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Responses of greenhouse-gas emissions to land-use change from rice to jasmine production in subtropical China

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ABSTRACT

We studied the impacts of an increasingly common anthropogenic change in land use from paddy field to jasmine fields on the emission of greenhouse gases (GHGs), which have supposed the transformation of more than 1200 ha only in the last decade in the surroundings of Fuzhou city in response to economic changes. The possible increases that this can suppose constitutes and environmental concern in China. We studied areas dedicated to rice crop that have been partially converted to jasmine cultivation with some parts still kept as rice fields. Emissions of CO_2, CH_4 and N_2O varied significantly among the seasons. CO_2 and CH_4 cumulative emissions and the global-warming potential (GWP) of these emissions were significantly lower in the jasmine than the paddy field. N_2O emission, N_2O cumulative emission, however, were higher in the jasmine than the paddy field, despite in some concrete studied periods the differences were not statistically significant. The total decrease in GHG emissions from the conversion from rice to jasmine production was strongly influenced by the indirect effects of various changes in soil conditions. The expected changes due to the great differences in water and fertilization use and management and organic matter input to soil between these two crops were in great part due to modified soil traits. According to structural equation models, the strong direct effects of the change from rice to Jasmine crop reducing the emissions of CO_2 and N_2O were partially decreased by the indirect effects of crop type change decreasing soil pH and soil [Fe^{2+}] for CO_2 emissions and by decreasing soil salinity and soil [Fe^{3+}] for N_2O emissions. The negative effects of the crop conversion on CH_4 emissions were mostly due to the globally negative indirect effects on soil conditions, by decreases in soil salinity, water content and [Fe^{2+}]. Soil salinity, water content, pH, [Fe^{2+}], [Fe^{3+}] and [total Fe] were significantly lower in the jasmine than the paddy field, but temperature had the opposite pattern. CO_2 emissions were generally correlated positively with salinity, temperature, and water content and negatively with [Fe^{3+}] and [total Fe] in both fields. CH_4 emissions were positively correlated with salinity, temperature, water content and pH in both fields. N_2O emissions were positively correlated with temperature and were negatively correlated with water content, pH, [Fe^{2+}], [Fe^{3+}] and [total Fe] in both fields. CO_2 was the most important GHG for the GWPs, and the total GWP was significantly lower for the jasmine than for the rice cropland field. The change in the land use in this area of paddy fields will decreased the global GHG emission, and the effect on the GWPs was mostly due to changes in soil properties.

Keywords: CO_2, CH_4, N_2O, emission, GWP, paddy field, jasmine cultivation

1. Introduction

Rice is the most important cereal crop for more than half of the world's population. The Food and Agricultural Organization of the United Nations (2009) estimated that rice production must increase by 40% by the end of 2030 to meet the rising demand from the increasing population. Rice cultivation, however, needs more water and labor and provides a lower income than other crops, such as groundnuts, sweet potatoes, and coffee (Bua and Ojirot, 2014). Land-use conversion, particularly within cropland, is common and driven by the market's economy (Houghton et al., 1999). Some paddy fields have been converted to vegetables in response to economic changes and the need for environmental conservation. The conversion of rice paddy fields to the production of other crop species frequently changes soil texture and microbial communities (Dai et al., 2016), soil aggregates and organic-carbon concentrations (Wang et al., 2014), methane emissions (Hu et al., 2016), plant diversity of rural herbs (Wu et al., 2016) soil bulk density and porosity (Li et al., 2017) and the soil carbon and nitrogen concentrations (Huang et al., 2009).. Paddy fields, though, are very important sources of greenhouse gases (GHGs), especially methane (CH_4) and nitrous oxide (N_2O) (Myhre et al., 2013), so minimizing the release of these very potent GHGs from paddies is a key aim for better management strategies to mitigate the adverse impacts on climate change by Chinese cropland activity as a whole. China has the second largest area of rice cultivation in the world, and the associated GHG emissions account for about 40% of the total agricultural sources of GHGs. Moreover, 90% of the paddies in China are in the subtropics, such as in Fujian, Jiangxi and Hunan Provinces.

Jasmine tea is unique, and China is the only country that has mastered the critical scenting technologies. Protecting this production system is thus important for the protection and inheritance of Chinese culture and traditional technologies. More than half of the jasmine tea in China is produced in Fuzhou Province (Xu et al., 2001; Yang et al., 2008; Xu, 2012). The system for culturing jasmine and other tea plants near the city of Fuzhou was added in 2014 to the Globally Important Agricultural Heritage Systems due to its long historic, ecological and cultural function in this region (Lin et al., 2014; Ren et al., 2015). The land area devoted to jasmine production is currently increasing due to the great economic benefits, mainly by conversion from rice cropland, but little is known about the quantitative changes in emissions and the possible changes in soil properties underlying this change in cropland activity. We studied the impacts of an increasingly common change in land use from paddy field to jasmine fields on the emission of greenhouse gases (GHGs), which had supposed the transformation of more than 1200 ha only in the last decade in the surroundings of Fuzhou city in response to economic changes. The possible impacts constitute and environmental concern in China.

To increase our understanding of the effects of land-use changes from rice to jasmine production on GHGs emissions, we: (1) identified the changes in soil properties associated with the conversion of rice to jasmine production, (2) measured GHG emissions and estimated global-warming potentials (GWPs) and (3) identified the mechanistic relationships among the shifts in GHG emissions and soil properties.

2. Material and methods

2.1. Study area and experimental fields

This study was conducted in the Changshan district of Fuzhou, Fujian province (China, Fig. 1). The climate is subtropical, with mean annual temperatures and precipitation of 19.7 ºC and 1348.8 mm, respectively (Wang et al., 2015a). The experimental period was from April 2015 to March 2016. During this period there were two rice seasons, early paddy season (from 16 April to 16 July), with transplantation at 16 April, and the late paddy season (from 25 July to 6 November), with transplantation on 25 July. The experiment was conducted at two sites, one a paddy field, and the other a jasmine field, a field before and after conversion from rice to jasmine production.

The soil of the rice paddy field was poorly drained, and the proportions of sand, silt and clay particles in the top soil (15 cm surface soil) were 28, 60 and 12%, respectively (Wang et al., 2016a). Other surface-soil properties were: bulk density 1.1 g cm^{-3}, pH (1:5 soil:H_2O) 6.5, organic carbon 18.1 g kg^{-1}, total nitrogen (N) 1.2 g kg^{-1} and total phosphorus (P) 1.1 g kg^{-1} (Wang et al., 2015b, c). The water level was maintained at 5-7 cm above the soil surface from 0 to 37 days after transplantation (DAT) by an automatic water-level controller, and the water was then drained between 37 and 44 DAT. The soils in paddy field were kept moist between 44 and 77 DAT, and the paddy field was subsequently drained two weeks before harvest. The paddy field was plowed to a depth of 15 cm with a moldboard plow and leveled two days before rice transplantation. Mineral fertilizers were applied in three batches as complete (N-P_2O_5-K_2O at 16-16-16%; Keda Fertilizer Co., Ltd. Jingzhou, China) and urea (46% N) fertilizers. Fertilizers were first applied one day before transplantation at rates of 42 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1}. A second application was done during the tiller-initiation stage (7 DAT) at rates of 35 kg N ha^{-1}, 20 kg P_2O_5 ha^{-1} and 20 kg K_2O ha^{-1} and a third application was done during the panicle-initiation stage (56 DAT) at rates of 18 kg N ha^{-1}, 10 kg P_2O_5 ha^{-1} and 10 kg K_2O ha^{-1}.

A nearby paddy field, with the same rice crop history and soil traits was converted to jasmine production about seven years ago. The jasmine growing season is from April to October. Currently the soil in the jasmine field contained 25, 59 and 16% sand, silt and clay, respectively. The soil had a bulk density of 1.2 g cm^{-3}, pH of 4.4, salinity of 0.15 mS cm^{-1} and concentrations of total carbon, total N, total P and total potassium of 11.7, 1.1, 0.5 and 13.3 g kg^{-1}, respectively. The jasmine was cultivated using a ridge and ditch system, with a ridge height of 20 cm, ridge width of 100 cm and ditch width of 30 cm. Jasmine branches 10 cm long were transplanted by hand in the ridges at a spacing of 3(width)×20 (length) cm in April 2008 and have grown for seven years. The jasmine field was not plowed, but the soil was ridged each year after the jasmine was cut. Jasmine branches and leaves began to grow from early April to early May. Budding and infancy were from early May to the end of May. Flowering was from early June to the end of September, when the final growth period began. A complete fertilizer (N:P_2O_5:K_2O=16:16:16%) was applied in two unequal splits. Fertilizers were first applied after the jasmine was cut at rates of 20 kg N ha^{-1}, 20 kg P_2O_5 ha^{-1} and 20 kg K_2O ha^{-1}. The second application was done one day after the first jasmine flowers were collected, at rates of 16 kg N ha^{-1}, 16 kg P_2O_5 ha^{-1} and 16 kg K_2O ha^{-1}.

2.2. Measurement of CO_2, CH_4 and N_2O emissions

Static closed chambers were used to measure soil CO_2, CH_4 and N_2O emissions, as described by Wang et al. (2015b). The chambers were made of rigid PVC and consisted of two parts, an upper opaque compartment (100 cm height, 30 cm width, 30 cm length) placed on a permanently installed bottom collar (10 cm height, 30 cm width, 30 cm length). Each chamber had two battery-operated fans to mix the air inside the chamber headspace, an internal thermometer to monitor temperature changes during gas sampling, a gas-sampling port with a neoprene rubber septum at the top of the chamber for collecting gas samples from the headspace and a vent to prevent pressure buildup. Three replicate chambers were used in each crop type. In each sampling time we collected 6 samples for each variable (2 crop types x 3 plots = 6)

Gas flux was measured for 30 min for all chambers once a week during the rice growing season, twice a week during the jasmine growing season and once a month during the other seasons. The temperature in the chamber did not vary significantly during the sampling. Gas samples were collected from the chamber headspace using a 100-ml plastic syringe with a three-way stopcock 0, 15 and 30 min after chamber deployment. The samples were immediately transferred to 100-ml air-evacuated aluminum-foil bags (Delin Gas Packaging Co., Ltd., Dalian, China), sealed with butyl rubber septa and transported immediately to the laboratory for the analysis of CO_2, CH_4 and N_2O.

CO_2, CH_4 and N_2O concentrations in the headspace air samples were determined by gas chromatography (Shimadzu GC-2010 and 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 (FID) and electron-capture detector (ECD) were used for the determination of the CO_2, CH_4 and N_2O concentrations, respectively. The operating temperatures of the column, injector and detector for the determination of the CO_2, CH_4 and N_2O concentrations were adjusted to 45, 100 and 280 °C; to 70, 200 and 200 °C and to 70, 200 and 320 °C, respectively. Helium (99.999% purity) was used as a carrier gas (30 ml min^{-1}), and a make-up gas (95% argon and 5% CH_4) was used for the ECD. The gas chromatograph was calibrated before and after each set of measurements using 503, 1030 and 2980 μl CO_2 l^{-1} in He; 1.01, 7.99 and 50.5 μl CH_4 l^{-1} in He and 0.2, 0.6 and 1.0 μl N_2O l^{-1} in He (CRM/RM Information Center of China) as standards. Three injections were used for each analysis. One sample was injected into the gas chromatograph for each analysis. The detection limits of the instrument for CO_2, CH_4 and N_2O were 1, 0.1 and 0.05 ppm, respectively. CO_2, CH_4 and N_2O fluxes were then calculated as the rate of change in the mass of CO_2, CH_4 and N_2O per unit of surface area and per unit of time. The cumulative emissions were calculated by multiplying the measured emissions in one hour in each sampling day by 24 hours and then the obtained value multiplied by the half of the days from the previous measurement day plus the half of the days until the next measurement day.

2.3. GWP

GWP is typically estimated using CO_2 as the reference gas, and a change in the emission of CH_4 or N_2O is converted to "CO_2-equivalents". The GWP for CH_4 is 34 (based on a 100-year time horizon and a GWP for CO_2 of 1), and the GWP for N_2O is 298 (Myhre et al., 2013). The GWP of the combined emission of CH_4 and N_2O was calculated as:

GWP = (cumulative CO_2 emission × 1) + (cumulative CH_4 emission × 34) + (cumulative N_2O emission × 298)

2.4. Measurement of soil properties

Three replicate soil samples were collected from the paddy and jasmine fields in each sampling moment. The samples were transported to the laboratory and stored at 4 °C until analysis. The temperature, pH, salinity and water content of the top 15 cm of soil were measured *in situ* at each plot on each sampling day. Temperature and pH were measured with a pH/temperature meter (IQ Scientific Instruments, Carlsbad, USA), salinity was measured using a 2265FS EC meter (Spectrum Technologies Inc., Paxinos, USA) and water content was measured using a TDR 300 meter (Spectrum Field Scout Inc., Aurora, USA). Soil samples were collected from the 0-15 cm layer from each plot for the determination of ferric, ferrous and total Fe concentrations. Total Fe concentration was determined by digesting fresh soil samples with 1M HCl. Ferrous ions were extracted using 1,10-phenanthroline and measured spectrometrically (Lu, 1999; Wang et al., 2014b). Ferric concentration was calculated by subtracting the ferrous concentration from the total Fe concentration.

2.5. Statistical analysis

Differences in soil properties and CO_2, CH_4 and N_2O emissions between the land uses were tested for statistical significance by general mixed models and by generalized mixed models if a variable was non-normally distributed, using plot as a random factor and time as nested factor within plot as random independent factors when time was included in the analysis. We used the "*nlme*" (Pinheiro et al., 2016) R package with the "*lme*" function. We chose the best model for each dependent variable using Akaike information criteria. We used the MuMIn (Barton, 2012) R package in the mixed models to estimate the percentage of the variance explained by the model.

The averaged soil properties and CO_2, CH_4 and N_2O cumulative emissions, each GWP and total GWP were tested for statistical significance as described above, with plot as a random factor. Statistical significance of the differences among emissions and soil variables throughout time were tested by repeated-measures analyses of variance. The relationships between mean GHG emissions and soil properties were determined by Pearson correlation analysis. These statistical analyses were performed using SPSS Statistics 18.0 (SPSS Inc., Chicago, USA).

We used structural modelling to analyse the factors explaining the maximum variance of the CO_2, CH_4 and N_2O emissions throughout the study period as a function of cultivation type and soil traits. This analysis provided information on how in this case the change in crop type and the related changes in soil types were related among them in the form that explained most variance of each studied gas emissions. In other words, we thus analysed how total effects of crop type change on gas emissions are mediated throughout the indirect effects of crop type on related soil traits shifts. This method elucidates the part of the relationships of the change of crop with the shifts of soil gas emissions due to the corresponding shifts in the studied soil variables. We fit the models using the sem R package (Fox et al., 2013) and acquired the most parsimonious model using the Akaike information criterion.

3. Results

3.1. CO_2 emissions from the paddy and jasmine fields

CO_2 emission generally varied significantly among sampling dates and between fields ($P<0.01$, Table 1, Fig. 2). CO_2 flux in the paddy field was generally higher from April to December (rice growth period, and the beginning of straw return for December, >264 mg m^{-2} h^{-1}) and lower from January to March (fallow period, <100 mg m^{-2} h^{-1}). CO_2 flux in the jasmine field was generally higher from April to August (jasmine rapid-growth period, >770 mg m^{-2} h^{-1}) and lower from September to March of the next year (jasmine slow-growth period, <300 mg m^{-2} h^{-1}) (Fig. 2). Cumulative CO_2 emission was lower in the jasmine than the paddy field ($P<0.05$, Table 2). CO_2 was the most important GHG for the GWPs, and total GWP was significantly lower in the paddy than the jasmine field ($P<0.05$).

3.2. CH_4 emissions from the paddy and jasmine fields

CH_4 emission generally varied significantly among sampling dates and between fields ($P<0.01$, Table 1, Fig. 2). CH_4 flux in the paddy field was generally higher from April to August (early growth period and the beginning of late growth period, >0.9 mg m^{-2} h^{-1}) than later (<0.7 mg m^{-2} h^{-1}). CH_4 flux was generally lower (<0.5 mg m^{-2} h^{-1}) in the jasmine field (Fig. 2). Cumulative CH_4 emissions were lower in the jasmine than the paddy field ($P<0.05$).

3.3. N_2O emissions from the paddy and jasmine fields

N_2O emission generally varied significantly among sampling dates and between fields ($P<0.01$, Table 1, Fig. 2). N_2O flux was generally lower (<200 μg m^{-2} h^{-1}) in the paddy field. N_2O flux in the jasmine field was generally higher from April to August (jasmine rapid-growth period, >300 μg m^{-2} h^{-1}) and lower from September to March of the next year (jasmine slow-growth period, <105 μg m^{-2} h^{-1}) (Fig. 2). Cumulative N_2O emissions were higher in the jasmine field ($P<0.05$, Table 2).

3.4. Differences in soil properties between the paddy and jasmine fields

Soil salinity, temperature, water content, pH and ferrous, ferric and total Fe concentrations varied among the sampling dates, fields and interactions of sampling dates and fields ($P<0.05$; Table 3, Fig. 3). Soil salinity, water content, pH, [Fe^{2+}], [Fe^{3+}] and [total Fe] were lower in the jasmine than the paddy field ($P<0.05$), but temperature was significantly higher in the jasmine than in the paddy field ($P<0.05$, Table 4).

3.5. Relationships between CO_2, CH_4 and N_2O emissions and soil properties

The seasonal variation of CO_2 emissions in the soils of the paddy fields was generally correlated positively with salinity, water content ($P<0.05$; Table 5), and temperature ($P<0.01$), and negatively correlated with soil pH ($P<0.05$; Table 5), and [Fe^{2+}], [Fe^{3+}], [total Fe] ($P<0.01$). CH_4 emissions were positively correlated with salinity, temperature, water content ($P<0.01$), negatively correlated with [Fe^{2+}] ($P<0.05$), and [Fe^{3+}], [total Fe] ($P<0.01$). N_2O emissions were positively correlated with [Fe^{2+}], [Fe^{3+}], [total Fe] ($P<0.05$), and negatively correlated with salinity, and water content ($P<0.05$).

In Jasmine cropland soils the seasonal variation of CO_2 emissions in the soils of the jasmine cropland was generally positively correlated with water content ($P<0.05$; Table 5), and salinity, temperature ($P<0.01$), and negatively correlated with soil pH, [Fe^{3+}], [total Fe] ($P<0.01$). CH_4 emissions were not significantly correlated with the environmental factors. N_2O emissions were positively correlated with salinity, and temperature ($P<0.01$), and negatively correlated with pH, [Fe^{3+}], and [total Fe] ($P<0.01$).

3.6. SEM analyses

The total decrease in GHG emissions in the conversion from rice to jasmine production was strongly influenced by the indirect effects of changing soil conditions. The strong indirect effects of the change in crop type came from the decrease in soil pH for CO_2 and N_2O, from the decrease in soil [Fe^{2+}] for CO_2 and from the decrease in soil salinity and [Fe^{3+}] for N_2O (Figures 4 and 5). These indirect effects were only partially counteracted by a positive direct effect of the change of crop type. The increases in cumulative N_2O emissions due to indirect effects, that were higher in magnitude than their direct negative effects resulted in increased emissions after the transition (Figures 4 and 5). The negative indirect effects of crop type on CH4 emissions by lowering soil salinity, water content and [Fe^{2+}] in the jasmine field were only partially balanced by a positive direct effect, so the global effect was a decrease in CH_4 emissions (Figures 4 and 5).

4. Discussion

4.1. Effects of changing from rice to jasmine production on soil properties

The soil properties of paddies were significantly different from those in jasmine crops. Rice crops have a period of flooding that jasmine crops do not have. Soil salinity and pH were lower in the jasmine than the paddy field, consistent with previous results (Yang and Zhang, 2014; Gaddanakeri et al., 2008). The higher salinity and pH in paddy resulted because about half year was flooded. Thus, many ions, such as K^+, Ca^{2+}, Na^+, Cl^- are then dissolved in the water, thereby incrementing the soil salinity and pH due to Fe^{3+} reduction consuming H^+ (Gribsholt et al., 2003). Moreover, the paddy receives higher fertilizer amounts, and the chemical fertilizer rich in K^+, which will also increase the soil salinity and pH. Furthermore, irrigation water in paddy field is from rivers rich in ions such as K^+, Ca^{2+}, Na^+, and Cl^- coming from seawater by tide, thereby increasing the soil salinity and pH (Sharma et al., 2012), whereas Jasmine crops in Fujian are only irrigated in very dry years, very infrequently. Temperature, however, was significantly higher in the jasmine than in the paddy field, specially for the paddy field flood period, likely due to the buffering effect of flooding on temperature in the paddy field. Soil active [Fe^{2+}], [Fe^{3+}] and [total Fe] were lower in the jasmine than in the paddy field, very probably as a result of the lower fertilizer application in the jasmine field with respect to rice crop. There are two reasons: fertilizer increases the iron reduction and oxidation by microbes (Gudzic et al., 2015) and alternation of wet and dry periods in the paddy drives the non-active Fe change to active Fe, thereby increasing the active Fe concentration (Fimmen et al., 2008).

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4.2. Effects of changing from rice to jasmine production on CO_2 emissions

CO_2 emissions varied significantly among the seasons. CO_2 emission varied seasonally, increasing with crop growth and temperature. This pattern has already been reported by Liu et al. (2011). Temperature controls CO_2 production and emission (Emmett et al., 2004; Asensio et al., 2007; Inglett et al., 2012; Treat et al., 2014) by not only increasing soil microbial activity (Vogel et al., 2014), but also by altering plant respiration (Atkin and Tjoelker, 2003; Slot et al., 2013). Besides temperature and crop growth, CO_2 emissions were correlated positively with salinity and water content and negatively with [Fe^{3+}] and [total Fe] in both fields. In both croplands, the salinity is very low, but the salinity increases can provide nutrients, thereby promoting the CO_2 production and emissions. The jasmine field or the non rice growth period of the paddy are dry, and when the water content increases there is an increase in the CO_2 production and emissions (Linn and Doran 1984). The CO_2 emission was negatively correlated with [Fe^{3+}] and [total Fe] in both fields. Soil Fe^{3+} concentration increment enhances the formation of iron plaque on the crop roots and thus limits the CO_2 transport to the atmosphere (Butterbach-Bahl et al., 1997; Wassmann and Aulak, 2000).

Moreover, when soil Fe, Fe^{3+} concentrations increase, the rate of Fe^{3+} reduction also increases, and reduced Fe^{2+} accumulates in the soil (Wang et al., 2015c), which could inhibit microbial activity (Wu et al., 2012) and thus lower soil CO_2 emissions (Tavares et al., 2015). CO_2 cumulative emissions were significantly lower in the jasmine than in the paddy field, consistently with the fact that the soil carbon concentration was higher in the paddy than the jasmine field (Wang et al., 2015a). Soil carbon is the substrate for the microbial growth, and thereby its consumption increases the respiration and CO_2 emissions (Dias et al., 2010; Carbone et al., 2011; De Deyn et al., 2011). Moreover, the observed lower rice root C:P, N:P ratios, and higher P concentration than in jasmine roots (Wang et al., 2015d; Wang et al., 2016b; Wang et al., 2017a), potentially linked to higher growth rates and general activity, could also influence in the higher CO_2 emitted from soil in rice than in jasmine crops.

4.3. Effects of changing from rice to jasmine production on CH_4 emissions

CH_4 emissions were positively correlated with salinity, temperature, water content and pH in paddy field whereas in jasmine soils, CH_4 emissions were not correlated with these soil variables. In paddy soils, the higher salinity can provide the nutrients that promote the CH_4 production and emission. Temperature is the limited factors, when the temperature increment, the soil production also increased (Wang et al., 2017b). Moreover, CH_4 production needs anaerobic environments (Minamikawa et al., 2014), such as those generated during water flooding periods in paddy fields.

Soil pH is also another factor that controls CH_4 production. Our study areas have a relatively acid soil, whereas the maximum CH_4 production occurs at neutral pH (Wang et al., 2017b). Despite of this, we did not observe correlations between soil pH and CH4 in both studied crops. The CH_4 emissions varied among the seasons but not consistently for both crop fields. In paddies, CH_4 emissions were lower soon after rice transplantation when the soil was not strictly anaerobic, and also during the final ripening and drainage periods, specially for early paddy. These results agreed with those observed by Minamikawa et al. (2014). But the CH_4 emissions in jasmine field did not change significantly in total (accumulative) and in most sampling days. Jasmine fields are in dryland soils with scarce anaerobic conditions not favourable for methane production (Minamikawa et al., 2014), although some production can exist in anaerobic microsites of soils that supported methanogenesis even under non-flooded conditions (Bhattacharyya et al., 2012).

CH_4 cumulative emissions were significantly lower in the jasmine than in the paddy field as a result of both the higher soil carbon concentration in the paddies than in the jasmine fields (Wang et al., 2015a) and the more anaerobic condition in the paddies during flooding period favoring the anaerobic environment necessary for methane production (Minamikawa et al., 2014). Lowering of the water table or soil water content decreased the abundance of the methanogenic archaeal population and hence CH_4 production and increased the abundance of methanotrophs and thus CH_4 oxidation (Ma and Lu, 2011), thereby the CH_4 emissions were higher in paddy than jasmine field.

4.4. Effects of changing from rice to jasmine production on N_2O emissions

N_2O emissions were positively correlated with [Fe^{2+}], [Fe^{3+}], [total Fe], and negatively correlated with salinity, and water content in paddy fields and positively correlated with salinity, and temperature, and negatively correlated with pH, [Fe^{3+}], and [total Fe] in jasmine crops. The higher soil temperature might favor a greater N mineralization rate and hence N_2O production (Granli and Bøckman, 1994). As the pulses in NH_4^+ availability after fertilization have been related to increment of N_2O production by NH_4^+ oxidation (Pathak et al., 2002), thereby the high water content during flooding decreased N_2O production. Soil pH was negatively related to N_2O emissions in jasmine crops. Previous studies have consistently observed that under alkaline treatment, N_2O production was decreased (Wang et al., 2015c). N_2O emissions were also negatively related with iron soil concentrations in both crop types. Soil Fe^{3+} concentration increment will enhance the formation of iron plaque on the crop roots and thus limiting the N_2O transport to the atmosphere (Butterbach-Bahl et al., 1997; Wassmann and Aulak, 2000). Moreover, when soil Fe, Fe^{3+} concentrations increase, the rate of Fe^{3+} reduction also increases, and reduced Fe^{2+} accumulates in the soil (Wang et al., 2015c), which could inhibit microbial activity (Wu et al., 2012) and thus lower soil N_2O emissions (Tavares et al., 2015).

N_2O cumulative emissions were higher in the jasmine than the paddy field. N_2O emission was low throughout the rice growing season. The paddies in this region are strongly N limited (Wang et al., 2015c), so together with the low levels of soil O_2, make that most of the N_2O produced is likely reduced to N_2, leading to very low emissions or even a net uptake of N_2O (Zhang et al., 2010). For the jasmine field, the higher N_2O emissions occurred mainly in the growth period because the N fertilizer is in the form of NH_4^+, and when the soil was dry, the NH_4^+ can be oxidized to N_2O. Pulses in NH_4^+ availability after fertilization have been related to increments of N_2O production (Pathak et al., 2002). Moreover, the lower [Fe^{3+}] in the jasmine field was also associated with these higher N_2O emissions. Fewer Fe^{3+} cations in the jasmine field would decrease the competition with nitrate as electron acceptors, thereby increasing the production of N_2O. These fewer Fe^{3+} cations together with the lower pH in the jasmine field could account for the indirect effects generating higher N_2O emissions.

4.5. Integrated analysis and best management practices to reduce GWP

In general, CO_2 and CH_4 emissions were both lower five years after a paddy field was converted to jasmine production, but by different mechanisms. The conversion directly decreased soil CO_2 emissions and increased CH_4 emissions but indirectly increased CO_2 emission and decreased CH_4 emissions through its effects on soil properties. The total soil emissions of both gases finally decreased. The conversion from rice to jasmine production increased N_2O emissions due to decreases in soil pH and [Fe^{3+}]. These results strongly suggest that the different management (fertilization), the flood/dry periods in the paddy field versus the more constant soil water content in the jasmine field and probably the different plant structure (grass versus tall shrub) greatly affected overall GHG emissions. The trend to substitute rice with jasmine production in some areas of China should thus contribute to eliminating the increases (or slight decreases) in GHG emissions in China.

CO_2 was the most important GHG for the GWPs, and the total GWP was significantly lower in the jasmine than the paddy field. Changes in soil properties associated to the changes in land uses play a relevant role in the decrease of GWPs in this cropland China area. A greater control of changes in soil pH and an improvement of the loads of Fe^{3+} during fertilization are advisable to further decrease GHG emissions by the conversion from rice to jasmine production.

5. Conclusions and implications

1. CO_2 and CH_4 emissions were lower, N_2O increased, but total GWP of the emissions decreased in the Jasmine crop with respect to the rice crop.

2. Soil properties also varied significantly among the seasons. Soil salinity, water content, pH, [Fe^{2+}], [Fe^{3+}] and [total Fe] were significantly lower in the jasmine than the paddy field, but temperature was significantly higher in the jasmine field. The changes in soil properties in the conversion from rice to jasmine production had larger effects on the GHG emissions.

3. The conversion from rice to jasmine production decreased GWP emissions, and a greater

control of changes in soil pH and an improvement of the loads of Fe^{3+} during fertilization are advisable to further decrease GWP emissions.

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Table 1

Results of mixed models (lme function in nlme package in R, and with GLMM of MuMIn package function to estimate the variance explained by fixed variables and total model) with different gas emissions and studied soil variables as dependent factors, crop type (rice and jasmine) as independent fixed factor and month of measurement nested within plot as random factor.

Variable (dependent)	Model and statistics	
CO_2 emission	lme(CO_2 ~ field type, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F=5.03 P=0.031	R^2m=0.05 R^2c=0.34
CH_4 emission	lme(CH_4 ~ field type, data=dades, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m =variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F=11.7 P=0.0016	R^2m=0.14 R^2c=0.15
N_2O emission	lme(N_2O ~ field type, data=dades, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F=7.8 P=0.0084	R^2m=0.095 R^2c=0.13
Soil salinity	lme(soilsal ~ field type, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F=165 P<0.0001	R^2m=0.52 R^2n=0.78
Soil temperature	lme(T ~ field type, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable,

		R^2n = variance explained by fixed + random variables)
	F=1.98 P=0.17	R^2m=0.0048 R^2c=0.83
Soil water content	lme(water ~ field type, random=~1|plot/month	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F=134 $P<0.0001$	R^2m=0.65 R^2n=0.66
Soil pH	lme(soilpH ~ field type, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2n = variance explained by fixed + random variables)
	F= 735 $P<0.0001$	R^2m=0.91 R^2n=0.92
Soil [Fe^{2+}]	lme(Fe2 ~ field type, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F=104 $P<0.0001$	R^2m = 0.54 R^2c = 0.63
Soil [Fe^{3+}]	lme(Fe3 ~ field type, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F= 74.0 $P<0.0001$	R^2m = 0.35 R^2c = 0.66
Soil [total Fe]	lme(totalFe ~ field type, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2c = variance explained by fixed + random variables)
	F=91.4 $P<0.0001$	R^2m=0.43 R^2c=0.67

Variable	General model lme(Variable ~ field type, data=dades, random=~1|plot/month)	
	Fixed variable statistics	Model R^2 (R^2m = variance explained by fixed variable, R^2n = variance explained by fixed + random variables)
CO_2 emission	F=5.03 P=0.031	R^2m=0.05 R^2c=0.34
CH_4 emission	F=11.7 P=0.0016	R^2m=0.14 R^2c=0.15
N_2O emission	F=7.8 P=0.0084	R^2m=0.095 R^2c=0.13
Soil salinity	F=165 P<0.0001	R^2m=0.52 R^2n=0.78
Soil temperature	F=1.98 P=0.17	R^2m=0.0048 R^2c=0.83
Soil water content	F=134 P<0.0001	R^2m=0.65 R^2n=0.66
Soil pH	F= 735 P<0.0001	R^2m=0.91 R^2n=0.92
Soil pH	F= 735 P<0.0001	R^2m=0.91 R^2n=0.92
Soil [Fe^{2+}]	F=104 P<0.0001	R^2m = 0.54 R^2c = 0.63
Soil [Fe^{3+}]	F= 74.0 P<0.0001	R^2m = 0.35 R^2c = 0.66
Soil [total Fe]	F=91.4 P<0.0001	R^2m=0.43 R^2c=0.67

Table 2

Global-warming potential (GWP) of paddy and jasmine fields (average±SE, N=3) analyzed by mixed models, with plot as a random factor.

Land use	Cumulative greenhouse-gas emission (g m^{-2})			GWP (kg CO_2-eq ha^{-1})			Total GWP (kg CO_2-eq ha^{-1})
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	
Paddy field	7245±335a	25.5±1.3a	0.56±0.08a	72453±3352.48a	8865±428.13a	1667±2284a	82784±3421a
Jasmine field	4744±125b	0.31±0.44b	3.36±1.15a	47437±1245.69b	105±150b	10013±3423b	57556±3056b

Different letters within a column indicate significant differences ($P<0.05$).

Table 3 Summary of the RM-ANOVAs for the greenhouse-gas emissions and soil properties for land use.

Greenhouse gases	*df*	*MS*	*F*	*P*
CO_2				
Types	1, 4	1467851.493	48.926	0.002
Time	11, 44	1684375.311	93.170	<0.001
Types × Time	11, 44	899110.027	49.733	<0.001
CH_4				
Types	1, 4	148.652	356.113	<0.001
Time	11, 44	39.305	49.797	<0.001
Types × Time	11, 44	38.700	49.031	<0.001
N_2O				
Types	1, 4	1840123.191	5.921	0.072
Time	11, 44	544852.929	6.144	<0.001
Types × Time	11, 44	545865.122	6.155	<0.001
Soil properties				
Soil salinity				
Types	1, 4	1.765	942.596	<0.001
Time	11, 44	0.106	39.766	<0.001
Types × Time	11, 44	0.028	10.592	<0.001
Soil temperature				
Types	1, 4	11.871	15.016	0.018
Time	11, 44	199.616	386.741	<0.001
Types × Time	11, 44	17.988	34.850	<0.001
Soil water content				
Types	1, 4	12358.837	498.721	<0.001
Time	11, 44	263.692	24.063	<0.001
Types × Time	11, 44	270.197	24.657	<0.001
Soil pH				
Types	1, 4	41.283	1168.044	<0.001
Time	11, 44	0.173	17.536	<0.001
Types × Time	11, 44	0.144	14.670	<0.001
Soil Fe^{2+}				
Types	1, 4	205.010	690.008	<0.001
Time	11, 44	8.863	71.891	<0.001
Types × Time	11, 44	5.997	48.642	<0.001
Soil Fe^{3+}				
Types	1, 4	1012.485	1333.573	<0.001
Time	11, 44	118.453	88.080	<0.001
Types × Time	11, 44	41.953	31.196	<0.001
Soil total Fe				
Types	1, 4	2128.854	4219.880	<0.001
Time	11, 44	178.700	120.264	<0.001
Types × Time	11, 44	72.470	48.772	<0.001

Table 4

Average soil salinity, temperature, water content, pH, [Fe^{2+}], [Fe^{3+}] and [total Fe] (average±SE, N=3) analyzed by mixed models, with plot as a random factor.

Land use	Salinity (mS cm^{-1})	Temperature (°C)	Water content (%)	pH	[Fe^{2+}] (mg g^{-1})	[Fe^{3+}] (mg g^{-1})	[Total Fe] (mg g^{-1})
Paddy field	0.443±0.032a	21.0±1.14b	55.8±2.06a	6.35±0.03a	4.47±0.35a	15.4±1.07a	19.9±1.39a
Jasmine field	0.130±0.016b	21.8±0.79a	29.6±0.94b	4.84±0.03b	1.10±0.11b	7.88±0.56b	8.97±0.56b

Different letters within a column indicate significant differences (*P*<0.05).

Table 5

Pearson correlation coefficients between soil traits and influencing factors.

Land use	Gas	Salinity	Temperature	Water content	pH	[Fe^{2+}]	[Fe^{3+}]	[Total Fe]
Paddy field (N=36)	CO_2	0.28*	0.58**	0.35*	-0.29*	-0.58**	-0.59**	-0.60**
	CH_4	0.65**	0.55**	0.58**	-0.07	-0.28*	-0.48**	-0.44**
	N_2O	-0.36*	-0.26	-0.34*	-0.14	0.28*	0.29*	0.29*
Jasmine field (N=36)	CO_2	0.73**	0.76**	0.29*	-0.66**	-0.16	-0.61**	-0.64**
	CH_4	0.01	0.17	0.06	-0.08	0.04	0.05	0.06
	N_2O	0.51**	0.55**	0.27	-0.44**	-0.05	-0.48**	-0.49**

* *P*<0.05, ** *P*<0.01.

Figure captions

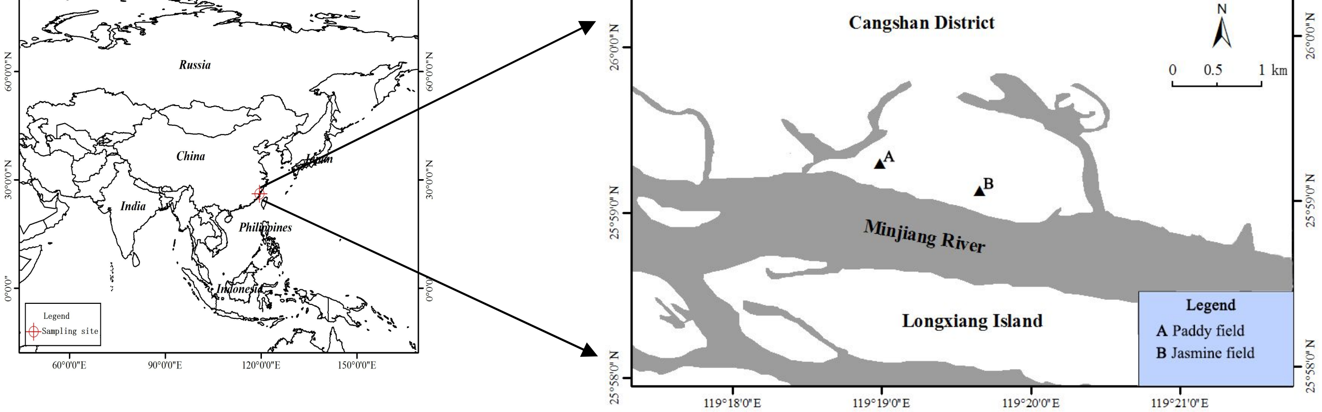
Fig. 1. Location of the paddy and jasmine fields.

Fig. 2. Seasonal variation of CO_2 (A), CH_4 (B) and N_2O (C) emission in the paddy and jasmine fields. Different letters indicate significant differences between land uses ($P<0.05$).

Fig. 3. Soil salinity (A), temperature (B), water content (C), pH (D), [Fe^{2+}] (E), [Fe^{3+}] (F) and [total Fe] (G) in the paddy and jasmine fields. Different letters indicate significant differences between land uses ($P<0.05$).

Fig. 4. Diagrams of the structural equation models that best explained the maximum variance of the CO_2, CH_4 and N_2O emissions, with the two crop types (rice and jasmine) and soil traits as exogenous factors and CO_2 (A), CH_4 (B) and N_2O emissions as endogenous variables. Positive and negative relationships are indicated by black and red arrows, respectively. The values on the arrows are standard estimates with their corresponding levels of significance. The total variance explained for each endogenous variable by the model (R^2) is also indicated beside the corresponding variable.

Fig. 5. Total, direct and indirect estimates of the effects of the variables on the final endogenous variable of each model: CO_2 (A), CH_4 (B) and N_2O (C) emissions for the structural equation models (SEMs) in Figure 4, with the corresponding level of significance of the standard estimates. * $P<0.05$, ** $P<0.001$, *** $P<0.0001$.


Russia
China
Japan
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90°0'0"E
120°0'0"E
150°0'0"E
Legend
Sampling site
Cangshan District
N
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A
B
Minjiang River
Longxiang Island
Legend
A Paddy field
B Jasmine field
26°0'0"N
25°59'0"N
25°58'0"N
119°18'0"E
119°19'0"E
119°20'0"E
119°21'0"E

Fig. 1.

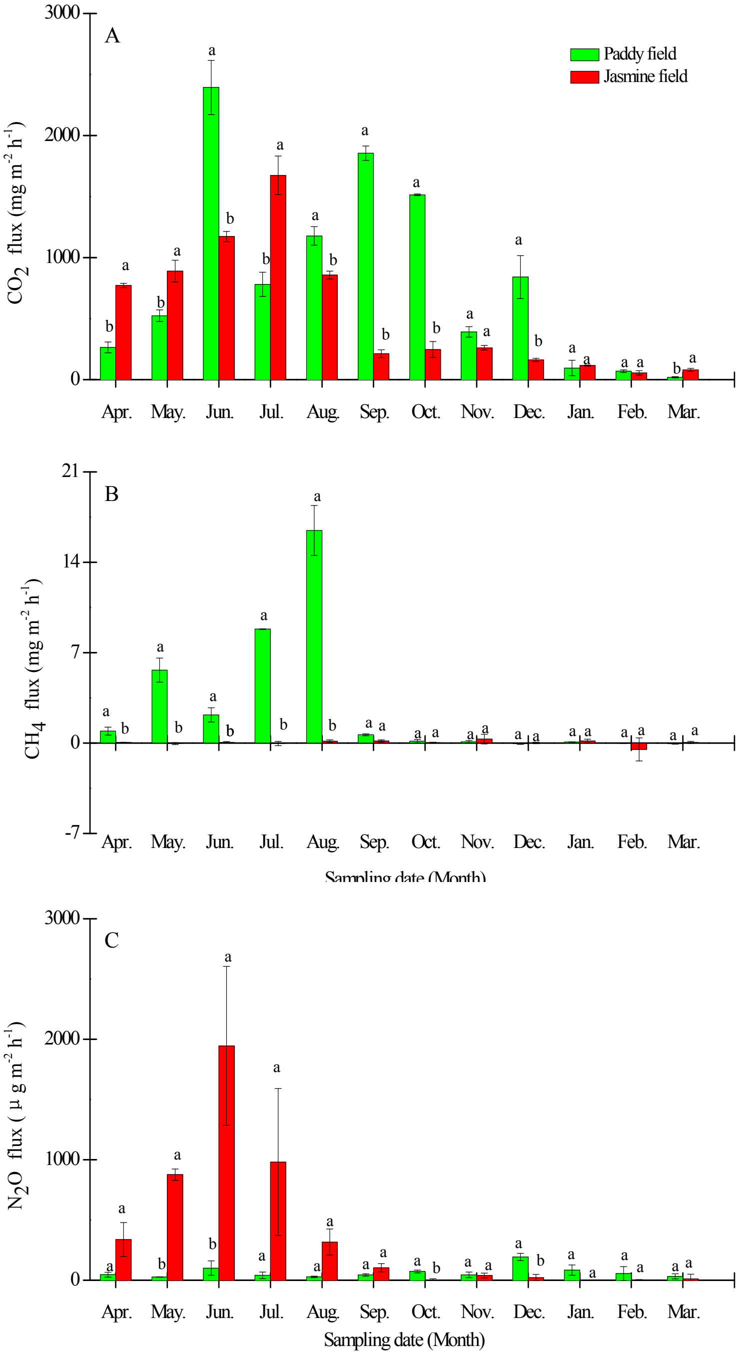
A
Paddy field
Jasmine field
CO$_2$ flux (mg m^{-2} h^{-1})
3000
2000
1000
0
b a b a a b b a a b a b a b a a a b a a a a b a
Apr.
May.
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
B
CH$_4$ flux (mg m^{-2} h^{-1})
21
14
7
0
-7
a b a b a b a b a b a a a a a a a a a a a a a a
Apr.
May.
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Sampling date (Month)
C
N$_2$O flux (μ g m^{-2} h^{-1})
3000
2000
1000
0
a a b a b a a a a a a a a b a a a b a a a a a a
Apr.
May.
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Sampling date (Month)

Fig. 2.

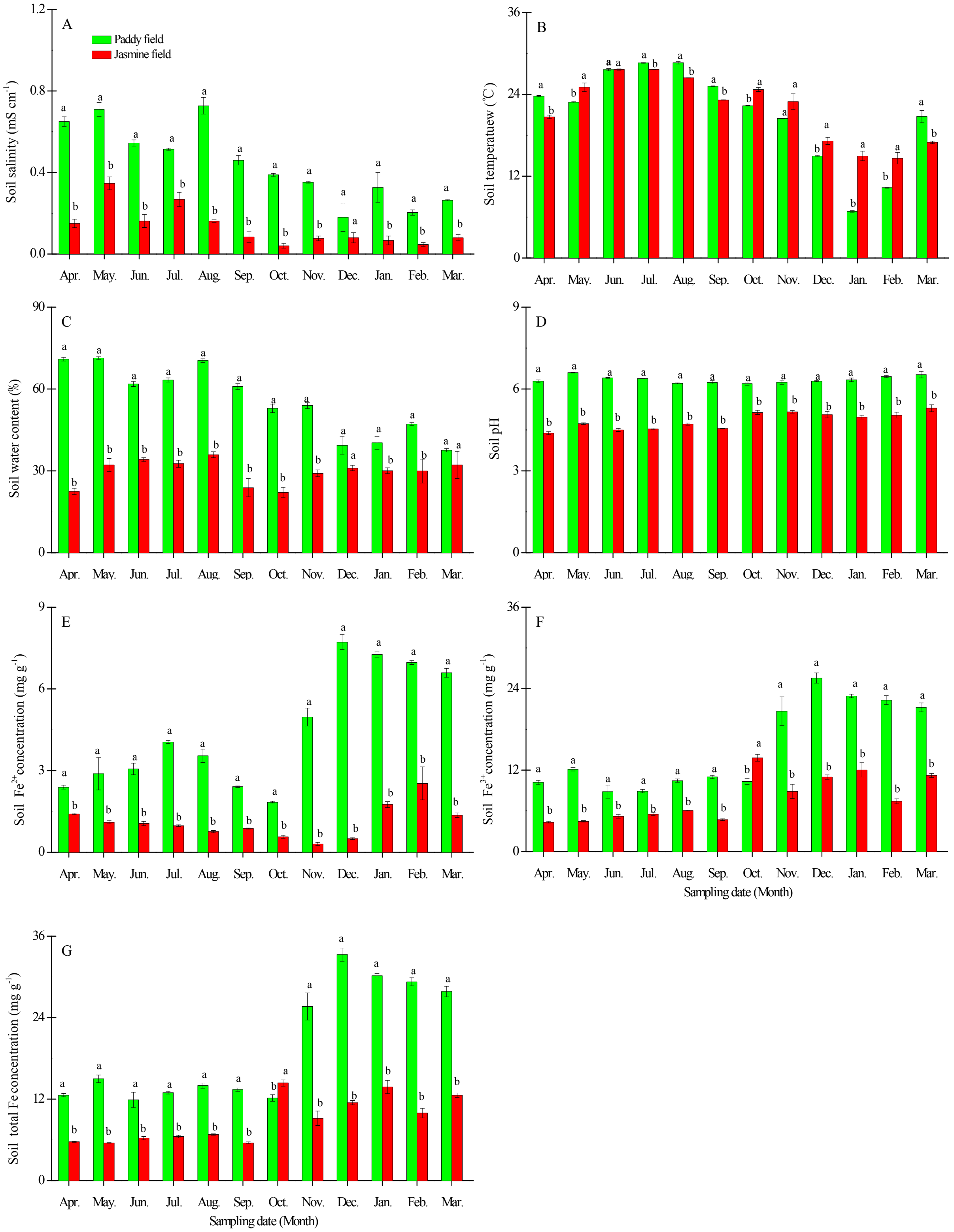
A
🟩 Paddy field
🟥 Jasmine field
Soil salinity (mS cm^{-1})
0.0
0.4
0.8
1.2
B
Soil temperatuew (℃)
0
12
24
36
C
Soil water content (%)
0
30
60
90
D
Soil pH
0
3
6
9
E
Soil Fe^{2+}concentration (mg g^{-1})
0
3
6
9
F
Soil Fe^{3+}concentration (mg g^{-1})
0
12
24
36
G
Soil total Fe concentration (mg g^{-1})
0
12
24
36
Apr.
May.
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Sampling date (Month)

Fig. 3.

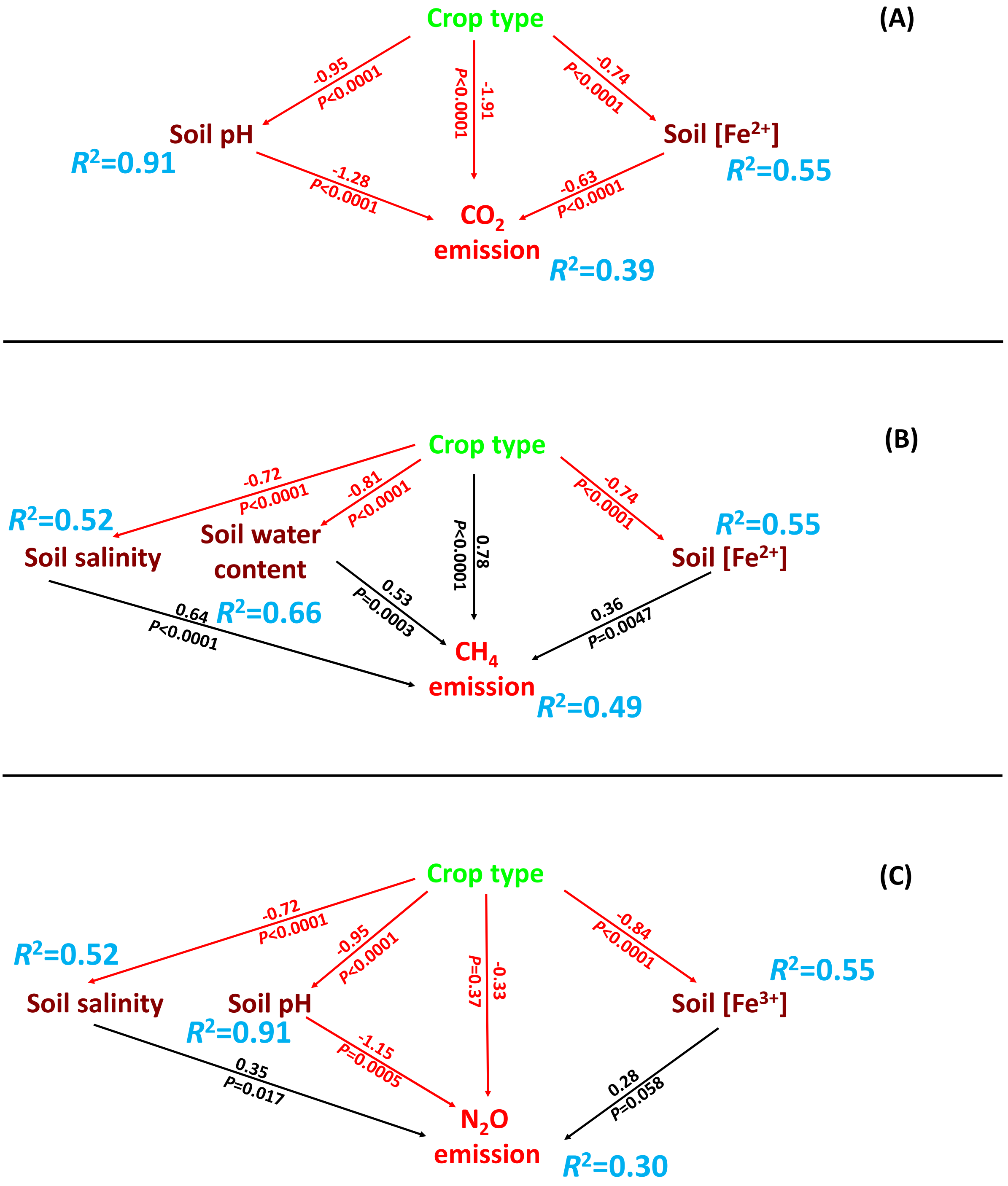
Crop type
(A)
-0.95
P<0.0001
P<0.0001
-1.91
-0.74
P<0.0001
Soil pH
R^2=0.91
Soil $[Fe^{2+}]$
R^2=0.55
-1.28
P<0.0001
-0.63
P<0.0001
CO_2 emission
R^2=0.39
Crop type
(B)
-0.72
P<0.0001
-0.81
P<0.0001
P<0.0001
0.78
-0.74
P<0.0001
R^2=0.52
Soil salinity
Soil water content
R^2=0.66
R^2=0.55
Soil $[Fe^{2+}]$
0.64
P<0.0001
0.53
P=0.0003
0.36
P=0.0047
CH_4 emission
R^2=0.49
Crop type
(C)
-0.72
P<0.0001
-0.95
P<0.0001
P=0.37
-0.33
-0.84
P<0.0001
R^2=0.52
Soil salinity
Soil pH
R^2=0.91
R^2=0.55
Soil $[Fe^{3+}]$
0.35
P=0.017
-1.15
P=0.0005
0.28
P=0.058
N_2O emission
R^2=0.30

Fig.4.

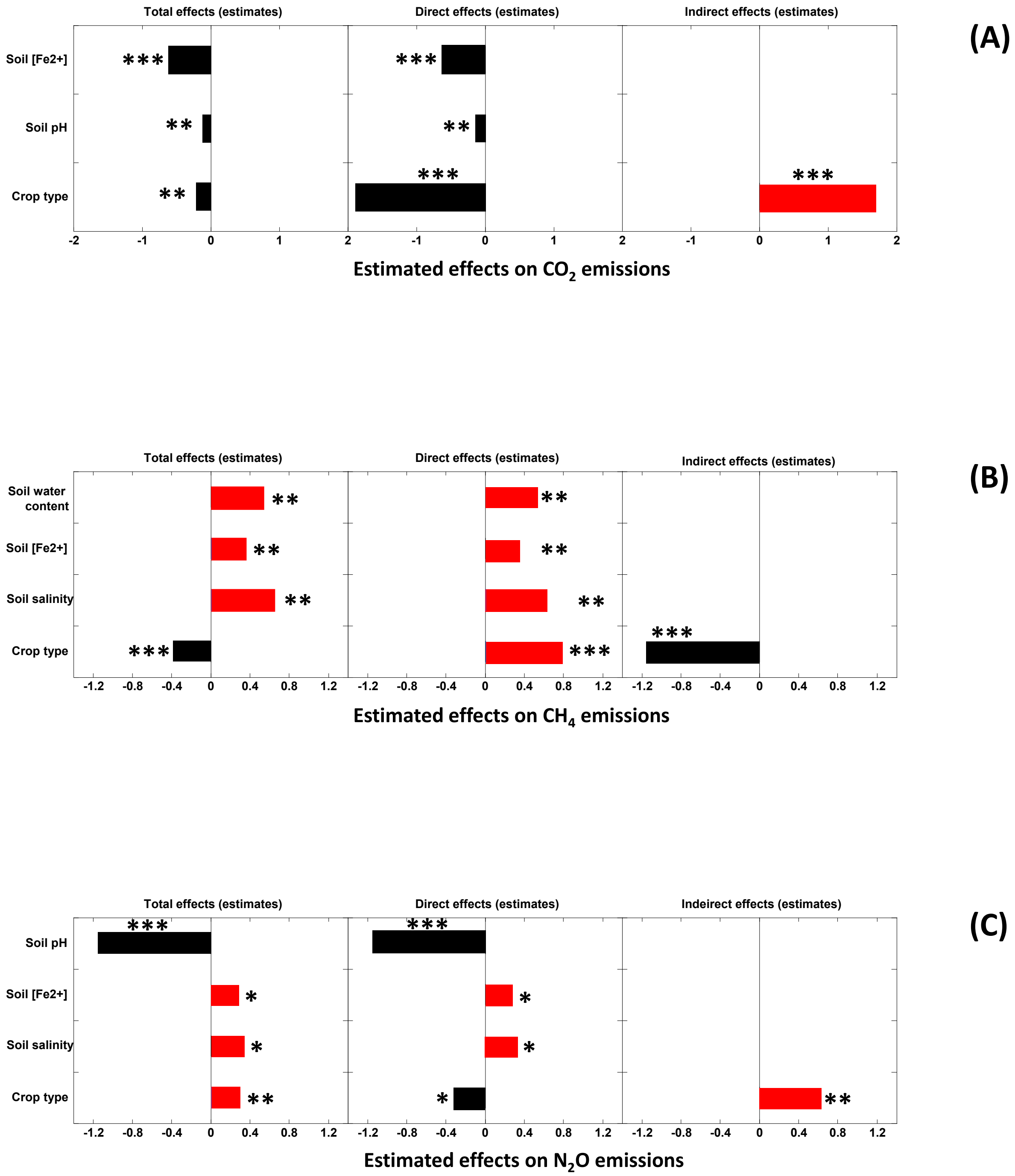
(A)
Total effects (estimates)
Direct effects (estimates)
Indirect effects (estimates)
Soil [Fe2+]
Soil pH
Crop type
***
**
**
***
**
***
***
-2
-1
0
1
2
Estimated effects on CO_2 emissions
(B)
Total effects (estimates)
Direct effects (estimates)
Indirect effects (estimates)
Soil water content
Soil [Fe2+]
Soil salinity
Crop type
**
**
**
***
**
**
**
***
***
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
Estimated effects on CH_4 emissions
(C)
Total effects (estimates)
Direct effects (estimates)
Indeirect effects (estimates)
Soil pH
Soil [Fe2+]
Soil salinity
Crop type
***
*
*
**
***
*
*
*
**
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
Estimated effects on N_2O emissions

Fig. 5.