Multiple trade-offs between maximizing yield and minimizing greenhouse gas production in Chinese rice croplands

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Funding Information
Catalan Governme, Grant/Award Number: SGR 2017-1005; European Research Council, Grant/Award Number: Synergy grant ERC-SyG-2013-610028; National Science Foundation of China, Grant/Award Numbers: 31000209, 41571287; Research Project of Public Institute of Fujian Province, Grant/Award Number: 2018R1034-1; Spanish Government mineco, Grant/Award Number: CGL2016-79835

Abstract
Globally, paddy fields are a major anthropogenic source of greenhouse gas (GHG) emissions from agriculture. There is, however, limited understanding of relationships between GHG production with fertilizer management, rice varieties, and soil variables. This information is crucial for minimizing the climatic impacts of rice agriculture. Here, we examined the relationships between soil GHG production and management practices throughout China. The current doses of N-fertilizer (73–272 kg ha⁻¹) were negatively correlated with rice yield and with CO2 or CH4 production and positively correlated with N2O production, thus suggesting N-overfertilization. Impacts on soil traits such as decreasing pH or the availabilities of other nutrients could be underlying these relationships. Rice yield was highest, and GHG production was lowest at sites using intermediate levels of P- and K-fertilization. CO2 and CH4 production and emissions were positively related with soil water content. The yield was higher, and N2O productions were lower at the sites with japonica rice. Our results strongly suggest that current high doses of N-fertilizers could be reduced to thus avoid the negative effects of excessive N input on GHG production without any immediate risk of rice production loss. Current intermediate doses of P- and K-fertilization should be adopted across China to further improve rice production without the risk of GHG emissions. The use of different rice varieties and strategies of water management should be reexamined in relation to crop production and GHG mitigation.

Keywords
greenhouse gases, nitrogen, paddy field, phosphorus, soil nutrients, yields

1 INTRODUCTION

Rice currently feeds more than 50% of the global population (Haque, Kim, Ali, & Kim, 2015), but production will need to increase by 40% by the end of 2030 worldwide to meet the demand for food from...
the growing population (Food and Agricultural Organization of the United Nations, 2009). Sustaining soil fertility and increasing rice yields are therefore of utmost importance. An increased nutrient supply can not only stimulate the growth and grain yield of rice plants (Ali, Oh, & Kim, 2008; Wang et al., 2014) but can also influence the potential of paddy fields to produce and emit greenhouse gases (GHGs). Globally, paddy fields are a major anthropogenic source of GHG emissions from agriculture (Tan, 2011). Paddy fields are very important sources of GHG, especially methane (CH₄) and nitrous oxide (N₂O; Myhre et al., 2013), so minimizing the release of these very potent GHG could contribute to mitigating their adverse impacts on climate change (Li, Salas, Deangelio, & Rose, 2006). Chinese GHG emissions from agricultural systems account for ~40% of Chinese GHG emissions, hence requiring detailed investigations. Furthermore, because 60% of the Chinese population depend on rice-based food, so protecting China's rice production for food security is important (Zhu, 2006).

There is, however, limited understanding of relationships between GHG production with fertilizer management, rice varieties, and soil variables. This information is crucial for minimizing the climatic impacts of rice agriculture, especially for the agricultural sustainable development in China. Improving the status of soil nutrients in paddy fields for improved rice yield while decreasing GHG emissions, or at least not increasing it, is a challenging option. However, intense fertilization can also induce rises in GHG emissions in paddy soils (Fan et al., 2016), and great soil nutrient concentration also can be related to GHG emissions in paddy soils (Wang et al., 2017). Rice crops in China are frequently overfertilized (Cheng & Li, 2007), so a general analysis of the relationships of fertilization and soil traits with GHG emissions and crop yield is necessary to detect the level of overfertilization, GHG emissions and yield, and moreover, to improve the future management of the sustainable development of rice agriculture. Here, we examined the relationships between soil GHG production and management practices throughout China.

Most current studies associating GHG emissions from paddy fields with soil properties have been conducted at a single location by applying different treatments that modify soil properties (Wang et al., 2014; Wassmann et al., 1998). Several strategies for managing rice crops, such as from fertilizer and herbicide application to straw or water management, are aiming to increase rice production. However, such management strategies may also increase or decrease CO₂, CH₄, and/or N₂O emissions (Ujang, Chen, Sun, Sang, & Huang, 2015; Launio, Asis, Manallili, & Javier, 2016; Li et al., 2005; Li, Wang et al., 2013; Li, Zhang, Guo, Cai, & Cao, 2013; Liu et al., 2016; Trinh et al., 2017; Wang, Wu, et al., 2016; Zhang et al., 2016; Zhang, Chen, Liu, Cao, & Li, 2016). Many of these studies have reported links between GHG emissions and various soil traits, such as pH (Wang, Lai, et al., 2017), redox potential, (Fan et al., 2016; Wang, Lai, et al., 2017; Wang, Sardans, et al., 2017), salinity (Olsson et al., 2015), sulfate concentration (Dong et al., 2011; Theint, Suzuki, Ono, & Bellingrath-Kimura, 2014; Wang, Lai, et al., 2017; Wang, Sardans, et al., 2017), N content (Wang et al., 2017; Wang, Lai, et al., 2017; Wang, Sardans, et al., 2017; Zhao et al., 2015; Zheng, Zhang, & He, 2013; Zhu, Zhang, & Cai, 2011), and soil P concentration (Adhya, Pattnaik, Satpathy, Kumaraswamy, & Sethunathan, 1998; Sheng et al., 2016; Zheng et al., 2013). However, only few studies have tested the differences in GHG productions and emissions at sites with different soil traits and management strategies, including fertilization. Studying soil conditions on a large scale, including coastal and inland paddy soils at large regional scales, and their relationships with GHG productions and emissions are thus warranted for increasing rice production while controlling GHG emissions.

We hypothesized that different fertilization practices, strategies of rice-crop management, rice varieties, concentrations of soil carbon (C) and other nutrients, salinity, or/and pH would explain a large part of the differences in GHG emissions and yield among sites, especially, the fertilization amount increment will increase the GHG emissions but not the yield. Our results will provide information for improving strategies and managing soil conditions toward more favorable traits to avoid a possible increase in GHG production without yield loss. We pursued this objective by determining (a) the relationships among fertilization dose, soil GHG production, and rice yield in China and (b) the relationships among GHG production, rice variety, and environmental traits, such as region (sites), location (coastal vs. inland), and cropping system (single or double) on these relationships.

2 | MATERIALS AND METHODS

2.1 | Study area

This study was conducted throughout China. China has 2.45 × 10⁷ ha of cultivated rice, and 90% of the paddies are in the subtropics. China has a large area of paddy rice, diverse soil types, and different tillage and fertilizer management practices, all of which may affect the content and distribution of nutrients and GHG emissions. We collected the soils in the whole China rice cultivation areas choosing sites with contrasting fertilization management. The studied ranges of fertilization were 73–272 kg ha⁻¹ for N fertilizer, 48–150 kg ha⁻¹ for P₂O₅, and 45–270 kg ha⁻¹ for K₂O. The main characteristics of the different studied sites are shown in Table S1. To analyze the role of sea proximity, we separated the studied sites between inland and coastal rice crops depending on the distance to sea line; when less than 20 km was considered coastal paddy field, and more than 20 km was considered inland paddy field. To analyze the role of fertilization intensity, we classified the distinct sites as low, intermediate, and high intensity fertilized. In the case of N-fertilization: Low <100 kg N ha⁻¹ yr⁻¹, intermediate between 100 and 150 kg N ha⁻¹ yr⁻¹, and high intensity >150 kg N ha⁻¹ yr⁻¹. In the case of P-fertilization: Low <60 kg P₂O₅ ha⁻¹ yr⁻¹, intermediate between 60 and 75 kg P₂O₅ ha⁻¹ yr⁻¹, and high intensity >75 kg P₂O₅ ha⁻¹ yr⁻¹. In the case of K-fertilization: Low <60 kg K₂O ha⁻¹ yr⁻¹, intermediate between 60 and 70 kg K₂O ha⁻¹ yr⁻¹, and high intensity >70 kg K₂O ha⁻¹ yr⁻¹.
2.2 Collection and measurement of soil samples

Soil samples were collected from 34 randomly selected paddy fields and five replicated plots throughout China using a small core sampler (length and diameter of 0.5 and 0.1 m, respectively) from the plowed (0–15 cm) soil layer in October to November 2015. A total of 170 samples (34 sites × 1 soil layer × 5 replicates) were thus collected. We attributed China into six regions for this study: Northeast China, North China, East China, Centre and South China, Southwest China, and Northwest China (Sun, Huang, Zhang, & Yu, 2010). Moreover, the sampling site characteristics and paddy field management were also investigated. The collected soil samples were also used for all analyses. The samples were air-dried, and roots and visible plant debris were removed. Total C and N contents were measured using a Vario EL III Elemental Analyzer (Elementar Scientific Instruments, Hanau, Germany, Wang et al., 2015; Wang et al., 2016; Wang, Vario EL III Elemental Analyzer (Elementar Scientific Instruments, Hanau, Germany, Wang et al., 2015; Wang et al., 2016; Wang, Sardans, et al., 2016). Labile organic carbon (LOC) content was determined by digestion with 333 mM KMnO4 (Wang, Lai, Wang, Pan, & Sardans, et al., 2016). Salinity was measured using a 2265FS EC Meter (Spectrum Technologies Inc., Paxinos, PA; Wang, Sardans, et al., 2016). Soil particle size (percent clay, silt, and sand contents) was measured by a Mastersizer 2000 laser particle-size analyzer (Malvern Scientific Instruments, Malvern, UK; Wang, Sardans, et al., 2016).

The soil CO2, CH4, and N2O productions were determined using anaerobic incubation consistent with soils under water saturation (Wang, Wang, Sardans, et al., 2015). Thirty grams of fresh soil of the five core samples for each site were placed in 120-mL incubation bottles, and two volumes of distilled water were added. The bottles were purged with N2 for 2 min to replace the O2 and were then sealed with a rubber stopper and incubated at 25°C for 3 days. Five milliliters of gas were extracted from the headspaces each day, about 24-hr interval in four times during incubation: 0, 24, 48, and 72 hours during incubation experiments. This method has been successfully used in several previous studies (Wang, Sardans, et al., 2017; Wassmann et al., 1998). We also use the method of Xu, Chen, and Xiong (2016) to calculate annual gas emissions from some days (in our case 3 days) of sampling (Xu et al., 2016).

The soil CO2 and CH4 concentrations in the samples of headspace air were determined by gas chromatography (Shimadzu GC-2010, Kyoto, Japan). The soil N2O concentrations in these samples were determined by gas chromatography (Shimadzu GC-2014; Kyoto, Japan) using a stainless-steel Porapak Q column (2 m length, 4 mm OD, 80/100 mesh). A methane conversion furnace, flame ionization detector, and electron capture detector were used for determining the CO2, CH4, and N2O concentrations, respectively. The operating temperatures of the column, injector, and detector were adjusted to 45°C, 100°C, and 280°C, respectively, for determining the CO2 concentrations; to 70°C, 200°C, and 200°C, respectively, for determining the CH4 concentrations; and to 70°C, 200°C, and 320°C, respectively, for determining the N2O concentrations. Helium (99.999% purity) was used as a carrier gas (30 ml min⁻¹), and a make-up gas (95% argon and 5% CH4) was used for the electron capture detector. The gas chromatograph was calibrated before and after each set of measurements using 503, 1,030, and 2,980 μl CO2 L⁻¹ in He; 1.01, 7.99, and 50.5 μl CH4 L⁻¹ in He and 0.2, 0.6, and 1.0 μl N2O L⁻¹ in He (CRM/RM information centre of China) as primary standards (Wang et al., 2015). We used linear equations for calculating CO2, CH4, and N2O productions.

Other soil variables were also analyzed. Bulk density was measured using three 15 × 3 cm cores (Wang, Sardans, et al., 2016) and was estimated by core mass dry weight divided by core volume, and represent the averaged bulk density of 0–15 cm. Soil water content was measured by the drying method (Lu, 1999). pH was measured with a PHS-3C pH meter (Orion Scientific Instruments, MN), and salinity was measured using a 2265FS EC Meter (Spectrum Technologies Inc., Paxinos, PA; Wang, Sardans, et al., 2016). Soil particle size (percent clay, silt, and sand contents) was measured by a Mastersizer 2000 laser particle-size analyzer (Malvern Scientific Instruments, Malvern, UK; Wang, Sardans, et al., 2016).

2.3 Determination of soil C and nutrient contents

The total C, N, and P contents, and LOC, available N, available P, NH4⁺-N, and NO3⁻-N contents in the 0–15 cm soil profile were estimated by following the approach of Mishra, Ussiri, and Lal (2010):

\[ C_S = \sum C_m \times \rho_b \times D \]

where \( C_S \) is the total C, N, or P contents or LOC, available N, available P, NH4⁺-N or NO3⁻-N content (kg m⁻²), \( C_m \) is the total C, N, or P content or LOC, available N, available P, NH4⁺-N or NO3⁻-N content (g kg⁻¹), \( \rho_b \) is the bulk density (kg m⁻³), \( D \) is the thickness of each soil layer (0.15 m).

The total C, N, and P contents, and LOC, available N, available P, NH4⁺-N and NO3⁻-N contents were calculated for each region by multiplying area content and areas of each paddy distribution. The contents for each measured variables across China were calculated as the sum for all regions.

2.4 Determination of soil CO2, CH4, and N2O productions

We used linear regressions for calculating soil CO2, CH4, and N2O productions (Wassmann et al., 1998):

\[ P = \frac{dc}{dt} \frac{V_H}{W_S} \frac{MW}{MW} \frac{T_{st}}{T_{st} + \frac{1}{T}} \]

where \( P \) is the rate of CO2, CH4, or N2O production (μg⁻¹ g⁻¹ day⁻¹), \( dc/dt \) is the recorded change in the mixing ratio of CO2, CH4, and N2O in the headspace over time (mmol mol⁻¹ day⁻¹), \( V_H \) is the
2.5 | Statistical analyses

One-way ANOVAs with N-, P-, and K-fertilization doses categorical (low, intermediate, and high intensity), regions, inland-coastal environments and cropping systems as independent variables and gas production variables, and yield as a dependent continuous variable were conducted with Bonferroni post hoc tests. The data were checked for normality and homogeneity of variance, and if necessary, were log-transformed. We used the Benjamini–Hochberg procedure to control the rate of false discovery (Benjamini & Hochberg, 1995) to analyze the relationships between gas emissions and all the studied environmental soil and climate variables. The different individual analyses were listed in rank order according with their ascending p value. Thereafter, for each single analyses, each p value was divided by the total number of test and thereafter multiplied by the false discovery rate (habitually 0.25), then the values below .05 were considered as significant. We also used Tukey’s method (Tukey, 1977) to detect and remove outliers.

We also performed multivariate statistical analyses. We used principal component analyses (PCAs) to determine the overall differences of the soil variables and CO$_2$, CH$_4$, and N$_2$O productions rates and annual accumulated emissions among fertilizer doses. We used all variables given the scarce multicollinearity existing among variables (see Table S1), with no $R^2 > 0.6$ between any pairwise variables. We have also estimated VIF for each independent fixed variables in the mixed models. We conducted one-way ANOVAs with Bonferroni post hoc tests of the scores of the first PC axis to determine differences among the treatments. We then used general discriminant analyses (GDAs) to determine the overall differences of soil traits; CO$_2$, CH$_4$, and N$_2$O productions rates and annual accumulated emissions and yield among fertilizer doses and productivities among sites with different yields. Discriminant analyses consist of a supervised statistical algorithm that derives an optimal separation between groups established a priori by maximizing between-group variance while minimizing within-group variance (Raamsdonk et al., 2001). GDA is thus an appropriate tool for identifying the variables most responsible for differences among groups. The GDAs and PCAs were performed using STATISTICA 8.0 (StatSoft, Inc., Tulsa, OK). Before conducting these multivariate analyses, we selected the sampling adequacy of individuals and the set of variables by the Barlett’s test of sphericity ($<0.05$) and the Kaiser–Meyer–Olkin measure ($>0.50$). We removed the variables with communality values $<0.5$ and perform the PCA and DGA analyses with the variables with communality $>0.5$. To perform these sampling adequacy analyses, we used the package PSYCH (Revelle, 2010).

Significant differences in CO$_2$, CH$_4$, and N$_2$O productions among doses of fertilizers, number of crops, crop location (inland vs. coastal), and soil traits were tested by general mixed models using location with topography, site, and plot as random nested factors. We used the ‘lme’ function of the ‘nlme’ R package (Pinheiro, Bates, DebRoy, Sarkar, & Core, 2016). Nonnormally distributed variables were log-transformed. We chose the best model for each dependent variable using the Akaike information criterion (AIC). We used the MUMIN (Barton, 2012) R package in the mixed models to estimate the percentage of the variance explained by the model. We conducted Tukey’s post hoc tests to detect significant differences in the analyses for more than two communities using the ‘multcomp’ (Hothorn, Bretz, & Westfall, 2013) R package with the ‘glht’ function. The relationships of each soil variable with CO$_2$, CH$_4$, and N$_2$O productions were determined by simple regressions using STATISTICA 8.0 (StatSoft, Inc., Tulsa, OK). We used the Benjamini–Hochberg procedure to control for rates of false discovery (Benjamini & Hochberg, 1995).

We used structural equation modeling (SEM) to study the total effects of fertilizer doses on accumulated gas emissions by both direct and indirect effects of soil traits. We fit the different models using the SEM R package (Fox, Nie, & Byrnes, 2013) and determined the minimum adequate model using AIC. Standard errors and significance levels (p values) of the total, direct, and indirect effects were calculated using bootstrapping (1,200 repetitions; Davison, Hinkley, & Schechtman, 1986; Mitchell-Olds, 1986).

3 | RESULTS

3.1 | Effects of fertilization doses, regions, rice variety, inland-coastal environments, and cropping systems on soil GHG productions and rice yield

One-way ANOVAs with N-, P-, and K-fertilization doses as independent categorical (low, intermediate, and high intensity) variables and gas production variables, and yield as a dependent continuous variable, indicated that the lowest levels of N fertilization ($<100$ kg N ha$^{-1}$ yr$^{-1}$) were associated with the highest annual yields. However, the highest levels of N fertilization ($>150$ kg N ha$^{-1}$ yr$^{-1}$) were associated with the lowest annual yields (Figures 1d and S1). The lowest doses of N fertilizer were associated with the highest soil CO$_2$ and CH$_4$ productions and the lowest N$_2$O productions, with the opposite patterns at the highest doses of N fertilizer. The intermediate doses of P ($60–75$ kg P$_2$O$_5$ ha$^{-1}$ yr$^{-1}$) and K ($60–70$ kg K$_2$O ha$^{-1}$ yr$^{-1}$) fertilizers were the best, because they were associated with the highest yields and the lowest CO$_2$ and CH$_4$ productions (Figures 2a,b, S2, 3a,
b, and S3). The correlations among all the studied variables were shown in Table S2.

The balance between yield and GHG production was worst in the East China rice crops, with the highest productions of CO₂, CH₄, and N₂O and the lowest annual yield (Figures 4 and S4). Coastal rice crops have higher CO₂ and CH₄ production (Figures 5a,b and S5a,b) and lower yield than inland rice crops (Figure 5d). Total annual yield was notably similar at the sites with one and two annual rice crops (Figure 6d). The CO₂ production rates were higher at sites with one annual crop than at sites with two annual crops (Figure S6a,c).

We excluded hybrid and glutinous rice varieties from the analysis of the effects of rice variety, because both were only at one site each. We focused on japonica and Hsien rice varieties, which were the main varieties planted at the sites. On average, the yield was higher, and N₂O productions were lower at the sites with japonica rice (Figure S7).

3.2 | Gas productions and environmental traits

We observed scarce relationships with studied gas emissions and production with the studied soil variables, the most strong was the positive relationships between total soil N concentrations and CO₂ emission and production and between soil water content and methane emission and production (Table S2). The variables that mainly loaded on PC1 (correlation >0.4) were Soil N concentration, LOC soil extractable NH₄⁺ and NO₃⁻ concentrations, soil pH, soil salinity, soil bulk density, sand %, MAP, soil NO₃⁻ content, CO₂ emission rates and yield. The variables that mainly loaded PC1 were soil total C, N, and P concentrations, soil P availability, soil NO₃⁻ concentrations and
contents, and soil salinity. A PCA of all available data also indicated that the rice crops under the low to intermediate doses of N fertilizer, and intermediate doses of P and K fertilizers had the highest yields and lower CO2 and CH4 productions (Figure 7a). Whereas, crops receiving high doses of N and K fertilizers had the lowest annual yields and the highest CO2 and CH4 productions, as shown along the PC1 axis (Figure 7b). The PCAs indicated that the North China and Northwest China rice crops were plotted by the two first PC axes toward higher yield and soil P availability, total P content, C:N ratio and sand content, and toward lower soil N:P ratio, labile C:N ratio and labile C:P ratio and lower CO2 and CH4 productions (Figure 7b). Fields in the East China, Centre and South China, and Southwest China regions had opposite patterns.

Coastal rice crops have higher CO2 and CH4 emissions and lower yield than inland rice crops. This was associated with higher soil N, water, and clay contents in coastal rice crops (Figure 7c). Figure 7d shows the overall differences in the environmental variables between the sites with one and two annual crops. These two groups of sites were clearly separated along the PC1 axis, with single-crop sites plotted toward higher annual yields and soil P contents, salinities, C:N ratios and pHs, whereas the double-crop sites were plotted toward higher soil N, water and LOC contents and N:P ratios, and higher CO2 productions.

The best mixed models (based on a low AIC and the highest $R^2$ and parsimoniousness), with rice variety and environmental traits as fixed independent variables; location, topography, site, and plot as random factors; and GHG productions as dependent variables, indicated that 26% of the total variance of annual accumulated CO2 productions was explained by the length of the growth period, soil water content, and bulk density (Table S3). Thirty-nine percent of the total variance of CO2 productions rates was explained by the growth-period length, soil water content, and P-fertilizer dose. Forty-seven and 50% of the total variance of annual accumulated CH4 productions and CH4 productions rate, respectively, were explained by the
growth-period length, soil water content, water source (river or groundwater), rice variety, bulk density, total soil N content, and P-fertilizer dose. Nineteen and 21% of the total variance of annual accumulated N2O productions and N2O productions rate, respectively, were explained by the cropping systems, soil P availability, and soil NO3−-N content. All six mixed models (Table S3), corresponding to each of the production variables, explained >99% of the corresponding total variance, while taking into account the random variables.

3.3 | Relationships between annual yield and gas productions; fertilization effects

The GDA indicated that the crop sites with high yields generally had the highest GHG productions, whereas crop sites with moderate yields generally had the lowest GHG productions (Figure S8). Lower doses of N fertilizer were surprisingly associated not only with higher yields but also with higher CH4 productions (Figure S9), whereas intermediate doses of N fertilizer were associate with higher N2O productions, consistent with the above results. Intermediate doses of P fertilizer were associated with the highest annual yields and the lowest CO2 and CH4 productions (Figure S10), whereas intermediate doses of K fertilizer were associated with the highest annual yields and the lowest CH4 productions (Figure S11) also consistent with the results of the one-way ANOVAs.

When the productivities at the various doses of N, P, and K fertilizers (yield kg−1 fertilizer) were used as grouping dependent factors in the GDA, the sites with high N productivity were associated with the highest N2O productions, sites with intermediate N productivity were associated with the highest CH4 productions, and sites with low N productivity were associated with higher CO2 productions (Figure S12). The lowest CO2, CH4, and N2O productions
were associated with sites with intermediate P fertilization (Figure S13), and sites with intermediate K fertilization were associated with the lowest CO₂ and CH₄ but not N₂O productions (Figure S14).

3.4 | SEM models

The SEM provided further evidence of the complex relationships among fertilizer doses, GHG productions, and annual yield. The N fertilization had a positive direct effect on GHG productions and a negative effect on annual yield, and P fertilization had the opposite pattern (Figure 8), and K fertilization did not significantly affect GHG productions but generally negatively affected yield (Figure 8c). The N fertilization also had indirect negative effects on annual yield by increasing the amount of labile soil carbon content and by lowering soil pH. We also detected a negative direct and indirect effect, by decreasing soil water content, effect of bulk density on soil CO₂ productions (Figure 8b).

4 | DISCUSSION

We studied potential emissions of carbon dioxide (CO₂), CH₄, and N₂O from paddy fields across China, because they are the most important GHG, contributing about 80% of the current global radiative forcing (Myhre et al., 2013). The statistical analyses of our database of 34 field sites throughout China clearly identified a general trend to over fertilization with N. The current dose of N fertilizer was negatively correlated with rice yield. This correlation was exacerbated by a positive correlation between N-fertilization and N₂O productions and negative correlations between N-fertilization and CO₂ and CH₄.
productions. These results are generally consistent with previous findings that have also observed that higher N application doses had detrimental effects on yield and/or increased gas emissions. Kim, Gwon, Jeong, Hwang, and Kim (2016) reported that rice yield increased with N-fertilizer dose to levels of 110–130 kg N ha\(^{-1}\) yr\(^{-1}\) and thereafter decreased at higher levels. A meta-analysis of 24 field studies of rice crops in China demonstrated that N fertilization increased CH\(_4\) and N\(_2\)O emissions and decreased the ratio of yield-to-GHG emission, which was highest for 150–200 kg N ha\(^{-1}\) yr\(^{-1}\) (Feng et al., 2013) very similar results than the observed in our study. Zhong, Wang, Yang, and Zhao (2017) observed that the percentage of N lost from leaching, ammonia volatilization, and denitrification increased with the N-fertilizer dose in a field experiment in China. Our results also provide evidence that both increased soil N and P availability increased rice yield (Figure S4), even though the N-fertilizer dose was negatively correlated with yield.

These results supported the hypothesis that increasing the doses of N fertilizer can have more detrimental than positive effects on yield and GHG productions, even though the availability of N to plants is important and positive for rice production. The results thus strongly suggest a possible N saturation and/or ineffective N fertilization beyond a certain level, with no extra positive effects but mostly negative effects of the higher N input on rice production. Current reports, however, demonstrate an interest to optimize N-fertilization doses in rice crops. Zhu, Zhang, Zhang, Deng, and Zhang (2016) reported a decrease in GHG emissions and an increase in rice yield as N-fertilizer doses decreased and plant density increased (~50% increase) in northeastern China. Zhang, Chen, et al. (2016) similarly demonstrated that the doses of N fertilizer typical of Nanjing paddy fields (China) could be decreased without decreasing rice yield but could decrease GHG emission.

Different studies have reported contradictory effects of N fertilization on GHG emissions from rice crops (see the review by Cai, Shan, & Xu, 2007). Several studies, however, have observed an increase in N\(_2\)O emissions with increases in N-fertilizer dose in rice croplands (Kim, Jeong, Kim, Kim, & Kim, 2016; Zhang et al., 2014). Our data analyses indicated that P- and K-fertilizer doses generally had positive effects on rice yield and decreased GHG productions. The relationships among P- and mainly K-fertilization, yield, and GHG productions in rice croplands have not been studied much, as compared with the corresponding relationships with N-fertilization. Our results are nonetheless consistent with other experimental studies (Datta, Santra, & Adhya, 2013; Li, Wang, et al., 2013; Li, Zhang, et al., 2013). Datta et al. (2013) found that N fertilization explained more of the changes in CH\(_4\) emissions than P or K fertilization. In contrast, Li, Wang, et al. (2013) and Li, Zhang, et al. (2013) observed that increasing the dose of P fertilizer decreased CH\(_4\) and N\(_2\)O emissions but increased yield.

However, our study has some potential limitations. The incubation period of 3 days could not be sufficient to capture the overall
patterns of GHG production and emission, and thus has limited reflection of the field condition, but it is still very useful to compare the potential emission among studied sites. In the paddy fields, the first peak of methane emission generally occurs within a month after transplanting, just according with our study. But a second peak would occur at approximately 2 months, and this is mainly governed by the stable low soil redox potential and neutral soil pH, and the increased release of plant-borne carbon sources (e.g., Ly, Jensen, Bruun, & de Neergaard, 2013; Vu et al., 2015). This can be partially corrected by using Xu et al. (2016) method to estimate all year gas emissions. But in all, this can explain why the estimated methane production in this paper is lower than in other reports in Asian countries (Vo et al., 2018; Yan, Ohara, & Akimoto, 2003).

Our results suggest that rice yield can be increased without increasing or even decreasing GHG productions. For example, our results indicated that yields were higher for the japonica than the Hsien varieties. The N₂O productions were several times higher for the Hsien varieties, leading to a better balance between yield and GHG productions in fields with japonica varieties, even though CH₄ productions were clearly higher for the japonica varieties. Adequate irrigation is fundamental for assuring high rice yield (Sun et al., 2016), but our data also suggest that GHG productions can be reduced by regulating doses of N-, P-, and/or K-fertilization. We have also observed that CH₄ and N₂O productions were much higher at sites irrigated and flooded with river water than at sites irrigated and flooded with groundwater or water from superficial reservoirs, whereas average yield did not differ significantly between these sites. This result is difficult to interpret in the context of this study; further studies should aim to find out the cause of these differences. The balance between yield and GHG production was worst in the East China rice crops, with the highest productions of CO₂, CH₄, and N₂O because in this area, the temperature is relatively higher, and there are more active substrates (Wang, Lai, Sardans, et al., 2015; Wang, Lai, Wang, et al., 2015; Wang, Sardans, Lai, et al., 2015; Wang, Wang, Sardans, et al., 2015). The North China and Northwest China rice crops had the opposite pattern because in this area, the lower temperature limits the substrates decomposition, such as soil organic carbon, and then the microbes act to convert plant residues into humus in the soil (Cui et al., 2008). The lower temperature can decrease decomposition and the CO₂ and CH₄ release from soil by mediating the microbe growth (Tang, Cheng, & Fang, 2017).

Moreover, in these paddy soils had relative higher pH and water comes from rivers that can provide more substrate to the paddy and also have longer growth period and more illumination than in other areas of China. Furthermore, the North China and Northwest China rice crops lower GHGs production was related with the higher C:N ratio. The C:N ratio controls the CO₂ and CH₄ release. There is more limited carbon decomposition with relatively higher C:N ratios (Windham, 2001). The soil GHG productions tendency to be lower significantly for CO₂ at inland than coastal sites because the coastal paddy fields had higher carbon and nitrogen concentration, and therefore more substrates for soil GHG productions (Delaune, White, Elsey-Quirk, Roberts, & Wang, 2018).

Moreover, the CO₂ production rates were higher at sites with one annual crop than at sites with two annual crops because the two annual areas, mostly in the south of China, had soils rich in ferric oxide, which, in turn, favored C fixation in soil, and more stable soil carbon, thus decreasing C release in form of methane (Wang et al., 2014). Furthermore, CH₄ production was higher under single crop. Single crop areas had lower temperature during the whole year, thus lowering decomposition, increasing carbon storage in the soil, and providing more substrates for CH₄ production when the temperature increases during rice growth period. However, N₂O is higher under double crops because of more applications of N fertilizer.

CH₄ production was higher under single crop. Single crop areas had lower temperature during the whole year, thus lower decomposition, and more carbon can be storage in the soil and more substrates is able for CH₄ production when the temperature increase during rice growth period. However, N₂O is higher under double crops, because along the year the N fertilizer applied is in higher amount in the doubles crop areas.

Our multivariate analysis of all data from all sites indicated that the highest average yields were accompanied by the highest GHG productions. Optimizing rice production and GHG production is thus interesting and challenging. Our analyses provide some clues for optimization, suggesting that some advances could be achieved by adjusting N-fertilization to a level that improve rice production but avoid the negative effects of excessive N input. Further, GHG productions could be reduced by maintaining adequate levels of P and K fertilizers, mostly at intermediate doses of the current range of P and K fertilizer across China, and by reexamining the use of different rice varieties and strategies of water management.

## 5 CONCLUSIONS

Rice production has historically been improved using N fertilizers, but we found that the current paddy field sites in China with relatively low N fertilization had high rice production and low soil CO₂ and CH₄ potential productions, even though rice yield was positively correlated with soil N availability. In contrast to N fertilization, sites using intermediate doses of P and K fertilizers had the highest rice yields and the lowest soil GHG potential productions. The large capacity of soil to accumulate P in nonavailable forms and the large capacity of K leaching by the high use of water in rice crops together with a less direct role of P and K in CH₄ and N₂O productions could explain these results.

The analysis of all our data strongly suggests that increasing rice yield and minimizing GHG productions can be further optimized in China. The use of different rice varieties and strategies of water management and fertilization with implications for minimizing GHG productions should thus be reexamined.

## ACKNOWLEDGMENTS

The authors would like to thank Zhu Defeng, Fu Rongfu, Yang Binjuan, Xu Hui, Zhou Jianxia, Liu Jianhui, Huang Jinlong, Chen Chuanbing, Chen Youyang, and Chen Xiaoxuan for their assistance.
with field sampling and laboratory analysis. Funding was provided by the National Science Foundation of China (41571287 and 31000209), Research Project of Public Institute of Fujian Province (2018R1034-1), Outstanding Young Research Talents in Higher Education of Fujian Province (2017), Spanish Government (grant CGL2016-79835), Catalan Government (grant SGR 2017-1005), and European Research Council Synergy (grant ERC-SyG-2013-610028).

CONFLICT OF INTEREST
The authors declare no conflicts of interest.

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How to cite this article: Wang W, Wang C, Sardans J, et al. Multiple trade-offs between maximizing yield and minimizing greenhouse gas production in Chinese rice croplands. Land Degrad Dev. 2020;31:1287–1299. https://doi.org/10.1002/ldr.3507