on average in the U.S according to the meta-analysis findings, with improving U.S. rice yield by 12.0% by enhancing soil health, promoting root development, reducing pests and diseases, increasing water efficiency, and improving nitrogen utilization (Bo et al., 2022; B. Zhang et al., 2016; H. Zhang et al., 2016). Thus, it is clear that non-continuous irrigation practice is an effective strategy for emission reduction. A notable instance of this was seen in California, where the prevalent use of more water-efficient irrigation techniques results in non-CO_2 GHG emissions being approximately 39% lower and rice yield 29% higher compared to Mississippi, which typically adopts traditional continuous irrigation.

4.4. Uncertainty and Future Work

We have assessed the uncertainty in the modeled net GHG balance caused by model parameters. However, other sources of uncertainty require attention and improvement to enhance estimates. First, there could be uncertainties introduced by the model forcing data sets. For instance, the crop-specific N fertilization data used to drive DLEM v4.0 was reconstructed from state-level surveys, which may need to accurately reflect the actual spatial variations in fertilizer use in magnitude and timing that may amplify the nitrogen fertilizer induced N_2O emission (Ma et al., 2010; You et al., 2022). Additionally, tillage intensity data are only available for recent decades, which could also introduce uncertainties (Lu et al., 2022). Thus, collaborative efforts within the scientific community are vital to improve the quality of model-forcing data sets. Second, under-representing some processes in DLEM v4.0 could also result in simulation biases. For instance, our model's representation of irrigation practices (without alternate wetting and drying) is relatively simple conventional continuous irrigation (You et al., 2022), leading to little simulated soil moisture that could impact GHG emission predictions (Bo et al., 2022; Gupta et al., 2021), especially for soil N_2O emissions estimation in California. Our meta-analysis revealed that non-continuous irrigation in U.S. rice paddies led to a substantial increase of 5.6% in soil N_2O emissions compared to continuous irrigation (Figure 10b). Specifically, the simulated soil N_2O emissions in California by DLEM v4.0 was approximately 47% lower than that in the meta-analysis (Figure 3). However, soil CH_4 emission was overestimated by about 15% relative to the meta-analysis results (Figure 3). These discrepancies may cause an overestimation or underestimation of total non-CO_2 GHG emissions in the U.S. rice paddies. Last, the lack of spatialized data on rice straw return practice, cover crop practice, ratoon cropping, biochar application, and other fallow-season practices, which can alter (de)nitrification processes and soil carbon source substrate that microbes depend on to survive, thus could have biased simulation results (Bai et al., 2019; Zou et al., 2005). This may be the reason for the low emulation of a net GHG emissions in Texas (Figure 4), which is not widely used in the current model of ratoon cropping and other fallow management measures.

Addressing these limitations will lead to more accurate estimates in estimates in future work. Despite some remaining uncertainties, we believe that any resulting biases would not significantly alter our main conclusions, as our simulated results are corroborated by a meta-analysis of numerous site experiments. Our results reveal that mitigation strategies for net soil GHG emissions in U.S. rice paddies can be centered on optimizing soil water management practices, including irrigation and drainage, along with optimal synthetic nitrogen and manure fertilization (Cui et al., 2018; Tilman et al., 2002, 2011). Future research should focus on perfecting high-precision and long-term data on agricultural management practices and their representation in models to incentivize best practices.

5. Conclusion

Using a comprehensive model-data integration approach, we conducted a state-of-the-art estimate of the spatiotemporal variations of the net soil GHG emission in U.S. rice paddies from 1960 to 2018. Results indicated that U.S. rice paddy was a growing net GHG emissions source (from 3.7 ± 1.2 Tg CO_2eq yr^{-1} in the 1960s to 8.9 ± 2.7 Tg CO_2eq yr^{-1} in the 2010s). Notably, however, the net soil GHG emissions per unit of grain exhibited a substantial decline over the study period, reaching 0.84 ± 0.18 kg CO_2eq kg^{-1} in the 2010s. This emphasizes an increasingly efficient rice production process marked by reduced GHG emissions. Soil CH_4 and N_2O emissions strongly contributed to net GHG emission growth by about 114% and 2% of total annual net soil GHG emissions in the 2010s, respectively, whereas soil CO_2 uptake limited GHG emission growth by about 16%. The intensification of rice cultivation area, synthetic N fertilizer usage and the application of manure, coupled with the elevation in atmospheric CO_2 concentration, emerged as the primary drivers behind the escalation in net soil GHG emissions. These factors significantly outweighed the compensating effect of their soil carbon change. Our study underscores the potential for optimizing fertilizer efficiency to effectively curtail net GHG emissions per yield, especially when combined with conventional tillage rather than reduced tillage. Nevertheless, addressing the intricate balance between soil CH_4 and N_2O emissions necessitates strategic interventions, such as optimal intermittent irrigation practices, which could mitigate around 50.6% and 39.2% of soil non-CO_2 GHG emissions on U.S. and global average, respectively. Besides, striving for a harmonious equilibrium between food security and ecological sustainability, mitigation strategies could concentrate on refining fertilizer applications alongside improved management techniques like biochar application, straw return, and other fallow-season practices and the selection of climate-resilient crop varieties. Such measures have the potential to create synergistic benefits by simultaneously reducing net GHG emissions and enhancing overall productivity.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in this study are publicly available. Daily climate data during the period 1901–2018 derived from the Climate Research Unit-National Center for Environmental Prediction (CRUNCEP) 6-hourly climate data sets is available at https://rda.ucar.edu/datasets/ds314.3/ (Viovy, 2018). Monthly atmospheric CO_2 concentration data from 1900 to 2018 were obtained from the NOAA GLOBALVIEW-CO_2 data set derived from atmospheric and ice core measurements at https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_gl.txt. The N fertilizer use maps and the crop-specific N fertilizer use maps reconstructed are publicly available at https://doi.org/10.1594/PANGAEA.883585 (Cao et al., 2017). The gridded data sets of manure N production and application in the contiguous U.S. are available at https://doi.org/10.1594/PANGAEA.919937 (Bian et al., 2020). The annual tillage intensity map from 1960 to 2018 was reconstructed from the county-scale tillage practices survey data (1989–2011) obtained from the National Crop Residue Management Survey (CRM) of the Conservation Technology Information Center at https://www.ctic.org/CRM. All result data in this study are publicly available via https://doi.org/10.6084/m9.figshare.24152160.v1 (Zhang & Tian, 2023).

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