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Co-benefits for net carbon emissions and rice yields through improved management of organic nitrogen and water

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Abstract

Returning organic nutrient sources (e.g., straw and manure) to rice fields is inevitable for coupling crop-livestock production. However, an accurate estimate of net carbon (C) emissions and strategies to mitigate the abundant methane (CH_4) emission from rice fields supplied with organic sources remain unclear. Here, using machine learning and a global dataset, we scaled the field findings up to worldwide rice fields to reconcile rice yields and net C emissions. An optimal organic nitrogen (N) management (OPTM) was developed considering total N input, type of organic N source, and organic N proportion. A combination of OPTM with intermittent flooding achieved a 21% reduction in net global warming potential and a 9% rise in global rice production compared with the business-as-usual scenario. Our study provides a solution for recycling organic N sources towards a more productive, carbon neutral and sustainable rice-livestock production system on a global scale.

Introduction

Agricultural organic residues (e.g., manure and crop straw) represent a large source of nitrogen (N). Globally, the average annual livestock manure N produced amounts to 130 Tg N, which is equivalent to the annual consumption of synthetic N fertilizer[1]. Recycling organic N sources in agroecosystems is crucial for keeping food systems within the planetary boundaries[2]. The majority of studies on recycling organic N sources focused in upland or rangeland crop production systems[3, 4]. Although organic N sources greatly increase soil organic carbon (SOC), they can lead to a significant methane (CH_4) emission[5]. The management of organic N sources to achieve high rice yield and carbon (C) neutrality remains a great challenge. Recent studies have underscored the need for sustainable rice production through improved resource-use efficiencies[6]. However, these studies have not addressed the challenge of C neutrality of rice production. Thus, it is imperative to explore appropriate management of organic N sources for sustainable, C neutral rice production on a global scale.

The net C emissions, based on the metrics of global warming potential (GWP), net GWP, and net GWP intensity (NGWPI), is a measure of the collective changes in soil nitrous oxide (N_2O), CH_4, and SOC[7], reflecting a balance between the emission of greenhouse gases (GHGs) and SOC sequestration. It is widely recognized that the application of organic N improves SOC sequestration[8, 9], with a concomitant drop in N_2O emission from rice fields[10]. However, it remarkably increases, up to 87% in some instances, methane emission from rice fields[11]. The growing concerns about the mitigation of CH_4 emission from rice fields led to a focus on water management, as the water regime regulates the soil redox conditions and thereby CH_4 emission[12]. Some studies have shown that intermittent flooding, i.e., alternate wetting-drying practice, mitigates CH_4 emission substantially[12], but it may accelerate N_2O emission and SOC decomposition rate[13]. Thus, individual management practices, such as application of organic N fertilizer or intermittent flooding, generally results in trade-offs between SOC sequestration and CH_4 and N_2O emission[13, 14]. Considering the magnitude of CH_4 emission from rice fields, the potential GHG savings (CO_2-eq) via reduced CH_4 emission through C budget-based management innovations may offset increased N_2O emission and SOC decomposition[13]. However, accurate global net C emissions for rice production under combined organic N source application and water management is poorly understood.

Numerous studies have endorsed the partial substitution of synthetic N fertilizer with organic N sources to improve rice yield[15, 16]. For example, the combined application of organic and synthetic N fertilizers increased rice yield by 11-13% compared with synthetic N fertilization alone[17], whereas a complete organic N fertilization may adversely affect crop yield[18, 19]. Therefore, a partial substitution of synthetic N fertilizer with organic N sources is crucial for maintaining (or even increasing) rice yield whilst minimizing net C emissions. Rice N fertilization rates vary greatly worldwide. For instance, excessive N use for rice production is commonplace in China, while N fertilization in Africa is seriously inadequate to maintain rice productivity and soil fertility[20, 21]. Two N-based organic source management practices, i.e., partial substitution of synthetic N with organic N source (SN) and the extra addition of organic N source to synthetic N (AN), are commonly adopted in rice production. Compared with just synthetic N fertilization, the SN provides the same amount of total N through a combination of organic and synthetic N sources resulting in less synthetic N input, while AN provides greater total N than that of synthetic N[22]. It is therefore essential to establish an optimal organic N management (OPTM) based on AN or SN option for increasing rice yield and concurrently reducing net C emissions in different regions worldwide.

In this study, we scaled the field findings up using machine learning to reconcile rice yields and net C emissions. A dataset comprised of 4654 observations was analyzed to determine the effects of organic N (i.e., type of organic N sources and proportions) and water management (i.e., conventional flooding and intermittent flooding) on yield, CH_4 emission, N_2O emission and SOC using hierarchical mixed-effect meta-analysis. After a comprehensive consideration of rice yield and various aspects of net C emissions with an emphasis on rice yield improvement, appropriate type of organic N source and proportion and water management were determined for AN and SN. The Random Forest models were used to scale up appropriate organic N and water management for rice fields worldwide. We quantified the potential rice production and net C emissions under integrated OPTM and intermittent flooding for different regions. Finally, region-specific optimal use of synthetic N and organic N was predicted.

Results

Specific organic N proportion and type of organic N source

Our analysis shows that rice yield was significantly influenced by the proportion of organic N (defined by organic N to total N input in SN, and organic N to synthetic N input in AN, respectively) (Fig. 1). Overall, the rice yield was rarely changed in SN compared with synthetic N fertilization alone. SN improved rice yield when it had a low organic N ratio (organic N: total N ≤ 25%), with no further yield gain at higher organic N: total N ratios (Fig. 1a). Indeed, the yield declined when the organic N: total N ratio was > 75% (lnRR = -0.09, Fig. 1a). In AN, rice yield was increased under different ratios of organic N to synthetic N, and the yield gain tended to be lower at high organic N ratio (> 75%) compared with other ratios (Fig. 1e, Extented Data Table 1). Thus, SN with low organic N ratio (≤ 25%) and most AN applications (namely low, low-medium, and medium-high organic N: synthetic N; more details in Methods) did increase rice yield. As for the type of organic N source, mixed-source organic N produced greater average yield (lnRR = 0.07) relative to a single-source animal-derived or plant-derived organic N in AN (Extented Fig. 1e) but the difference was not statistically significant (Extented Data Table 1). This suggests that, to improve rice yield, a mixed-source of organic N was preferable for AN, while no such source preference was evident for organic N in SN (Extented Figs. 1a and e).

The CH_4 emissions from rice fields under SN (lnRR = 0.52) and AN (lnRR = 0.76) were greater than those fertilized with synthetic N alone (Figs. 1b and f), which may be due to the exogenous C input from organic N source (Extented Fig. 2l). The organic N ratio did not alter CH_4 emission in SN significantly, but higher organic N ratios did increase CH_4 emission in AN (Fig. 1f; $Q_M = 11.9$, $P = 0.008$, Extented Data Table 1), suggesting a lower organic N ratio is required to reduce CH_4 emission. Among types of organic N source, the plant-derived organic N resulted in greater CH_4 emissions in both SN (lnRR = 0.68) and AN (lnRR = 0.79) (Extented Figs. 1b and f), making it less effective in reducing CH_4 emission in both SN and AN. The N_2O emission declined with increasing organic N ratio in SN, and N_2O emission was significantly lower than that from synthetic N fertilization when the ratio of organic N to total N input was > 75% (Fig. 1c). Furthermore, a negative correlation was observed between the effect size of N_2O emission and organic C input (Extented Fig. 3g). For AN, a low organic N ratio and plant-derived organic N significantly decreased N_2O emission compared with synthetic N fertilization alone (Fig. 1g and Extented Fig. 1g). In general, the SOC was increased with organic N source additions relative to synthetic N fertilization (lnRR = 0.12 for AN and lnRR = 0.14 for SN) (Figs. 1d and h), and it increased with higher organic N ratios in AN (Fig. 1h; $Q_M = 27.7$, $P < 0.0001$, Extented Data Table 1), under which condition the effect size of SOC increased logarithmically with organic C input under AN (Extented Fig. 3o). In brief, a low organic N ratio using animal-derived organic N source for SN and a low-medium organic N ratio with mixed-source organic N for AN are the most appropriate N options for higher rice yield with lower net C emissions.

Potential global rice yield and net C emissions with OPTM

Random Forest models were used to determine spatial patterns of change in rice yield,

CH_4 and N_2O emission, and SOC content on a global scale. When worldwide adoption of SN for rice production was modelled, rice yield was decreased by 5% globally (Figs. 2a and m) except for East Asia and South Asia. A marked reduction in rice yield, ca. 20%, was observed in Africa and Latin America with SN (Fig. 2a), indicating that SN is not suitable for those areas (Extented Data Table 2). However, rice yield was increased by 8% on average with AN management (Fig. 2e), but it would exacerbate environmental pollution without a reduction in synthetic N use. The OPTM referred to as SN was replaced by AN in some grid cells where SN resulted in negative response ratio of rice yield. As such, the global average rice yield was increased by 7% in OPTM compared with synthetic N fertilization alone (Figs. 2i and m), implying that OPTM could be recommended for achieving high rice yield with minimized synthetic N input on a global scale.

The organic N application has increased CH_4 emission, regardless of management strategy (Figs. 2b, f, j, and n). Rice fields emitted more CH_4 from AN compared with SN, which might be attributed to greater organic C input in AN, as indicated by the positive correlation between the effect sizes of CH_4 emission and organic C input (Extented Fig. 2l). In comparison with AN, OPTM resulted in lower CH_4 emission, notably in East Asia and South Asia (Figs. 2f and j). Yet, OPTM resulted in 72% more CH_4 emission than synthetic N fertilization globally, which necessitates further measures to reduce CH_4 emission.

The inclusion of organic N sources, however, decreased N_2O emission, which varied greatly among SN, AN, and OPTM. Compared to AN and OPTM, N_2O emission was much lower in SN (Figs. 2c, g, k, and o). Also, in general, application of organic N source increased SOC in rice fields globally (Figs. 2d, h, l, and p). The mean SOC concentration was increased by 18% in SN, 17% in AN, and 16% in OPTM relative to synthetic N fertilization, respectively. Regions with the most marked changes in SOC were in north China under SN and AN (Figs. 2d and h). The OPTM could also substantially increase SOC in both China and India (Figs. 2l and p).

Compared with synthetic N fertilization alone, the OPTM increased GWP by 2256 kg CO_2-eq ha^{-1} per cropping potential (Table 1). The net GWP was higher for OPTM than synthetic N fertilization alone, indicating that the effect of decreased N_2O emission and the increased SOC sequestration could not fully offset the increased CH_4 emission in OPTM. Yet, it is important to note that the net GWP intensity was similar between OPTM (858 kg CO_2-eq Mg^{-1} grain) and synthetic N fertilization alone (832 kg CO_2-eq Mg^{-1} grain), which was mainly attributed to higher rice yield in the OPTM (Table 1).

Intermittent flooding reduced CH_4 emission

In the context of organic N fertilizer use in rice production, intermittent flooding could improve rice yield relative to conventional flooding by 294 kg ha^{-1} (Fig. 3a). Moreover, intermittent flooding substantially decreased CH_4 emission, as much as 54 kg C ha^{-1} per cropping season (Fig. 3b), without increasing N_2O emissions (Fig. 3c). Also, intermittent flooding did not decrease SOC sequestration compared with conventional flooding (Fig. 3d). These results imply that intermittent flooding is a promising strategy towards the dual goal of high rice yield and low C emission under organic N fertilizer application.

The global CH_4 emission from rice cultivation was significantly lower under OPTM with intermittent flooding than that of OPTM with conventional flooding (by an average of 58 kg C ha^{-1} per cropping season, Fig. 4j) based on the simulation by the Random Forest model. Notably, there was a marked decrease in CH_4 emission in China, up to 124 kg C ha^{-1} per cropping season (Figs. 4b and f; Table 2); so it is imperative to adopt intermittent flooding when organic N sources are used in China. Overall, global N_2O emissions were similar under integrated OPTM and intermittent flooding (Figs. 4c, g, and k). In addition, there were no significant changes in rice yield (Figs. 4a, e, and i) and SOC sequestration (Figs. 4d, h, and l) with OPTM between conventional flooding and intermittent flooding.

The apparent GWP under the integrated OPTM and intermittent flooding (5507 kg CO_2-eq ha^{-1} per cropping season) was similar to that of business-as-usual scenario (BAU) (5183 kg CO_2-eq ha^{-1} per cropping season; Fig. 5g). East Asia and North India were the hotspots of GWP under BAU, and their GWP was substantially decreased under the integrated OPTM and intermittent flooding (Figs. 5a, d, and g). In comparison with BAU, the net GWP was notably decreased by 1050 CO_2-eq ha^{-1} per cropping season (Figs. 5b, e, and h), and the NGWPI was lowered by 176 kg CO_2-eq Mg^{-1} grain (Figs. 5c, f, and i) under the integrated OPTM and intermittent flooding. These results indicate that the increased GWP occurring with organic N sources can be mitigated through decreased C emission by adopting integrated OPTM and intermittent flooding.

Implementation of integrated organic N and water management

The organic N sources are applied as base fertilizers before rice transplanting. During the early growth stage, the flooding is needed to re-establish and rejuvenate transplanted seedlings. From the tillering stage to harvesting stage, intermittent flooding was implemented to reduce CH_4 emission by promoting methanotrophs and inhibiting methanogenesis. The scenario analyses from Radom Forest models showed that, in comparison with BAU, integrated OPTM and intermittent flooding increased global rice production by 9%, i.e., up to 824 Tg yr^{-1} (Fig. 6a). In Africa, rice production was increased by approximately 25% by integrated OPTM and intermittent flooding, and China's rice production was increased by 13%, which is 27 Tg yr^{-1} more than the current production. Further, integrated OPTM and intermittent flooding significantly decreased total net GWP by 21% (Fig. 6b). Integrated OPTM and intermittent flooding in China's rice production could play an important role in mitigating the net GWP from rice fields at global level, i.e., the net GWP can be decreased from 185 Tg CO_2-eq yr^{-1} to 83 Tg CO_2-eq yr^{-1} (Fig. 6b). Similarly, India's rice production decreased net GWP by 19% compared with BAU. Moreover, OPTM could reduce global synthetic N consumption by 23% in rice production with an increased annual organic N source consumption of 5.48 Tg N yr^{-1} (Fig. 6c), implying the practicality of substituting synthetic N with organic N sources for global rice production.

Different OPTM strategies are applicable in different countries or regions because of their distinct N fertilization practices (Extented Data Table 2). China, India, and Africa account for 57% of global rice production, and they may need to adopt different OPTM strategies because of their contrasting nutrient availabilities. In China, 90% of the rice-producing areas were best suited to adopt SN to increase rice yield, with only

10% of the area being suitable for AN. As for India, 65% of rice cultivation could adopt SN with the remaining needing more N fertilization. In Africa, most of the rice-producing area should adopt AN, and only 2% of the area could use SN to increase rice yield. Intermittent flooding is not harmful to rice yield under OPTM, since the rice yield was secured in China (8153 kg ha^{-1}), India (5536 kg ha^{-1}), and Africa (5023 kg ha^{-1}) (Table 2). More importantly, intermittent flooding can substantially decease CH_4 emission under OPTM. For instance, the CH_4 emission was decreased from 278 kg C ha^{-1} under integrated OPTM and conventional flooding to 154 kg C ha^{-1} under integrated OPTM and intermittent flooding in China. As a result, the net GWP and NGWPI were substantially decreased in China, India, and Africa under integrated OPTM and intermittent flooding compared with BAU or integrated OPTM and conventional flooding. These results further confirm the potential of integrated OPTM and intermittent flooding for securing sufficient rice production whilst minimizing net GHG emission across extensive rice-producing areas globally.

Discussion

Although substantial CH_4 emissions with the application of organic N sources in rice production have been widely reported[11, 23], an accurate net C emissions that considers CH_4 and N_2O emission, and SOC sequestration, was lacking[6, 24]. Here we found that the increase in SOC sequestration and the decrease in N_2O emission cannot fully offset the massive CH_4 emission under organic N application in conventionally flooded fields. Indeed, organic N fertilization results in higher net GWP compared with synthetic N fertilization. However, intermittent flooding, as an effective water management strategy, improved rice yield and further lowered CH_4 emissions. This study demonstrated that the co-benefits of reduced net C emission and increased rice yield globally can be achieved by region-specific integrated organic N source with intermittent flooding. Thus, we identified a feasible approach for recycling organic N sources in rice fields with a win-win outcome for rice production and net C emission reduction.

Enhanced rice production. Although numerous site-specific studies have shown that appropriate combinations of synthetic and organic N fertilizers can increase rice yield by 6%–30% compared with synthetic N fertilization alone[15, 16], here we found that an integrated OPTM and intermittent flooding can increase global rice production by 9% with reduced net C emissions compared to BAU without expanding crop production area. The increase in rice production (69 Tg yr^{-1}) would satisfy the amount of rice needed to feed 0.57 billion people annually[25], contributing to 60% of the additional demand for global rice production by 2035 (116 Tg)[26]. Global rice production would be increased by 32% as rice productivity could rise up to 75% of the yield potential[6] once new rice cultivars, advanced nutrient management, and pest control technologies were integrated[27]. Here, we highlight that the nature-based solutions, i.e., use of appropriate organic N source and water management can contribute significantly to achieve global food security, as the projected 9% growth in rice production on the same land area decreases nearly one third of the exploitable yield gap globally. The solution provided by this study is different from the practice of organic N fertilization alone as it has resulted in recurrent crop failure. The combined use of organic N and synthetic N fertilization is better able to meet the N demand for rice growth compared with organic fertilization alone, because the synthetic N supplies available N at a time when the crop needs such as during rapid tillering at the early growth stage. Whereas, organic sources can increase soil N retention that gradually release N with time, ensuring adequate N supply at rice anthesis and grain filling stages[28]. The application of organic N source also improves soil aggregation, soil porosity, and nutrient cycling and availability (calcium, magnesium and micronutrients), which promote rice growth and yield[29].

Based on our analyses, rice yield increases differently in different regions with OPTM (Table 2). There is a great potential to increase rice yield on the basis of the current lower yield level in Africa (with just 20%-40% of the yield potential)[6], where yield can be increased by >20% compared with BAU. Importantly, although China's current rice production is now 75%-80% of its biophysical potential[27], a further increase in rice production is plausible (ca. 10% of rice yield) through adoption of OPTM and intermittent flooding, particularly for the double-rice systems[27]. Hence, there is a need to prioritize integrated OPTM and intermittent flooding to achieve rice self-sufficiency in China.

Favourable C budget. The CH_4 emission is the principal obstacle for C neutral budgets in rice, and we have shown that increased SOC did not offset the increased CH_4 emission under organic N inputs without intermittent flooding. The CH_4 emission from rice fields accounts for ca. 10% of total anthropogenic CH_4 emissions[30]. The application of organic N source without intermittent flooding increases CH_4 emission by 72% which will clearly endanger the international efforts to limit global warming to 1.5°C. However, integrated OPTM and intermittent flooding substantially decreased CH_4 emissions. This would reduce the annual net GWP by 110 Tg CO_2-eq from global rice fields, representing 4% of integral mitigation targets (2759 Tg CO_2-eq, baseline 2017) by 2050[31]. This potential reduction in net GWP from rice production is considerable given the current increase of 500 Tg CO_2-eq year^{-1} globally[32]. The likely mechanism explaining the observed reduction in CH_4 emission is that alternate wetting-drying cycles can alleviate the continuous anaerobic condition resulting in decreased CH_4 emission[33, 34]. The production of CH_4 generally occurs with low redox condition, but the intermittent flooding substantially lifts redox potential and consequently reduces CH_4 production. Moreover, the increased diffusion of O_2 with the intermittent flooding also facilitates methanotrophic processes[35].

A favourable C budget for rice fields was also the result of increased SOC sequestration and reduced N_2O emission. Our projection showed an average SOC sequestration rate of 0.51-0.56 Mg C ha^{-1} per rice crop cycle with OPTM (Fig. 4), which was similar to the experimental outcomes of a long-term field study with double-rice systems (1.14-1.36 Mg C ha^{-1} yr^{-1})[36]. SOC sequestration rate is lower in rice fields than in upland (0.13 *vs.* 0.25 kg C per kg C input ha^{-1} yr^{-1})[29], which may be due to a higher initial SOC concentration[8, 9] and faster decomposition of organic inputs with changing soil conditions[37]. Nevertheless, flooded rice production systems play a key role in sequestering C, as they carry a high proportion of global SOC stock relative to other croplands[14]. In line with previous studies[9], the organic N inputs tended to have lower N_2O emission than synthetic N fertilizer (Figs. 1c and g), which might be attributed to the low inorganic N content and high C:N ratio of mixed-source organic N fertilizers (C:N ratio = 20). Organic fertilizers with a high C:N ratio promote microbial N immobilization, resulting in less substrates to produce N_2O[38]. Although organic N source application with animal manure can increase N_2O emission in uplands[19], the anaerobic rice fields should facilitate complete denitrification from nitrate to dinitrogen[39]. Although intermittent flooding is effective in reducing C emissions in rice fields using organic N sources, water management alone will have a limited effect on C neutrality because the decreased CH_4 emission (CO_2-eq) was partially offset by the increased N_2O emission (CO_2-eq) and reduced SOC sequestration[13]. Therefore, an improved management of integrated OPTM and intermittent flooding is integral to achieve the favourable net C emission.

The application of organic N sources should consider current conventional practices, since large variations for N rates exist in different countries or regions, as seen in China (~ 220 kg N ha^{-1}), India (~ 90 kg N ha^{-1}) and Africa (~ 50 kg N ha^{-1}). The SN management is suitable for China while the African rice production will be most benefitted with AN management (Extented Data Table 2). Appropriate specific organic N fertilization is important for different countries or regions. Less synthetic N fertilization can accrue rice production and attenuate environmental pollutions in intensive Chinese rice production systems. In contrast, SN would decrease rice yield in Africa because the rice yield is mainly limited by insufficient N input (N < 50 kg N ha^{-1})[21]. In Africa, AN instead of SN should be encouraged to produce greater rice yield, and contributes to ‘Zero Hunger’, a key sustainable development goal proposed by the United Nations[40].

Limitations and implications. The uncertainty of results reported here may come from the lack of practical measurements in some regions, such as the few observations of CH_4 and N_2O emissions reported in Africa. Therefore, more site-specific measurements of soil C emission in Africa are needed to improve the accuracy of prediction. Climate change, particularly global warming, may decrease rice yield to some extent. For instance, annual global rice yields are decreasing by 0.3% on average because of global climate change[41]. Therefore, the effect of global warming should be considered in estimates of future rice production. Additionally, intermittent flooding is suitable for China when ‘organic substitution action’, a government promoted strategy for reducing synthetic fertilizer input in agriculture, is carried out around rice fields to facilitate the ‘carbon neutrality’ goal in agriculture. But intermittent flooding sometimes causes crop failure because of unpredictable climate events and the need for more sophisticated agronomic operations[42]. More specific polices offering incentives, such as subsidy, free training, crop insurances should be implemented to ensure the efficacy and widespread adoption of these approaches in different regions.

Our study clearly established that rice field is important and ideal for sustainable recycling of organic N sources by an integrated OPTM and intermittent flooding strategy. Thus, this strategy forms a new perspective for addressing the challenge of coupling livestock and crop production systems in rice-producing areas. To fulfill the OPTM with intermittent flooding, at least three steps are needed. First, a range of policy measures from financial compensation to knowledge transfer is needed to encourage producers adopt the correspondingly suitable approach. Second, the technological reform is also needed to apply organic N sources to paddy soil, and more easy-to-use systems for technology application and appropriate infrastructure will accelerate technology adoption by rice producers. Third, a proactive approach of region-specific OPTM with intermittent flooding demonstration programs in different regions are needed for its successful implementation of OPTM with intermittent flooding. Although integrated OPTM and intermittent flooding would largely reduce C emissions, use of new more productive rice varieties with low CH_4 emissions[43], nitrification inhibitors or controlled release urea, C-based nutrient sources and practices that conserve SOC[44], would also be required to achieve C neutrality in rice production globally.

Methods

Data compilation

Data were extracted from peer-reviewed and published articles (from 2000 to 2019) using several databases, i.e., Web of Science (https://www.webofscience.com/), Baidu Xueshu (https://xueshu.baidu.com/), China National Knowledge Infrastructure (https://www.cnki.net/) and China Wanfang Data (https://www.wanfangdata.com.cn/). The terms, ‘paddy’ OR ‘rice’ AND ‘nitrogen’ OR ‘organic amendment’ OR ‘animal manure’ OR ‘green manure’ OR ‘crop residue’ AND ‘yield’ OR ‘nitrous oxide’ OR ‘methane’ OR ‘soil organic carbon’ OR ‘greenhouse gas’, were used to search papers.

The articles identified using these search terms were further screened using the following criteria: (i) Studies were conducted under field conditions; (ii) Studies should simultaneously include at least one treatment (application of organic N source) and a control (synthetic N fertilization), and furthermore, the treatment and control should have equal total N application in SN or same synthetic N rate as that of control (synthetic N fertilization) in AN; (iii) Organic N source-specific information (e.g., animal manure, crop residue, and mixed-source fertilizers); (iv) To avoid data duplication, the same observations from different articles were used once only. When the data were presented as figures, GetData Graph digitizer software (version 2.26.0.20) was used to extract the data. The data compilation followed the PRISMA protocol (Extented Fig. 4). In total, we collected 1935 paired observations from 199 articles for the meta-analysis database.

Currently, the substitution of synthetic N with organic N sources (SN) and the application of organic N sources combined with synthetic N (AN) are two dominant organic N management strategies. Synthetic N fertilization alone and SN provide the same total amount of N to rice, while AN provides more N than the synthetic N fertilization alone[22]. The number of paired observations for SN and AN was 948, and 987, respectively. In addition, we collected 251 published papers to analyze the effects of water management on rice yield, emissions of CH_4 and N_2O, and SOC sequestration. In this study, water management was categorized into two groups according to the definition from original paper: conventional flooding (continuous flooding and single drainage), and intermittent flooding (alternate wetting-drying and multiple drainages). Finally, 2719 observations of water management were extracted to compare the yield (conventional flooding, 770; intermittent flooding, 355), CH_4 emission (conventional flooding, 426; intermittent flooding, 384), N_2O emission (conventional flooding, 270; intermittent flooding, 283), and SOC sequestration (conventional flooding, 180; intermittent flooding, 51).

The information of location (latitude, longitude), climate (mean annual temperature, MAT; mean annual precipitation, MAP), and soil (soil clay content, initial SOC, pH) of each observation was also collected. For the missing climate records in articles, we extracted MAT or MAP from WorldClim 2 (https://www.worldclim.org/) based on latitude and longitude. Moreover, soil clay content was provided based on USDA texture class according to soil texture. Overall, this dataset covered the main rice-producing region with 200 sites on the globe (http://www.earthstat.org/,).

Data analyses

To analyze the effects of different managements of organic N source on target variables (rice yield, CH_4 emission, N_2O emission and SOC), the observations were grouped into different categorizes. We defined organic N ratio in SN as organic N rate divided by total N input (synthetic N + organic N), and the organic N ratio in AN as organic N rate divided by synthetic N. The organic N ratio was classified into four categories, namely low (≤ 25%), low-medium (25-50%), medium-high (50-75%), and high (> 75 %). According to the organic N origin, there was animal-derived organic N source (livestock manure), plant-derived organic N source (crop residue and green manure) and mixed-source organic N (both animal and plant). The cropping system also had different categories (single rice, double rice and paddy-upland cropping rotations). The duration of experiment encompassed short (≤ 3 years), moderate (4-10 years), and long experimental duration (> 10 years), respectively.

The effect sizes were presented as log-response ratios (lnRR), calculated as $\ln(X_t) - \ln(X_c)$ for each target variable, where X_t and X_c are means of treatment (organic N source application) and control (synthetic N fertilization alone) for the variable (X), respectively. The variance was calculated using sample sizes (n) and standard deviations (SD) described by Hedges and Curtis[45]. The effect sizes were weighted based on the inverse of variance. We used the mean variation coefficient ($SD/X \times 100\%$) from the studies within the same regions when SD was not reported. Because of non-independence of the effect sizes from multiple treatments with the same control, we analyzed the data by taking the variance-covariance matrix into account[46]. For groups with less than two paired observations, it was not possible to calculate confidence intervals (CIs), and therefore, these data were not presented in forest plots. The effect sizes were considered statistically significant when their CIs did not overlap zero. The mixed-effect meta-analysis was performed using '*metafor*' package (version 4.4-0) with '*REML*' method in R[47].

A hierarchical mixed-effect meta-analysis was performed to examine the effect sizes of target variables (rice yield, emissions of CH_4 and N_2O, and SOC) from organic N source application treatment, where the fixed effects were explanatory variables (Fig. 1 and Extented Fig. 1) and random effects were the hierarchical dependence of multiple observations within a study[48].

The heterogeneity of effect sizes was assessed using the chi-square distribution[49]. The effect sizes of yield, CH_4 emission, N_2O emission, and SOC had high heterogeneity in our meta-analysis (Q_T, $P < 0.0001$, Extented Data Table 1). The variables with high collinearity determined by the variance inflation factor (VIF) were excluded among 13 explanatory variables (4 categorical variables: organic N ratio, type of organic N source, cropping system, experimental duration; 9 numeric variables: MAT, MAP, soil clay content, soil pH, initial SOC concentration, C:N ratio in organic N source, organic C input, synthetic N input, organic N input or total N rate). Differences of effect sizes between categories were tested via Q_M statistics, and the significance level was set at $P < 0.05$ (Extented Data Table 1).

Publication bias was evaluated by Funnel plots and Egger tests. The response of rice yield to SN had some publication bias, as did for the response of rice yield in SN,

CH_4 emission and SOC in AN ($P < 0.05$, Extented Fig. 5). Furthermore, we used 'Rosenberg's fail safe-numbers' to evaluate whether these results were robust in terms of publication bias[50]. The analysis showed that the slight publication bias did not affect analysis in this study because Rosenberg's fail safe-numbers were large enough with significant levels ($P < 0.0001$, Extented Fig. 5).

Random Forest model and projections

In the Random Forest model, the number of trees (n_{tree}) and the number of variables at each node (m_{try}) were chosen based on the reduction in error rates and robust results, respectively. A tenfold cross-validation was conducted to evaluate the parameters of Random Forest model, with 70% of the data used as training data and the rest of the data used for validation (Extented Data Table 3, Extented Fig. 6 and Extented Fig. 7). The importance of explanatory variables was ranked based on the increase in the mean squared error of 'out-of-bag' data in Random Forest model (Figs. S2 and S3). The '*metaforest*' package (version 0.1.3) and '*randomForest*' package (version 4.7-1.1) were used to predict effect sizes and the absolute value of target variables in R software, respectively.

After a comprehensive consideration of rice yield and net C emissions with an emphasis on rice yield improvement, we chose the appropriate management of organic N source and ratio for SN and AN management. The OPTM could be recommended for achieving high rice yield with appropriate type of organic N source and proportion to minimize synthetic N application on a global scale. The OPTM was selected through two steps. Initially, by considering both net C emissions and rice yield in the meta-analysis, we selected the most appropriate combination of organic N and synthetic N with low net C emissions and high rice yield for AN and SN, i.e., a low organic N ratio with animal-derived organic N source in SN and a low-medium organic N ratio with mixed-source organic N in AN. Moreover, SN was replaced by AN in some grid cells where SN caused negative response ratio of rice yield. Climatic factors (MAT, MAP) from WorldClim 2 (https://www.worldclim.org/), soil properties (soil clay content, initial SOC, soil pH) from Harmonized World Soil Database1.2 (https://www.fao.org/soils-portal/en/), and fertilization conditions from EARTHSTAT (http://www.earthstat.org/) were used to project rice yields across the globe.

Data availability

The data used in this study is publicly available, Climatic factors from WorldClim 2 (https://www.worldclim.org/), soil properties from Harmonized World Soil Database1.2 (https://www.fao.org/soils-portal/en/), and fertilization conditions from EARTHSTAT (http://www.earthstat.org/). Source data are provided with this paper. All data in this study are uploaded at Figshare (https://doi.org/10.6084/m9.figshare.25193996).

Code availability

The code used in this study are available, and All code in this study are uploaded at Figshare (https://doi.org/10.6084/m9.figshare.25193996).

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Author contributions

X.C. and Z.L. designed the work. B.L., C.G., J.X., and Q.Z. performed the data extraction and analysis. B.L. wrote the first draft of the manuscript. All co-authors reviewed and revised the paper.

Competing interests

The authors declare no competing interests.

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Table 1 Carbon budget under synthetic N fertilization and OPTM in global rice field. OPTM refers to the optimal management of organic N source. GWP represents global warming potential, and NGWPI is net global warming potential intensity.

Item	**Management**	
	Synthetic N fertilizer	OPTM
GWP (kg CO_2-eq ha^{-1} per cropping season)	5184 (1740, 9345)	7440 (4912, 11373)
Net GWP (kg CO_2-eq ha^{-1} per cropping season)	4675 (218, 8989)	5382 (2649, 8984)
NGWPI (kg CO_2-eq Mg^{-1} grain)	832 (53, 1616)	858 (435, 1517)

The values presented are mean, and those in parentheses are values of 5th and 95th quantiles, respectively. The calculated details of GWP, net GWP and NGWPI are shown in supplementary information.

Table 2 Changes in yield, GWP, net GWP, and NGWPI in the main rice-producing countries/regions. BAU is business as usual; OPTM+CF is integrated optimal organic N management and conventional flooding; OPTM+IF is integrated optimal organic N management and intermittent flooding. GWP represents global warming potential, and NGWPI is net global warming potential intensity.

Country/Region	Management	Rice yield (kg ha^{-1})	CH_4 emission (kg C ha^{-1})	N_2O emission (kg N ha^{-1})	SOC sequestration (Mg C ha^{-1} season^{-1})	GWP (kg CO_2-eq ha^{-1})	Net GWP (kg CO_2-eq ha^{-1})	NGWPI (kg CO_2-eq Mg^{-1} grain)
China	BAU	7435 (6269, 8172)	202 (122, 297)	1.07 (0.32, 2.32)	0.22 (-0.32, 0.80)	7183 (4348, 10117)	6372 (3112, 9713)	865 (402, 1342)
	OPTM+CF	8455 (6558, 9781)	278 (208, 380)	0.67 (0.38, 1.01)	0.83 (0.40, 1.30)	9558 (7164, 12945)	6524 (4464, 9416)	787 (480, 1188)
	OPTM+IF	8153 (6468, 10256)	154 (96 202)	0.94 (0.62, 1.37)	0.72 (0.50, 0.95)	5512 (3565, 7186)	2866 (234, 4693)	356 (27, 583)
India	BAU	5354 (4149, 6369)	124 (33, 251)	1.06 (0.47, 2.15)	0.24 (-0.01, 0.61)	4563 (1568, 8749)	3653 (329, 7483)	682 (65, 1433)
	OPTM+CF	5497 (4979, 7045)	189 (128, 258)	0.72 (0.48, 1.15)	0.60 (0.36, 0.79)	6601 (4576, 8851)	4453 (2214, 6855)	807 (418, 1220)
	OPTM+IF	5536 (4859, 7221)	136 (95, 170)	0.94 (0.58, 1.31)	0.59 (0.44, 0.84)	4929 (3533, 6061)	2748 (877, 4016)	506 (157, 751)
Africa	BAU	4091 (3141, 5175)	125 (40, 214)	1.32 (0.57, 3.28)	0.28 (0.03, 0.60)	4730 (1665, 7683)	3701 (166, 6997)	862 (46, 1702)
	OPTM+CF	5039 (4670, 5727)	176 (141, 228)	0.96 (0.77, 1.30)	0.52 (0.24, 0.73)	6280 (5122, 8005)	4369 (2724, 6398)	871 (536, 1285)
	OPTM+IF	5023 (4626, 5627)	152 (116, 180)	0.99 (0.69, 1.23)	0.54 (0.41, 0.70)	5478 (4322,6410)	3482 (2422, 4537)	700 (485, 907)
World	BAU	5649 (3470, 4744)	143 (40, 270)	0.97 (0.39, 2.30)	0.14 (-0.25, 0.74)	5184 (1740, 9345)	4675 (218, 8989)	832 (53, 1616)
	OPTM+CF	6366 (4744, 9395)	213 (136, 334)	0.78 (0.42, 1.28)	0.56 (0.24, 1.08)	7440 (4912, 11373)	5382 (2649, 8984)	858 (435, 1517)
	OPTM+IF	6247 (4767, 9595)	155 (97, 215)	0.77 (0.56, 1.26)	0.51 (0.44, 0.89)	5495 (3608, 7619)	3625 (630, 5495)	656 (90, 895)

The values presented are mean, and those in parentheses are the values of 5th and 95th quantiles, respectively.

The calculated details of GWP, net GWP and NGWPI are shown in supplementary information.

List of figure captions

Fig. 1 Influences of organic N ratio on rice yield, CH_4 and N_2O emission, SOC. a–h, Change in rice yield (a,e), CH emission (b,f), N_2O emission (c,g) and SOC (d,h) under SN (a–d) and AN (e–h). Low, low-medium, medium-high and high organic N ratio refer to ≤25%, 25–50%, 50–75% and >75%, respectively. In the forest plots, points stand for mean effect sizes, and error bars are 95% calculated CIs. The numbers of observations and literature (in parentheses) are listed on the right side of each figure.

Fig. 2 Projected the effect sizes of rice yield, CH_4 and N_2O emission, SOC on a global scale. a–l, Spatial patterns of the effect sizes of rice yield (a, e, i), CH_4 emission (b, f, j), N_2O emission (c, g, k), and SOC (d, h, l) under SN (a–d), AN (e–h) and OPTM (i–l). m-p**,** Summaries of the effect sizes of rice yield (m), CH_4 emission (n), N_2O emission (o), and SOC (p). The short black solid line and red diamond within each box, respectively represent median and mean value. The lower and upper edges of each box are 25th and 75th percentiles, and bars of each box indicate 10th and 90th percentiles.

Fig. 3 Comparisons of rice yield, CH_4 and N_2O emission, SOC sequestration under water managements. a–d, Effect of water management on rice yield (a), CH emission (b), N O emission (c) and SOC sequestration (d) under application of organic N source. CF, conventional flooding; IF, intermittent flooding. The P values are calculated using two-sided unpaired Student's t-test, and significant difference is set at $P < 0.05$. The black solid line within each box represents median value**.** The lower and upper edges of each box are 25th and 75th percentiles, and bars of each box indicate 10th and 90th percentiles.

Fig. 4 Projected rice yield, CH_4 and N_2O emission, SOC sequestration under OPTM+water managements on a global scale. a–h, Spatial patterns of rice yield (a,e), CH_4 emission (b,f), N_2O emission (c,j) and SOC sequestration (d,h) under OPTM + CF (a–d) and OPTM + IF, (e–h). i–l, Summaries of the rice yield (i), CH emission (j), N O emission (k) and SOC sequestration (l). OPTM + CF, integrated management of optimal organic N source and conventional flooding; OPTM + IF, integrated management of optimal organic N source and intermittent flooding. The short black solid line and red diamond within each box, respectively represent median and mean value. The lower and upper edges of each box are 25th and 75th percentiles, and bars of each box indicate 10th and 90th percentiles.

Fig. 5 Comparisons of GWP, net GWP and NGWPI between two scenarios. a–**f**, Spatial patterns of GWP (**a**,**d**), net GWP (**b**,**e**) and NGWPI (**c**,**f**) in rice-producing areas under integrated organic N source and water managements BAU (**a**–**c**) and OPTM+IF (**d**–**f**). g–i, Summaries of GWP (g), net GWP (h) and NGWPI (i) (for calculated details, see Supplementary Information). The short black solid lines and red diamonds in boxes, lower and upper edges, and bars represent median and mean values, 25th and 75th percentiles, and 10th and 90th percentiles, respectively.

Fig. 6 Comparisons of rice production, total net GWP, and total N consumption between two scenarios. a–c, Projection of global rice production (a), total net GWP (b) and total N consumption (c) (calculated details are given in Supplementary Information).

Fig. 1

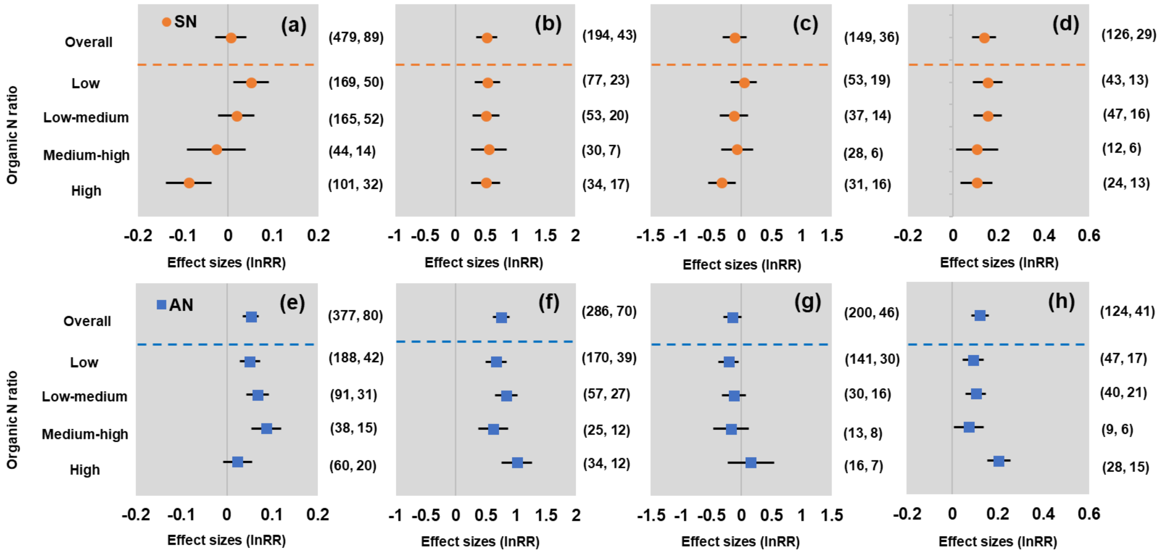

● SN
■ AN
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Organic N ratio
Overall
Low
Low-medium
Medium-high
High
(479, 89)
(169, 50)
(165, 52)
(44, 14)
(101, 32)
(194, 43)
(77, 23)
(53, 20)
(30, 7)
(34, 17)
(149, 36)
(53, 19)
(37, 14)
(28, 6)
(31, 16)
(126, 29)
(43, 13)
(47, 16)
(12, 6)
(24, 13)
(377, 80)
(188, 42)
(91, 31)
(38, 15)
(60, 20)
(286, 70)
(170, 39)
(57, 27)
(25, 12)
(34, 12)
(200, 46)
(141, 30)
(30, 16)
(13, 8)
(16, 7)
(124, 41)
(47, 17)
(40, 21)
(9, 6)
(28, 15)
-0.2 -0.1 0 0.1 0.2
-1 -0.5 0 0.5 1 1.5 2
-1.5 -1 -0.5 0 0.5 1 1.5
-0.2 0 0.2 0.4 0.6
Effect sizes (lnRR)

Fig. 2

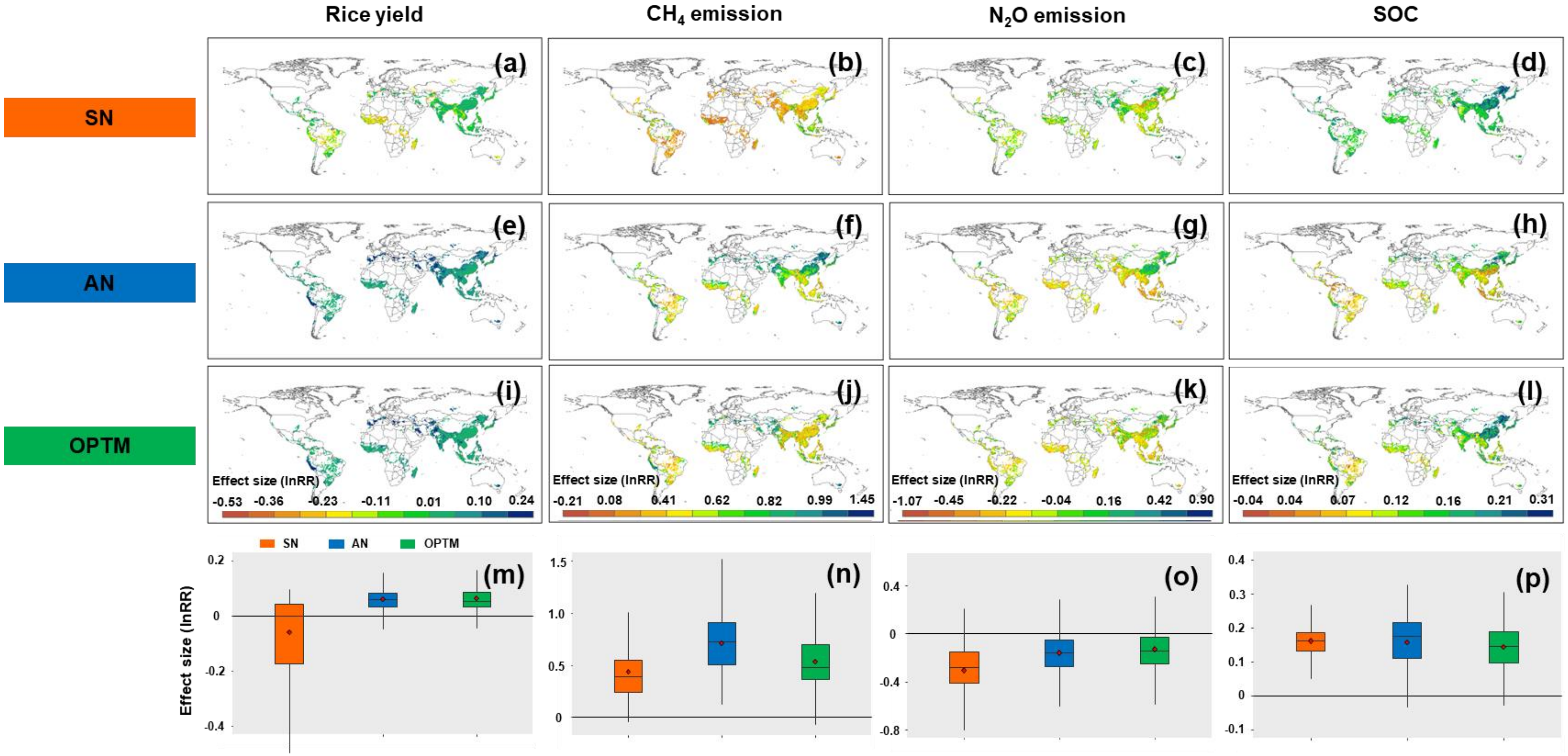
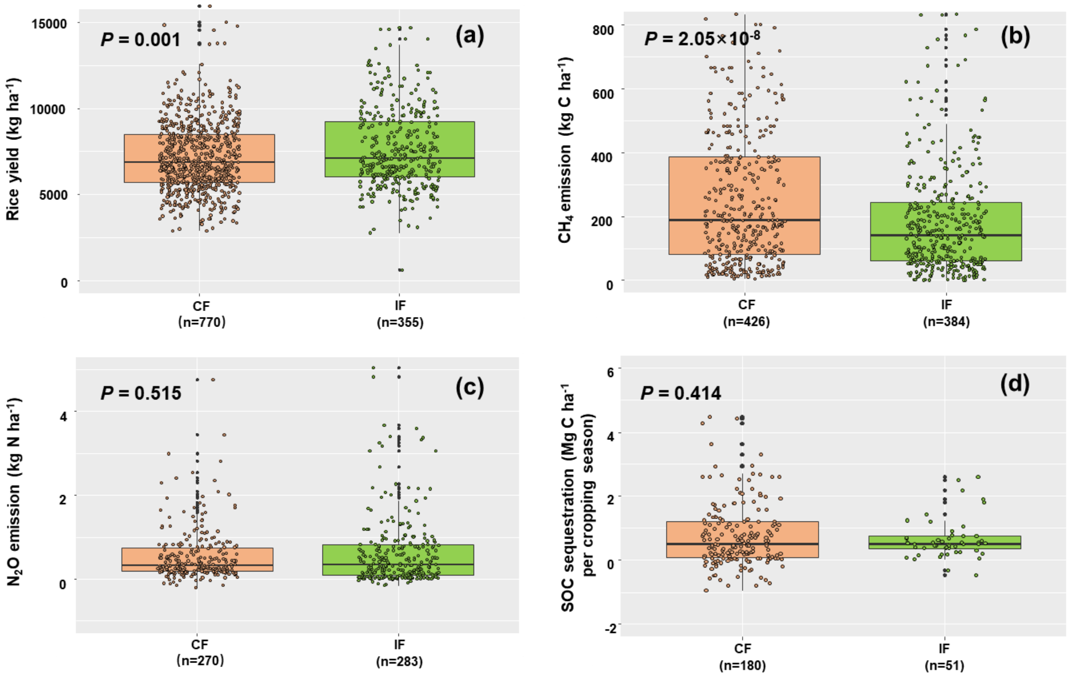

Rice yield
CH$_4$ emission
N$_2$O emission
SOC
SN
AN
OPTM
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
Effect size (lnRR)
-0.53 -0.36 -0.23 -0.11 0.01 0.10 0.24
Effect size (lnRR)
-0.21 0.08 0.41 0.62 0.82 0.99 1.45
Effect size (lnRR)
-1.07 -0.45 -0.22 -0.04 0.16 0.42 0.90
Effect size (lnRR)
-0.04 0.04 0.07 0.12 0.16 0.21 0.31
SN
AN
OPTM
(m)
(n)
(o)
(p)
Effect size (lnRR)
0.2
0
-0.2
-0.4
1.5
1.0
0.5
0
0.4
0
-0.4
-0.8
0.4
0.3
0.2
0.1
0
-0.1

Fig. 3



Rice yield (kg ha^{-1})
15000
10000
5000
0
P = 0.001
(a)
CF
(n=770)
IF
(n=355)
CH_4 emission (kg C ha^{-1})
800
600
400
200
0
$P = 2.05\times10^{-8}$
(b)
CF
(n=426)
IF
(n=384)
N_2O emission (kg N ha^{-1})
4
2
0
P = 0.515
(c)
CF
(n=270)
IF
(n=283)
SOC sequestration (Mg C ha^{-1}
per cropping season)
6
4
2
0
-2
P = 0.414
(d)
CF
(n=180)
IF
(n=51)

Fig. 4

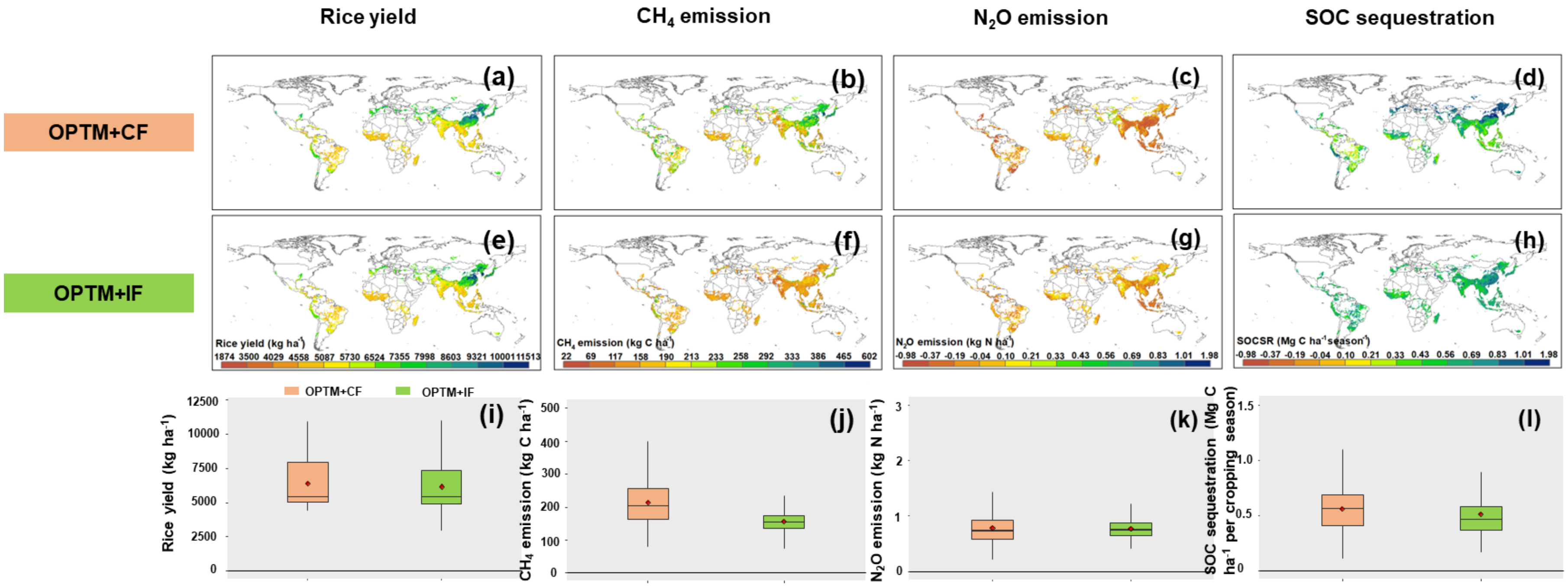

Rice yield
CH$_4$ emission
N$_2$O emission
SOC sequestration
OPTM+CF
OPTM+IF
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Rice yield (kg ha^{-1})
1874 3500 4029 4558 5087 5730 6524 7355 7998 8603 9321 10001 11513
CH$_4$ emission (kg C ha^{-1})
22 69 117 158 190 213 233 258 292 333 386 465 602
N$_2$O emission (kg N ha^{-1})
-0.98 -0.37 -0.19 -0.04 0.10 0.21 0.33 0.43 0.56 0.69 0.83 1.01 1.98
SOCSR (Mg C ha^{-1}season^{-1})
-0.98 -0.37 -0.19 -0.04 0.10 0.21 0.33 0.43 0.56 0.69 0.83 1.01 1.98
OPTM+CF
OPTM+IF
(i)
(j)
(k)
(l)
Rice yield (kg ha^{-1})
12500
10000
7500
5000
2500
0
CH$_4$ emission (kg C ha^{-1})
500
400
300
200
100
0
N$_2$O emission (kg N ha^{-1})
3
2
1
0
SOC sequestration (Mg C ha^{-1} per cropping season)
1.5
1.0
0.5
0

Fig. 5

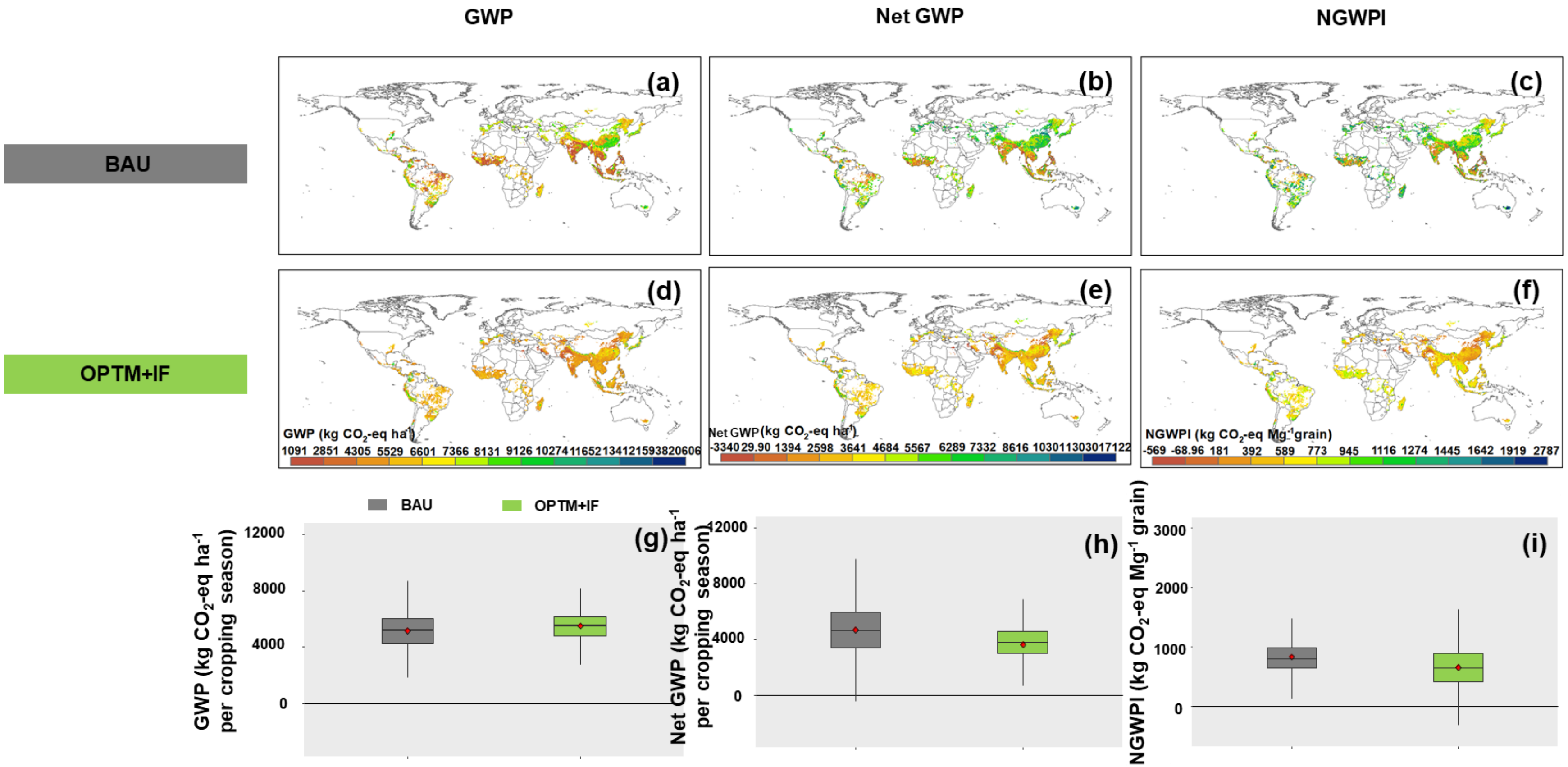
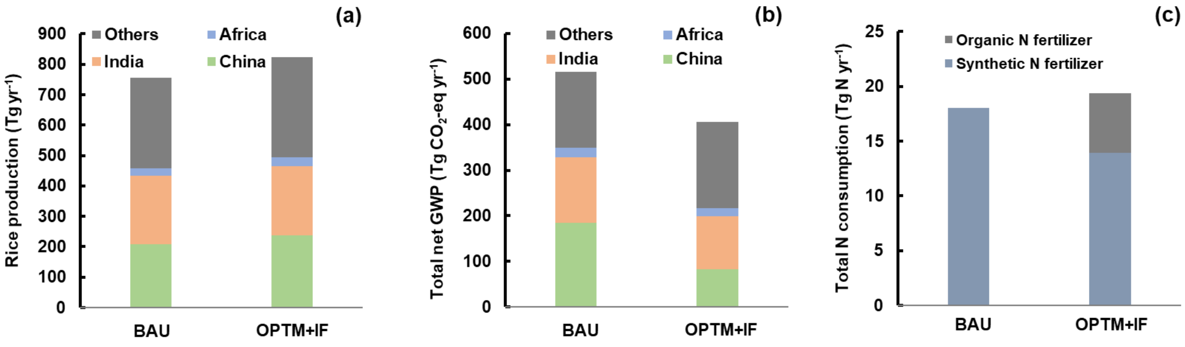

GWP
Net GWP
NGWPI
BAU
OPTM+IF
(a)
(b)
(c)
(d)
(e)
(f)
GWP (kg CO_2-eq ha^{-1})
1091 2851 4305 5529 6601 7366 8131 9126 10274 11652 13412 15938 20606
Net GWP (kg CO_2-eq ha^{-1})
-3340 29.90 1394 2598 3641 4684 5567 6289 7332 8616 10301 13030 17122
NGWPI (kg CO_2-eq Mg^{-1}grain)
-569 -68.96 181 392 589 773 945 1116 1274 1445 1642 1919 2787
BAU
OPTM+IF
GWP (kg CO_2-eq ha^{-1} per cropping season)
12000
8000
4000
0
(g)
Net GWP (kg CO_2-eq ha^{-1} per cropping season)
12000
8000
4000
0
(h)
NGWPI (kg CO_2-eq Mg^{-1} grain)
3000
2000
1000
0
(i)

Fig. 6


(a)
Rice production (Tg yr^{-1})
0
100
200
300
400
500
600
700
800
900
Others
Africa
India
China
BAU
OPTM+IF
(b)
Total net GWP (Tg CO$_2$-eq yr^{-1})
0
100
200
300
400
500
600
Others
Africa
India
China
BAU
OPTM+IF
(c)
Total N consumption (Tg N yr^{-1})
0
5
10
15
20
25
Organic N fertilizer
Synthetic N fertilizer
BAU
OPTM+IF