

Article

# Optimal Coupling of Straw and Synthetic Fertilizers Incorporation on Soil Properties, Active Fe Dynamics, and Greenhouse Gas Emission in *Jasminum sambac* (L.) Field in Southeastern China

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**Abstract:** In agriculture, synthetic fertilizers have played a key role in enhancing food production and keeping the world's population adequately fed. China's participation is essential to global efforts in reducing greenhouse gas (GHG) emissions because it is the largest producer and consumer of synthetic fertilizers. A field experiment was conducted in a *Jasminum sambac* (L.) field to evaluate the impact different doses of fertilizers (half, standard, and double) and their combination with straw on ecosystem (including crop plants and soil) GHG emissions. The results showed that in comparison with the control or straw treatments, the straw + standard fertilizer treatment increased the soil water content. The fertilizer treatments decreased the soil pH, but the straw and combination treatments, especially the straw + standard fertilizer treatment, had higher soil pH in comparison with the fertilizer treatment. The active soil Fe ( $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$ ) concentration was slightly increased in the straw + standard fertilizer treatment in comparison with the control. Moreover, fertilizer increased the  $\text{CO}_2$  emission, and we detected a positive interaction between the straw application and the double fertilization dose that increased  $\text{CO}_2$  emission, but the straw + standard fertilizer treatment decreased it. Fertilizer decreased  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions, but when straw and fertilizer treatments were applied together, this increased  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions. Overall, considering the soil properties and GHG emissions, the straw + standard fertilizer treatment was the best method to enhance soil water retention capacity, improve soil acid, and mitigate greenhouse gas emissions for sustainable management of *J. sambac* dry croplands.

**Keywords:** soil properties; GHG emission; synthetic fertilizer; straw; *Jasminum sambac* (L.)

## 1. Introduction

Croplands are the ecosystems that support human life [1]. Synthetic fertilizers play a key role in the continuous increase of agriculture production. Currently, considering the environmental benefits that sustainable agriculture management provide, reduction of synthetic fertilizers by combination amendments of them with organic fertilizer or straw are used to decrease gas emissions and improve soil conditions [2,3]. Organic and inorganic fertilizer amendments cause distinct effects on soil properties. In general, long-term amendment of synthetic fertilizers can decrease soil pH, but when combining synthetic fertilizer with organic straw and manure, the pH will be higher than when using the sole synthetic fertilizer amendment [4]. Different soil environment conditions and management methods, including different types and fertilizer combinations can cause different responses in available Fe concentration, soil water content, pH, and salinity [5–7].

Global warming induced by increasing greenhouse gas (GHG) concentrations in the atmosphere is a matter of great environmental concern. The agroecosystems play a substantial role in the global budget of GHGs [8]. Agriculture is responsible for about 50% of the global anthropogenic CH<sub>4</sub> and for about 60% of N<sub>2</sub>O [9], and it can be an important source or sink of GHGs. Agricultural CH<sub>4</sub> and N<sub>2</sub>O emissions have increased by nearly 17% from 1990 to 2005 [9], and agricultural N<sub>2</sub>O emissions are predicted to increase between 23 and 60% by 2030 due to increased synthetic fertilizers and manure nitrogen inputs [10]. However, the effects of fertilization on soil GHG emissions are complicated, with conflicting results reported [11–15].

Fertilization, especially the application of synthetic fertilizers, is one of the most important and commonly used methods for plantation management and has a significant effect on soil GHGs emissions [15–18]. Nitrogen (N) fertilizer applications have been reported to increase primary production in most terrestrial ecosystems across the world [19], but their effects on soil GHGs emissions are not fully understood or they are contradictory [11–15,18,20,21]. These contradictory results may be attributed to differences in the initial C and N status, the microbial community composition, the fertilizer type and application rate [11,12,16]. For organic amendment types in the field, such as straw addition, CO<sub>2</sub> and CH<sub>4</sub> emission increased, but combination amendments with steel slag or biochar decreased the CO<sub>2</sub> and CH<sub>4</sub> emissions [6]. Therefore, considering different mixes of fertilizer amendments may be the most effective practice for agriculture sustainability. Changes or responses to increases in GHGs emissions mainly depend on a number of microbial-mediated processes in soils, and these processes are influenced by many environmental factors such as atmospheric, plant, and soil properties [22–24]. Fertilization management can influence soil variables such as soil Fe<sup>3+</sup>, temperature, pH, and salinity that strongly influence soil GHGs emissions [6,24].

To the best of our knowledge, no information is available on the effects of combined straw and fertilizer amendments on GHGs emissions in subtropical *J. sambac* plantations. A better understanding of the suitability of this combined amendment to reduce GHGs is needed, as the jasmine tea productions increasing globally. The impacts and consequences of the combined application of straw and synthetic fertilizer on soil nutrient fertility and GHGs emission, however, are poorly known. This information would provide the tools for introducing new management strategies (such as the combination of straw and synthetic fertilizers) to achieve long-term optimal nutrient conditions for the system as a whole, including an equilibrium among soil quality, crop yield and quality and the pollution/eutrophication risk from the leaching of excess exchangeable soil nutrients.

*Jasminum sambac* (L.) is a perennial and water-intensive crop, and the jasmine flower is the most important raw material for *Jasmine sambac* tea production. Developing effective strategies to enhance or maintain the yield of *J. sambac* flowers without increasing GHGs emissions from *J. sambac* plantations in subtropical China is considered an important policy for minimizing future problems of adverse climate change. More than half of the jasmine tea in China is produced in Fuzhou City [25–27]. Moreover, the organic cultivation of jasmine can increase agricultural income in comparison with common cultivation methods. Previous experiments have observed that the jasmine flower production yield did not significantly change under organic versus conventional management [28].

Moreover, after organic cultivation, soil pH and soil carbon, nitrogen, and phosphorus concentrations improved [28].

We aimed to test whether straw application, both alone and in combination with fertilizer, can improve soil conditions for jasmine production and simultaneously reduce GHGs emissions. We conducted a field study using control (CK), and different doses of standard fertilizer and straw addition. The objectives of this study were: (1) to examine the combined effects of straw and fertilizer on soil active Fe chemical forms, pH, salinity, temperature, and water content; (2) assess the active Fe dynamics and its response to soil properties; and (3) determine the relationships between environmental factors and GHG emissions. Investigating the suitability of straw and fertilizer amounts and the combination method for the management of *J. sambac* plantations and GHGs emissions is necessary for finding better ways to improve fertilizer efficiency without environmental risks.

## 2. Materials and Methods

### 2.1. Study Site and Experimental Design

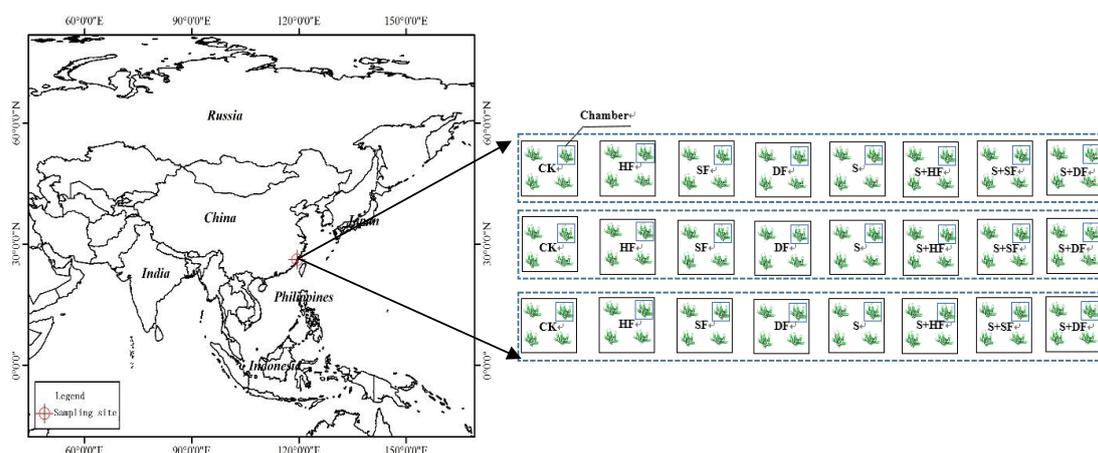
A field experiment was conducted in the Difengjiang field of *Jasminum sambac* (L.) Aiton of the Fujian Minrong Tea Co., Ltd. (Figure 1, 25°59'10"N, 119°20'7"E) in Fujian Province, China, during the *J. sambac* growing season from April to October. This region has a subtropical monsoonal climate, with a mean air temperature of about 25 °C during the study period and a mean annual precipitation of approximately 1400 mm. About 80% of the total rainfall is concentrated in the rainy season between May and October. The soil in the *J. sambac* field contained 25, 59 and 16% sand, silt and clay, respectively. The soil at the beginning of the study period had a bulk density of 1.2 g cm<sup>-3</sup>, pH of 4.4, salinity of 0.15 mS cm<sup>-1</sup> and concentrations of total carbon, total N, total P and total potassium of 11.7, 1.1, 0.5 and 13.3 g kg<sup>-1</sup>, respectively. Air temperatures and humidity during the studied period are shown in Figure S1.

The *J. sambac* was cultivated using a ridge and ditch system, with 100 cm of land (ridge) being left for plant growth between the ditches. The ridge height was 20 cm. Double-valve *J. sambac* branches 10 cm long were transplanted by hand into the ridges in April 2008 and have grown for seven years. The cultivation density was 1300 plants per plot of 20 m<sup>2</sup>. The *J. sambac* was cut to about 7 cm at the end of March or early April each year when the air temperature was about 20 °C. The *J. sambac* field was not plowed, but the soil was ridged each year after the *J. sambac* was cut. *J. Sambac* 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<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O = 16:16:16%) was applied in two unequal splits.

The common management method is standard fertilization with synthesized fertilizers. For standard fertilization, the first application was 130 kg ha<sup>-1</sup> one day after the *J. sambac* was cut, and the second application was 100 kg ha<sup>-1</sup> one day after the first *J. sambac* flowers were collected. In order to find the best fertilization management, we set decrement and increment fertilization treatments; moreover, we also set the combination of straw and fertilization to find the best choice for *J. sambac* production and the environment values. In the study site straw was never previously applied. In our study straw was applied at a rate of 3.5 Mg ha<sup>-1</sup>. The treatments involved in the experimental design are shown in Table 1. Triplicate plots (each one 20 m<sup>2</sup>) were established for the seven treatments and control in a completely randomized block design with three blocks (replicates of each control/treatment) (Figure 1). We used straw because it can provide basically two great advantages: it is in high availability and second using it as amendment we can improve water-holding capacity.

**Table 1.** Characteristic of the control and treatments of this experiment.

Treatment	Straw	First Time Fertilizer (One Day after The <i>J. sambac</i> Was Cut)	Second Time Fertilizer (One Day after the First <i>J. sambac</i> Flowers Were Collected)
No fertilizer + no straw (control, CK)	No	No	No
Half fertilization + no straw (HF)	No	65 kg ha <sup>-1</sup>	50 kg ha <sup>-1</sup>
Standard fertilization + no straw (SF)	No	130 kg ha <sup>-1</sup>	100 kg ha <sup>-1</sup>
Double fertilization + no straw (DF)	No	260 kg ha <sup>-1</sup>	200 kg ha <sup>-1</sup>
No fertilizer + straw (S)	3.5 Mg ha <sup>-1</sup>	No	No
Half fertilization + straw (S + HF)	3.5 Mg ha <sup>-1</sup>	65 kg ha <sup>-1</sup>	50 kg ha <sup>-1</sup>
Standard fertilization + straw (S + SF)	3.5 Mg ha <sup>-1</sup>	130 kg ha <sup>-1</sup>	100 kg ha <sup>-1</sup>
Double fertilization + straw (S + DF)	3.5 Mg ha <sup>-1</sup>	260 kg ha <sup>-1</sup>	200 kg ha <sup>-1</sup>

**Figure 1.** Locations of the study area, sampling site (▲) in Fujian Province, southeastern China.

## 2.2. Measurement of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O Emissions

The experimental period was from April 2015 to March 2016. Static closed chambers were used to measure ecosystem level CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions, as described by Wang et al. [5]. 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 and a gas-sampling port with a neoprene rubber septum at the top of the chamber for collecting gas samples from the headspace. Three replicate chambers in each treatment were developed. The chambers had a vent to avoid pressure buildup. The measured emissions included the contributions from both above and below ground plant biomass, and the soils.

Gas emissions were measured for all chambers twice weekly during the growing season and four times a week during the other seasons. The temperature in the chamber did not significantly change during the 30 min sampling process. 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<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O.

CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O 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 (2m length, 4mm 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<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O concentrations, respectively. The operating temperatures of the column, injector and detector for the determination of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O 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<sup>-1</sup>), and a make-up gas (95% argon and 5% CH<sub>4</sub>) was used for the ECD. CO<sub>2</sub> concentration in samples was measured by first conversion to methane with a methane-conversion furnace, and thereafter determination with a flame ionization detector (FID). CH<sub>4</sub> concentration was measured with a flame ionization detector (FID) and N<sub>2</sub>O concentration was measured with an electron-capture detector (ECD). In each sampling date we sampled in each chamber. 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. Each sample was immediately transferred to 100-ml air-evacuated aluminum-foil bags (Delin Gas Packaging Co., Ltd., Dalian, China) sealed with butyl rubber septa. Each aluminum-foil bag gas sample was used to determine the CO<sub>2</sub> concentration (Shimadzu GC-2010), CH<sub>4</sub> concentration (Shimadzu GC-2010), and N<sub>2</sub>O concentration (Shimadzu GC-2014) by three gas different injections and chromatographies. The gas chromatograph was calibrated before and after each set of measurements using 503, 1030, and 2980 μlCO<sub>2</sub> l<sup>-1</sup> in He; 1.01, 7.99 and 50.5 μlCH<sub>4</sub> l<sup>-1</sup> in He and 0.2, 0.6, and 1.0 μlN<sub>2</sub>O l<sup>-1</sup> in He (CRM/RM Information Center of China) as standards. CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions were then calculated as the rate of change in the mass of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O per unit of surface area and per unit of time. Three injections were used for each analysis. One sample was injected to the GC for each analysis. The detection limits of the instrument for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O were 1, 0.1 and 0.05 ppm, respectively.

### 2.3. Measurement of Soil Properties

Three replicates of the soil samples were collected from each treatment. The samples were transported to the laboratory and stored at 4 °C until analysis and analyzed as in Wang et al. (2016) [28]. Briefly, 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, CA, USA), salinity was measured using a 2265FS EC meter (Spectrum Technologies Inc., Paxinos, PA, USA) and water content was measured using a TDR 300 meter (Spectrum Field Scout Inc., Aurora, CO, USA). Soil bulk density was measured from three 5 × 3 cm cores per layer. The soil particle size (clay, silt and sand) was measured by a Mastersizer 2000 laser particle-size analyzer (Malvern Scientific Instruments, Suffolk, UK). C and N concentrations were determined using a Vario MAX CN Elemental Analyzer (Elementar Scientific Instruments, Hanau, Germany). Total soil P concentration was determined by perchloric-acid digestion followed by ammonium-molybdate colorimetry and measurement using a UV-2450 spectrophotometer (Shimadzu Scientific Instruments, Kyoto, Japan). Total K concentration was determined by FP 640 flame photometry (Shanghai Electronic Technology Instruments, Shanghai, China).

Soil samples were collected from the top 15 cm layer from each plot for the determination of active Fe<sup>3+</sup> ion and Fe<sup>2+</sup> ion. The total active Fe concentration was determined by digesting fresh soil samples with 1M HCl. This total active soil Fe constitutes a proxy of the Fe soil fraction available for plants. Fe<sup>2+</sup> ions were extracted using 1,10-phenanthroline and measured spectrometrically [29]. The Fe<sup>3+</sup> concentration was calculated by subtracting the Fe<sup>2+</sup> concentration from the total Fe concentration [29].

### 2.4. Statistical Analysis

To disentangle the possible interaction effects between time and treatments, we used repeated-measures analyses of variance (RM-ANOVA). The relationships between Fe dynamics, GHG emissions and soil properties were determined by Pearson correlation analysis. The significance

of treatments was tested by Bonferroni's post hoc tests. These statistical analyses were performed using SPSS Statistics 18.0 (SPSS Inc., Chicago, IL, USA).

We also performed multivariate statistical analyses using general discriminant analysis (GDA) to determine the overall differences of soil salinity, pH, water content, total active Fe concentration, Fe<sup>2+</sup> concentration and Fe<sup>3+</sup> concentration, soil temperature and CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions among control and the different fertilization and straw treatments. We used sampling dates as an independent categorical variable. 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. GDA is thus an appropriate tool for identifying the variables most responsible for the differences among groups while controlling for the component of the variance due to other categorical variables—in this case, sampling dates. The GDA was performed using Statistica 8.0 (StatSoft, Inc., Tulsa, OK, USA).

### 3. Results

#### 3.1. Soil and Properties

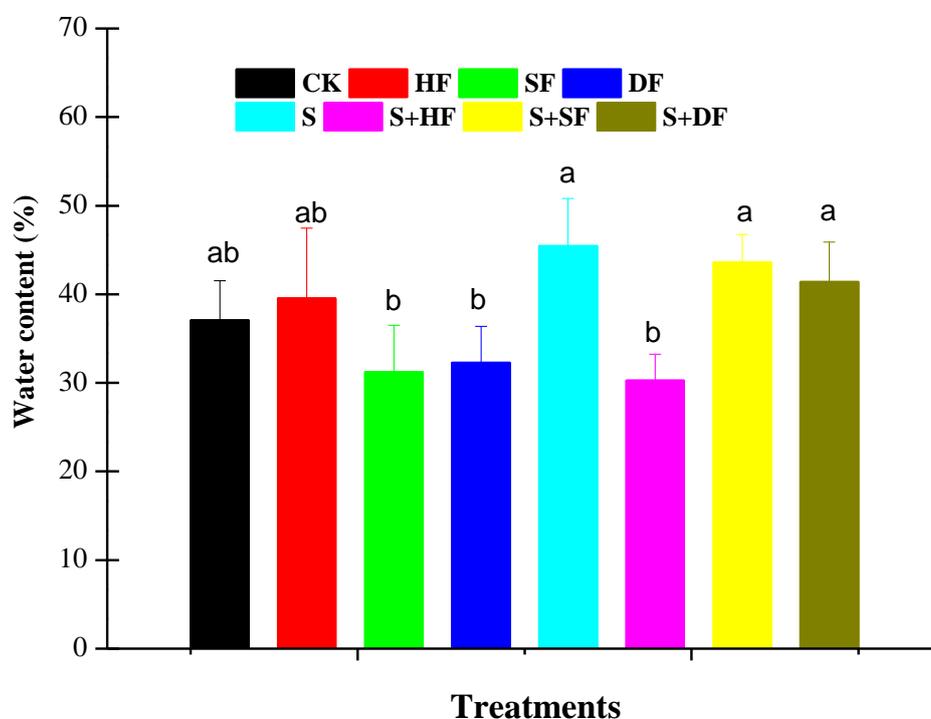
The soil water content varied significantly across sampling dates, and the interactions between treatments and sampling dates ( $p < 0.01$ , Table 2, Figure 2), but not for treatments. Soil water content was higher in the straw treatment compared with the control (an increase of about 17.5%); this was especially the case for the straw + standard fertilizer treatment, which was significantly higher than that of the control ( $p < 0.05$ ), as it showed an increment of about 22.6% ( $p < 0.05$ ). Moreover, this was also higher than that of the standard fertilizer treatment, which showed an increment of about 14.8% ( $p < 0.05$ ). Soil temperature varied significantly across treatments, sampling dates, and the interactions between treatment and sampling date ( $p < 0.01$ , Table S1, Figure 3). Compared with the control, the soil temperature was relatively low in the only-straw treatment, at about 1%. Soil pH varied significantly across treatments, sampling dates, and the interactions between treatments and sampling dates ( $p < 0.01$ , Table S1, Figure 3). In general, the standard and double fertilizer amendments significantly decreased the soil pH in comparison with the control ( $p < 0.05$ )—this was about 10.4% and 15.7%. However, the straw + standard fertilizer and double fertilizer amendments increased the soil pH in comparison with the relative fertilizer treatments (about 2.7% and 6.0%). Soil salinity varied significantly across sampling dates ( $p < 0.01$ , Table S1, Figure 3), but not for the interactions between treatments and sampling dates and treatments. Salinity was higher in the straw treatment than in the control, and it increased by about 39.8%. This was especially the case for the straw + standard fertilizer treatment, which was significantly higher than that of the control ( $p < 0.05$ ), and showed an increase of about 74.2%. During the experiment, plants receiving only fertilizer grew less in height ( $25 \pm 1.2$  cm) than plants receiving both fertilizer and straw ( $30 \pm 1.4$  cm) ( $p < 0.05$ ).

**Table 2.** Summary of the repeated-measures analyses of variances (RM-ANOVAs) for the greenhouse-gas emissions for the various amendments.

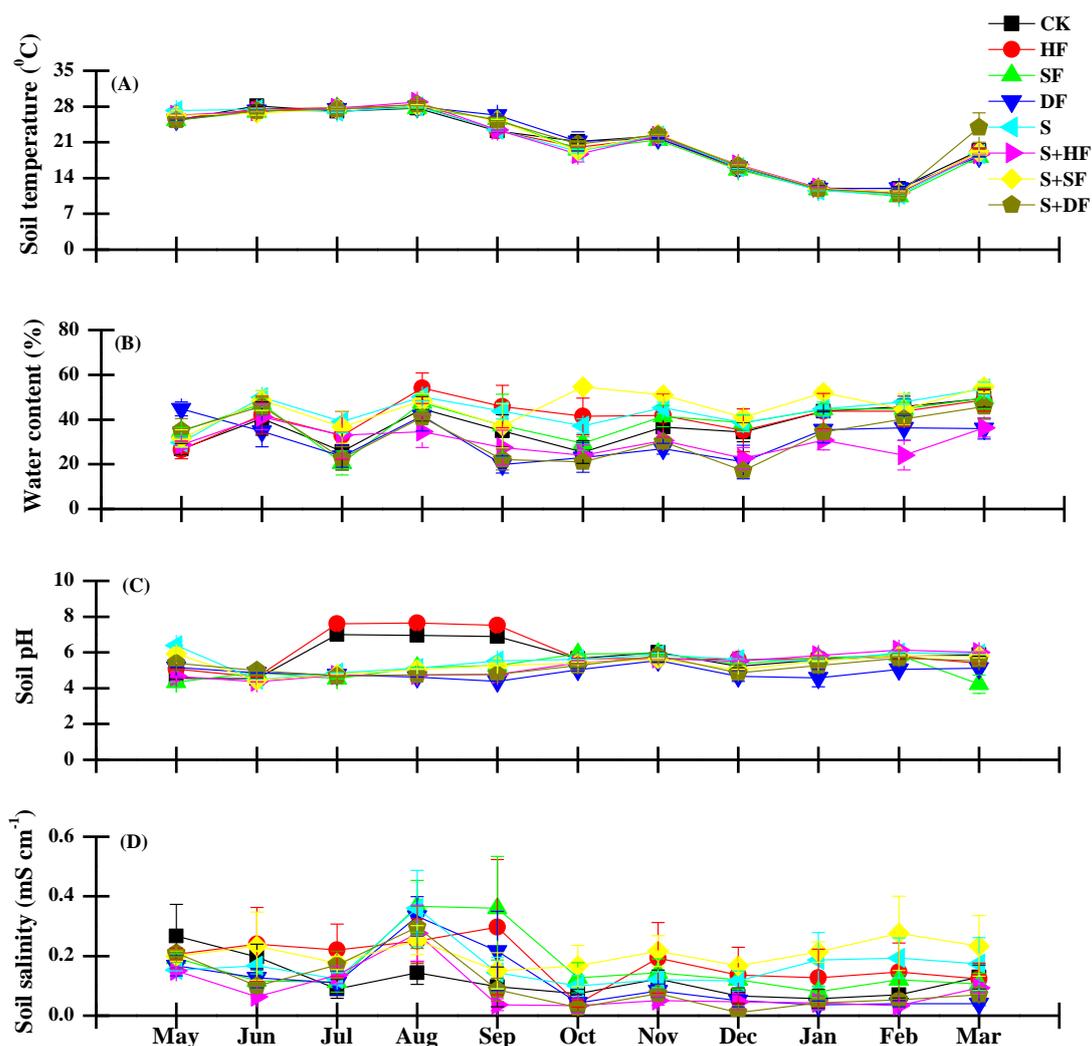
Index	Variables	df	MS	F	P
CO <sub>2</sub>	Treatments	7	2,013,690	1.27	<0.01
	Time	10	23,182,135	42.71	<0.01
	Treatments × Time	70	4,654,081	1.23	0.15
CH <sub>4</sub>	Treatments	7	119,844	4.07	<0.01
	Time	10	155,377	4.94	<0.01
	Treatments × Time	70	1,689,456	7.68	<0.01
N <sub>2</sub> O	Treatments	7	20,378	11.71	<0.01
	Time	10	212,118	85.85	<0.01
	Treatments × Time	70	488,849	28.26	<0.01

### 3.2. Soil Active Fe Dynamics

Soil total active iron, in the form of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$ , varied significantly across treatments, sampling dates, and the interactions between treatments and sampling dates ( $p < 0.01$ , Table S1, Figure 4). In general, active iron, including total active Fe,  $\text{Fe}^{2+}$ , and  $\text{Fe}^{3+}$  concentrations, were higher after September until the *J. sambac* was cut in the next year. In general, for total active Fe, the half and double fertilizer treatments decreased the concentrations in comparison with the control, by about 14% and 2%; however, the standard fertilizer treatment increased total active Fe by about 3%. The straw, straw + half fertilizer, and straw + double fertilizer treatments also decreased the total active Fe in comparison with the control, by about 7%, 1%, and 3%, respectively; however, the straw + standard fertilizer treatment increased Fe by about 1%. It appeared that this treatment represented the optimum fertilizer value for active Fe production. For the  $\text{Fe}^{2+}$  concentration, the straw + standard fertilizer treatment significantly increased the concentration by about 25%. For the  $\text{Fe}^{3+}$  concentration, straw, and the combined amendments with different amounts of fertilizer all decreased the concentration, and this may be due to straw being associated with  $\text{Fe}^{2+}$ .



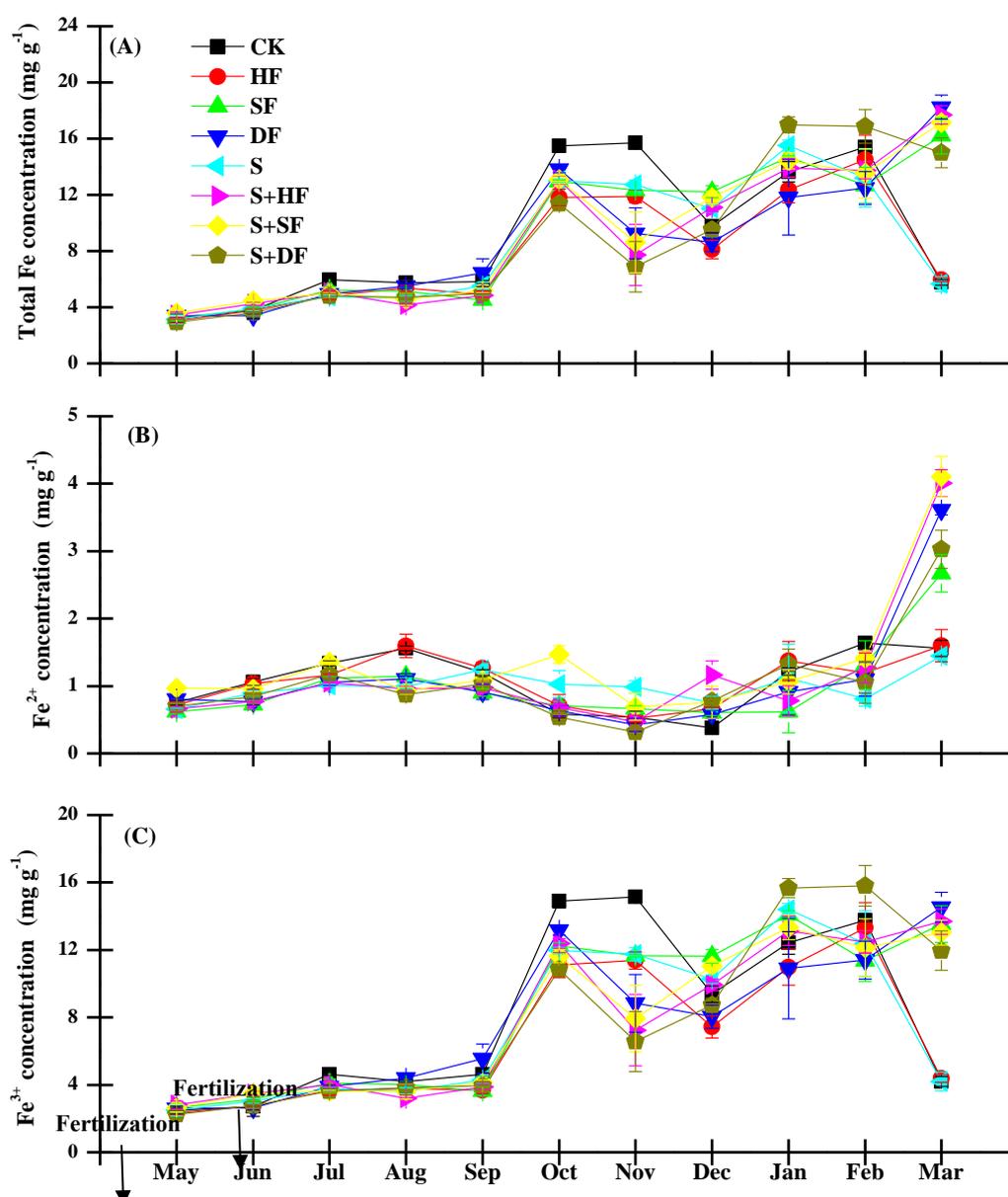
**Figure 2.** Soil water content (Mean  $\pm$  S.E., average during the studied period) in CK, HF, SF, DF, S, S + HF, S + SF, and S + DF treatments. Bar above the lines represents standard errors. CK: control, HF: half fertilizer, SF: standard fertilizer, DF: double fertilizer, S: straw, S + HF: straw + half fertilizer, S + SF: straw + standard fertilizer, S + DF: straw + double fertilizer. Different letters indicate significant differences among treatments.



**Figure 3.** Soil and plant physicochemical properties (Mean  $\pm$  S.E., in each month during the studied period). (A) soil temperature (B) soil moisture, (C) soil pH and (D) soil salinity during the whole observation period in CK, HF, SF, DF, S, S + HF, S + SF, and S + DF treatments. Bar above the lines represents standard errors. CK: control, HF: half fertilizer, SF: standard fertilizer, DF: double fertilizer, S: straw, S + HF: straw + half fertilizer, S + SF: straw + standard fertilizer, S + DF: straw + double fertilizer.

### 3.3. Relationship between Soil Fe Dynamics and Soil Properties

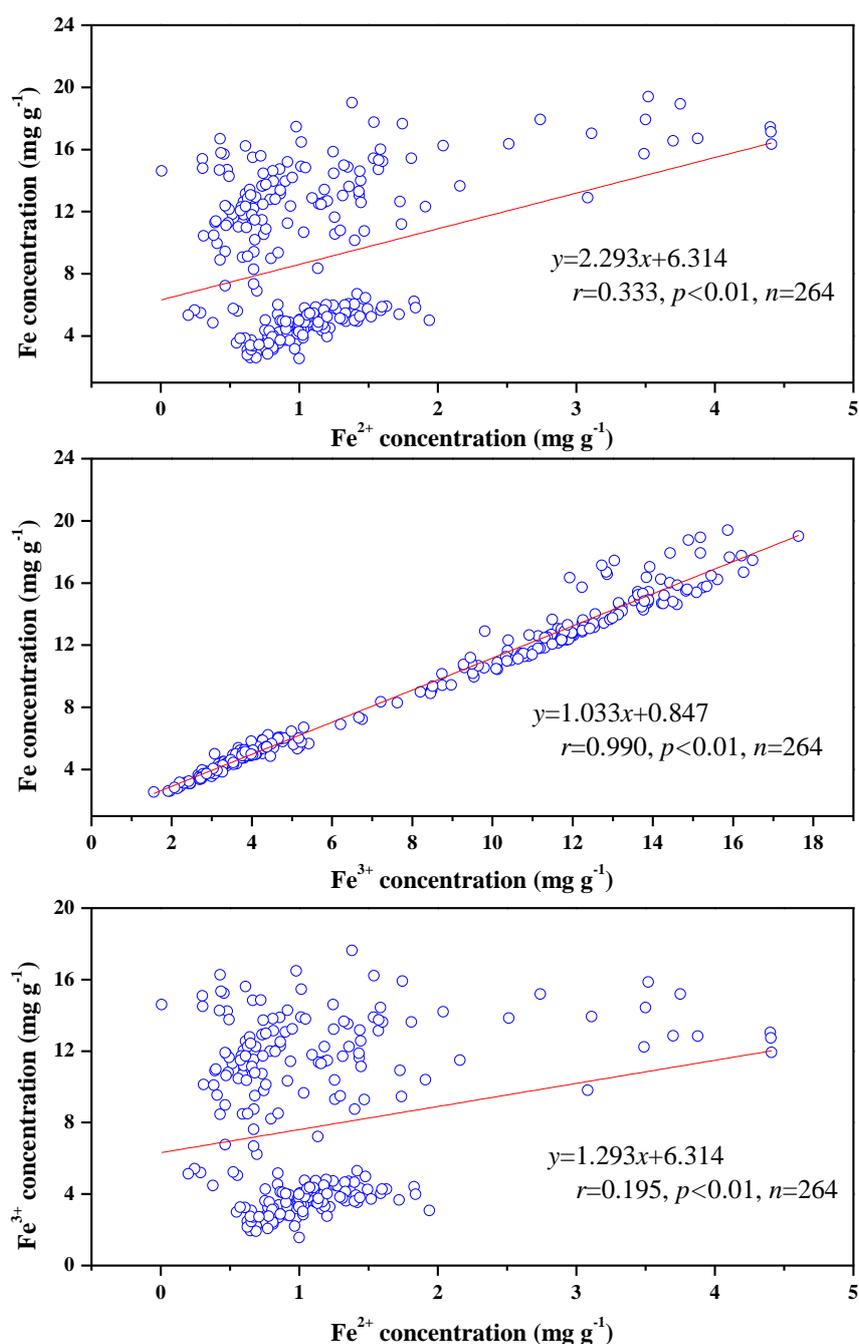
Soil total active Fe, Fe<sup>2+</sup>, and Fe<sup>3+</sup> were all significantly and positively correlated with each other (Figure 5, Table S2). Whereas, soil active Fe and Fe<sup>3+</sup> were positively related with soil pH in standard fertilization, straw + half fertilization, straw + standard fertilization, and straw + double fertilization treatments, soil Fe<sup>2+</sup> was negatively related with soil pH in standard fertilization and straw + half fertilization treatments (Table S2). Soil Fe<sup>2+</sup> was significantly and positively correlated with soil water content in control, straw, and straw + double fertilization treatments (Table S2).



**Figure 4.** Iron soil concentration (Mean  $\pm$  S.E., in each month during the studied period). (A) total Fe (B) Fe<sup>2+</sup> (C) Fe<sup>3+</sup> in CK, HF, SF, DF, S, S + HF, S + SF, and S + DF treatments during the whole observation period. CK: control, HF: half fertilizer, SF: standard fertilizer, DF: double fertilizer, S: straw, S + HF: straw + half fertilizer, S + SF: straw + standard fertilizer, S + DF: straw + double fertilizer.

### 3.4. Greenhouse Gas Emissions

CO<sub>2</sub> emissions varied significantly in each sampling date across treatments (Table 2, Figure 6), but not for the interactions between treatments and sampling dates. In general, CO<sub>2</sub> emissions increased from March (<640 mg m<sup>-2</sup> h<sup>-1</sup>), and reach a peak in July (>625 mg m<sup>-2</sup> h<sup>-1</sup>), and then decreased as the temperature declined and *J. sambac* growth slowed until the *J. sambac* was cut in the next year (Figure 6). In general, the CO<sub>2</sub> emissions were higher in the standard and double fertilizer treatments, which increased by about 1% and 11% in comparison with the control; however, the optimum straw or combination of straw and fertilizer amendment, such as straw, straw + half fertilizer, and straw + standard fertilizer treatments lowered the CO<sub>2</sub> emissions in comparison with the control, about 23%, 13%, and 8%, respectively.

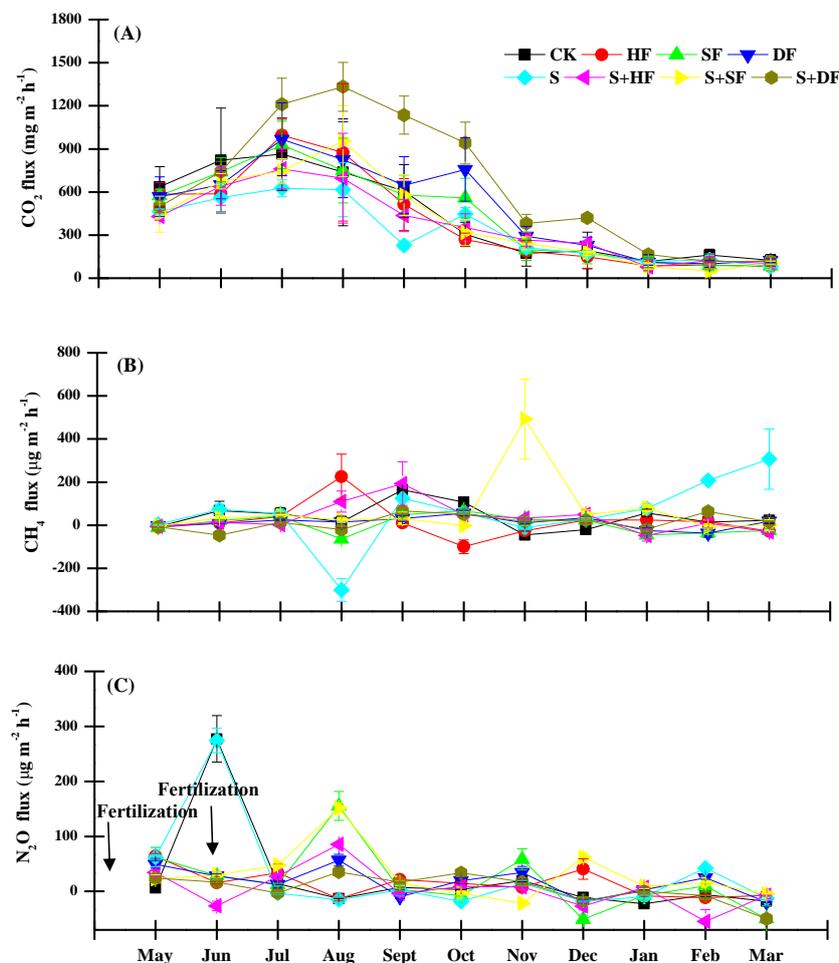


**Figure 5.** Pair-wise relationships between soil total Fe and  $\text{Fe}^{2+}$  (Top), soil total Fe and  $\text{Fe}^{3+}$  (Middle), and soil  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  (Bottom) in all treatments during the whole observation period.

$\text{CH}_4$  emissions varied significantly across different sampling dates and in different form depending on treatments (Table 2, Figure 6). In general, fertilizer treatments decreased the  $\text{CH}_4$  emission: the half, standard, and double fertilizer treatments decreased  $\text{CH}_4$  by about 57%, 89%, and 69% in comparison with the control, respectively. However, the straw treatment increased the  $\text{CH}_4$  emission, by about 45%. Moreover, the  $\text{CH}_4$  emission in the straw + half fertilizer, straw + standard fertilizer and straw + double fertilizer treatments were increased in comparison with the half, standard and double fertilizer treatments (Figure 6).

$\text{N}_2\text{O}$  varied significantly across different sampling dates and in different form depending on treatments (Table 2, Figure 6). In general,  $\text{N}_2\text{O}$  emissions were higher before September and only

had a significant emission peak for the control and fertilizer treatments, and then decreased as the temperature declined and *J. sambac* growth slowed until the *J. Sambac* was cut in the next year (Figure 6). In general, fertilizer treatments decreased the N<sub>2</sub>O emission: the half, standard, and double fertilizer treatments decreased N<sub>2</sub>O by about 39%, 16%, and 30% in comparison with the control, respectively. Moreover, the combinations of straw and fertilizer lowered the N<sub>2</sub>O emission more: the straw + half fertilizer and straw + double fertilizer treatments decreased N<sub>2</sub>O in comparison with the half fertilizer and double fertilizer treatments, by about 67% and 62%.



**Figure 6.** Greenhouse gas emissions (Mean  $\pm$  S.E., in each month during the studied period). (A) N<sub>2</sub>O–N (B) CH<sub>4</sub>–C (C) CO<sub>2</sub>–C in CK, HF, SF, DF, S, S + HF, S + SF and S + DF treatments. Bar above the lines represents standard errors. CK: control, HF: half fertilizer, SF: standard fertilizer, DF: double fertilizer, S: straw, S + HF: straw + half fertilizer, S + SF: straw + standard fertilizer, S + DF: straw + double fertilizer.

### 3.5. Relationship Between GHG and Soil Properties

CO<sub>2</sub> emission was significantly and positively correlated with the N<sub>2</sub>O emission only in control, straw + half and straw + double fertilization ( $p < 0.01$ , Table S3). CO<sub>2</sub> emission was significantly and positively correlated with soil temperature in all treatments and with soil salinity in control, double fertilization and straw + double fertilization treatment (Table S3), and was significantly and negatively correlated with soil water content in control and standard fertilization treatment, total active Fe in all treatments, Fe<sup>2+</sup> only in straw + double fertilization and with Fe<sup>3+</sup> in all treatments (Table S3). CH<sub>4</sub> emission was significantly and positively correlated with soil pH in half fertilization treatment (Table S3). CH<sub>4</sub> emission was significantly and positively correlated with soil temperature in double

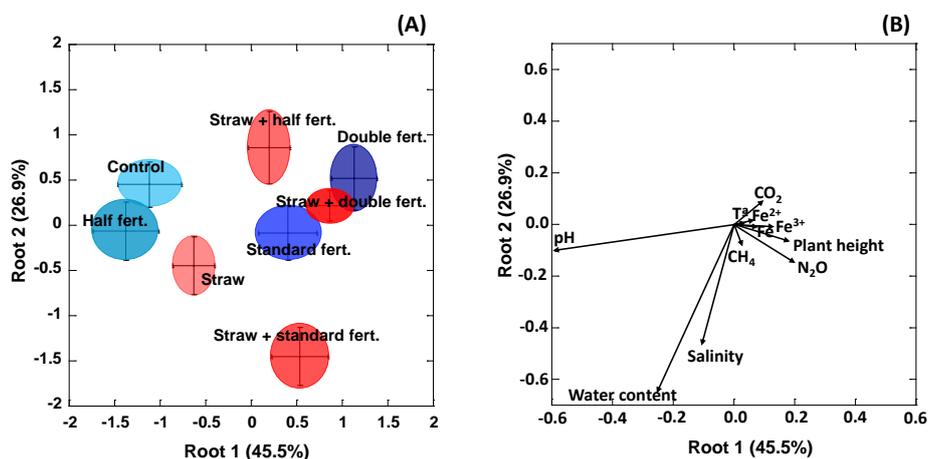
fertilization treatment and with soil salinity in standard fertilization and straw + double fertilization treatments (Table S3).  $N_2O$  emissions were positively related with soil temperature in straw and straw + fertilization treatments with soil salinity in straw + half fertilization and was negatively correlated with soil water content in straw + half fertilization treatment, with soil pH in control, straw, straw + half fertilization, and straw + standard fertilization, with total active Fe in all treatment less in straw + standard fertilization and straw + double fertilization, with  $Fe^{2+}$  in half fertilization treatment and with  $Fe^{3+}$  in half, standard, and double fertilization treatments and straw + half fertilization treatment ( $p < 0.01$ , Table S3).

### 3.6. Plant Height

In most of the treatments plants tend to reach higher height than in controls but only plants growing in straw + double fertilization plots grow significantly more in height than plants in control and in half fertilization plots (Figure S2).

### 3.7. General Discriminant Analysis

The plot formed by the first two roots of the GDA, with all studied variables as independent continuous variables, showed that the treatment with straw + standard fertilization was clearly placed along route 2 towards the highest soil water content and salinity, variables that mainly loaded the second root (Figure 7). This analysis also showed that soil pH, plant height, and  $N_2O$  emissions are the variables that mainly loaded root 1, whereas soil water content and soil salinity mainly loaded root 2 and, thus, were the variables that mainly separated the different treatments (Tables S4 and S5, Figure 7). Thus this multivariate analysis clearly showed that soil traits and plant size had highly proportion role in treatment overall differences whereas soil emissions have lower role in treatment differences (Tables S4 and S5, Figure 7). Most treatments were separated in the GDA model (Table S5), and we observed that straw plus standard fertilization was separated from other treatments including control and only standard fertilization by higher soil water content and salinity and did not differ practically for gas emissions that in fact had low separation role among treatments.



**Figure 7.** Results of the General Discriminant Analysis (GDA) performed with soil pH, water content, salinity, temperature, total Fe,  $Fe^{2+}$ , and  $Fe^{3+}$ , plant height, and soil  $CO_2$ ,  $CH_4$ , and  $N_2O$  emissions as independent continuous variables, different treatments as dependent categorical grouping variables, and the time of sampling as the controlling categorical independent variable. Layout (A) showed the distribution (mean  $\pm$  95% confidence intervals) of different treatments and the control in the layout formed by the first two roots of the GDA, together explaining 72.4% of the total variance. Plot (B) shows the independent variable distributions according to their layouts on these first two root axes.

## 4. Discussion

### 4.1. Effects of Straw, Fertilizer Doses, and Their Combination on Soil Properties

Soil water content was higher in the straw treatment in comparison with the fertilizer treatment, which could be attributed to the ability of straw in absorbing water, therefore keeping the soil wetter. Also, the addition of straw could reduce soil temperature and hence evaporation of soil water, which helps to retain water in the soil [30]. The average soil water content during the studied crop period was higher in straw, straw + standard fertilization and straw + double fertilization treatment (Figure 2). The soil pH was lower in the fertilizer treatments compared with the control, because of nitrification of  $\text{NH}_4^+$  from the fertilizer, leading to the most acid material being kept in the soil, thereby decreasing the soil pH [31]. These lower nitrification rates in only fertilization treatments are consistent with the lower soil pH in these treatments given that the optimum pH for nitrification is around 8.5. However, the combination amendment of straw and fertilizer increased the soil pH compared with the fertilizer treatments, especially for the straw + standard fertilizer treatment, which could be explained by straw containing many alkaline compounds [5,27]. Salinity was higher for the straw + fertilizer treatments compared with the fertilizer treatments and control. Straw contains numerous elements essential for plant growth, including nitrogen, phosphorus, potassium, calcium, sodium, etc. [3,32,33] that following straw decomposition could contribute to increase of salinity. Moreover, the optimum fertilizer promotes straw decomposition [34] and then these elements, including nitrogen, phosphorus, potassium, calcium, sodium, etc., can be released more quickly.

### 4.2. Effects of Straw, Fertilizer Doses, and Their Combination on Active Iron Dynamics in the Soil

In general, total active Fe and  $\text{Fe}^{3+}$  concentrations were lower in treatment plots compared with the control, except for the straw + standard fertilizer treatment, for which  $\text{Fe}^{3+}$  was the main form of total active Fe, which was similar to previous work [6]. Moreover, in our study,  $\text{Fe}^{3+}$  ions and total active iron was significantly correlated, which is consistent with Fe characteristics in dry land sites [6]. In our study, the  $\text{Fe}^{3+}$  concentration was decreased by the fertilizer treatment. The fertilizer included N in  $\text{NH}_4^+$  form, which could stimulate the production of hydroxylamine through the biological oxidation of  $\text{NH}_4^+$  in dryland conditions. Hydroxylamine may have further reacted to result in the chemical reduction of  $\text{Fe}^{3+}$  [35] or may have induced microbial activity by  $\text{Fe}^{3+}$  reduction [36]. The straw also decreased  $\text{Fe}^{3+}$  concentration, likely because it is a carbon substrate that can promote  $\text{Fe}^{3+}$  reduction [37] and thus lower the  $\text{Fe}^{3+}$  concentration. Furthermore, straw, alone and in combination with fertilizer, increased plant growth [38], and more Fe can be absorbed and accumulated in plant biomass. Moreover, in our study, the pH was lower than 7.0, which does not favor rapid  $\text{Fe}^{2+}$  oxidation, thereby lowering  $\text{Fe}^{3+}$  production [39]. In our study, soil pH was lower in the fertilizer treatment compared with the control, and therefore had lower  $\text{Fe}^{3+}$  concentrations after fertilizer amendments. The period from July to September coincided with summer and thus with strong rain and irrigation. Under these conditions, controls and half fertilization treatment would have less capacity to affect soil's interchangeable complex and thus mobilization of more  $\text{H}^+$  than other treatments. They also have less capacity to retain water in soil in particular with respect treatments providing straw and thus partially avoiding leaching.

### 4.3. Active Iron Correlations and Their Influencing Factors

Soil total active Fe,  $\text{Fe}^{2+}$ , and  $\text{Fe}^{3+}$  were all significantly and positively correlated with each other. The results showed that the different forms of soil Fe were the transformation substrates for each other [40–42]. Soil  $\text{Fe}^{3+}$  was significantly and negatively correlated with soil salinity, because higher salinity inhibits bacterial iron oxidation [43], then  $\text{Fe}^{3+}$  was lowered once the soil  $\text{Fe}^{3+}$  was absorbed by the plant [44], thus lowering the  $\text{Fe}^{3+}$  concentration in the soil. Soil  $\text{Fe}^{2+}$  was significantly and positively correlated with soil water content, which can induce flooding and the development of anaerobic conditions favoring  $\text{Fe}^{3+}$  ion reduction [45], and microbial  $\text{Fe}^{3+}$  ion reduction, and increasing  $\text{Fe}^{2+}$  concentration [46].

#### 4.4. Effects of Straw, Fertilizer Doses, and Their Combination on CO<sub>2</sub> Emission

CO<sub>2</sub> emission varied seasonally, increasing with plant growth and temperature. Temperature controls CO<sub>2</sub> production and emission by increasing soil microbial activity [47], as well as altering plant respiration. The observed relationships between CO<sub>2</sub> emissions and plant growth were consistent because more active plant activity was likely associated with greater rates of growth and activity, thereby favoring higher overall ecosystem CO<sub>2</sub> emissions. In general, the CO<sub>2</sub> emissions were higher in the fertilizer treatments compared with the control for several potential reasons. Firstly, fertilization, such as N fertilization, promotes the deposition of photosynthetically derived C into soil organic carbon pools [48], and soil CO<sub>2</sub> emissions could increase after the labile carbon substrates increase [49]. Secondly, fertilizer can provide many nutrients for microbial growth [50], and an increase in microbial activity promotes soil respiration and thus the emission of CO<sub>2</sub> [51]. Thirdly, NH<sub>4</sub><sup>+</sup> from fertilizers can be oxidized to NO<sub>3</sub><sup>-</sup> when soil is drained, increasing soil NO<sub>3</sub><sup>-</sup> concentration. The NO<sub>3</sub><sup>-</sup> would be reduced when the soil is reflooded by the mechanism that oxidizes organic carbon producing CO<sub>2</sub> [5]. Moreover, the NH<sub>4</sub><sup>+</sup> amendment may have been associated with Fe<sup>3+</sup> ion reduction by improving N supply for iron reducing bacteria, which would also increase the production and release of CO<sub>2</sub> as described on the previous sentence. [52]. Moreover, the Fe<sup>3+</sup> ion reduction increment should also decrease the number of iron plaques on the roots, which would promote root ventilation and increase the transport of materials throughout the plants [53], so more CO<sub>2</sub> is produced and transported through the internal system of the plants. Moreover, in the straw + standard fertilizer treatments in particular, we observed a decrease of CO<sub>2</sub> emission in comparison with the control. Some studies have already observed that fertilization management among farming practices can be the best tool to drive soil organic carbon(SOC) balances in cropping lands [54]. Both standard fertilization treatment and standard fertilization despite not having significantly different consequences in plant growth, thus have different soil CO<sub>2</sub> emissions. This strongly suggested that the low ecosystem CO<sub>2</sub> emissions observed following straw incorporation was probably due to microbial changes rather than plant root activities.

#### 4.5. Effects of Straw, Fertilizer Doses, and Their Combination on CH<sub>4</sub> Emission

The different peak and lowest fluxes of CH<sub>4</sub> were caused mainly by the integrative effect of soil pH, salinity, and water content [24]. In our study, fertilizer treatment decreased CH<sub>4</sub> emissions. Fertilizer included N in the form of NH<sub>4</sub><sup>+</sup>, which can quickly oxidize to NO<sub>3</sub><sup>-</sup> in aerobic dryland [55]. NO<sub>3</sub><sup>-</sup> is the most important electron acceptor, which can inhibit methane production [5], because NO<sub>3</sub><sup>-</sup> reducing bacteria tends to outcompete methanogens. Moreover, methane can be oxidized by NO<sub>3</sub><sup>-</sup> through nitrate reducing bacteria and later denitrification-dependent anaerobic methane oxidation can increase methane oxidation [56]. In addition, NO<sub>3</sub><sup>-</sup> reduction produces nitrite, and nitrite can have a toxic effect on methane producing microbes, and therefore inhibiting methane production [57]. Moreover, the NH<sub>4</sub><sup>+</sup> amendment in our study may have been associated with Fe<sup>3+</sup> ion reduction [52], which, as one of the most important electron acceptors, should also decrease CH<sub>4</sub> production via a similar mechanism as NO<sub>3</sub><sup>-</sup>. Besides the above, fertilization also increases the availability of nutrients and raises the plant biomass, which will promote soil oxygen concentration, and then inhibit CH<sub>4</sub> production and emissions from microbes. Moreover, the straw, straw + half fertilizer, and straw + standard fertilizer treatments increased the CH<sub>4</sub> emission. Straw would lead to more organic C input into soils, and thus, as the production substrate increases, CH<sub>4</sub> emission increases [58]. Moreover, in our study, the soil water content also increased for the straw, alone and in combination with the fertilizer. This water increment induces a relatively anaerobic environment, which promotes methane production [59].

#### 4.6. Effects of Straw, Fertilizer Doses, and Their Combination on N<sub>2</sub>O Emission

N<sub>2</sub>O emission was higher during the first month of fertilizer application as compared to later stages. A high N<sub>2</sub>O emission during the first month was probably associated to the conversion of nitrate (coming from NH<sub>4</sub><sup>+</sup> oxidation) from N fertilizer into N<sub>2</sub>O [60] because the beginning of our experiment was during the rainy season in the study areas. A decreased N<sub>2</sub>O emission after the first month would be explained by the decreased availability of nitrate because of its conversion into N<sub>2</sub>O. Previous studies have reported significant increases in N<sub>2</sub>O emissions upon addition of fertilizers and a subsequent decrease with time [61–63]. High N<sub>2</sub>O emissions were observed in all treatments during the initial stage of fertilizer application, suggesting that addition of the N substrate increased microbial activity [60]. However, in general, the averaged N<sub>2</sub>O emissions were lower in the fertilizer treatments, because the study area was N limited. Indeed, a previous study reported decreased N<sub>2</sub>O emissions in the same paddy fields after fertilizer amendment [64]. In our study, the N added in the fertilizer was quickly absorbed into the plant biomass, which lowered the soil N concentration, thereby leading to decreased N<sub>2</sub>O production and emissions. We also observed that under straw treatments, the N<sub>2</sub>O emissions were also decreased, which was related to increased C:N substrate input that strengthened the N limitation in the soil [5]. However, if straw and fertilizer are used, as in the straw + fertilizer treatment, N<sub>2</sub>O emissions can also be increased.

#### 4.7. Relationship between GHG and Soil Properties

CO<sub>2</sub> emission was positively correlated with the N<sub>2</sub>O emission. This could be due to the production of both of these GHGs occurring simultaneously, and NO<sub>3</sub><sup>-</sup> reduction can also produce these GHGs. Despite these results some previous studies have observed that, CO<sub>2</sub> can limit the NH<sub>4</sub><sup>+</sup>-oxidizer microbe populations [65]. CO<sub>2</sub> emission was significantly and positively correlated with soil temperature. Temperature controls CO<sub>2</sub> production and emission not only by increasing soil microbial activity [47], but also by altering plant respiration [48]. Moreover, CO<sub>2</sub> emission was significantly and positively correlated with soil salinity in our study and the salinity was relatively low (<1 mS cm<sup>-1</sup>). Salinity is formed by the presence of numerous elements, including nitrogen, phosphorus, potassium, calcium, sodium, etc., which are essential for plant [66] and microbe growth [67], therefore favoring higher plant and microbe CO<sub>2</sub> emissions. However, CO<sub>2</sub> emission was significantly and negatively correlated with soil water content, consistent with higher anaerobic conditions, which would lead to lower respiration and CO<sub>2</sub> emission [68]. Moreover, the CO<sub>2</sub> emission was significantly and negatively correlated with soil active Fe because Fe is the most important cementing material, which can combine carbon by chemical bonds, and make it more stable [69]. Following this, the active carbon substrate is lowered, which then decreases the organic matter metabolic use and mineralization, thus reducing CO<sub>2</sub> production and emission [70].

CH<sub>4</sub> emission was significantly and positively correlated with soil pH. This relationship is consistent in our study because the soil is acidic; this type of soil inhibits methane producing microbes and methane production. Therefore, the optimum methane production occurs when the pH is near neutral, and methane production increases as the pH rises.

N<sub>2</sub>O emission was significantly and positively correlated with soil temperature, because as temperature increases, soil microbial NH<sub>4</sub><sup>+</sup> oxidation is promoted, and the nitrification process can produce more N<sub>2</sub>O and increase N<sub>2</sub>O emission [71]. N<sub>2</sub>O emission was significantly and positively correlated with soil salinity. A previous study showed that a salinity increment promoted N<sub>2</sub>O emission [72]. In our study, NO<sub>3</sub><sup>-</sup> was the main N substrate in the dryland, and the N<sub>2</sub>O production pathway maybe dominated by denitrification, which was promoted as salinity increased, and was then responsible for higher N<sub>2</sub>O production and emission [73]. N<sub>2</sub>O emission was significantly and negatively correlated with soil pH; N<sub>2</sub>O production is enhanced in slightly acidic pH [74], but in our study, the soil pH value was habitually lower than 7.0, thereby favoring the negative correlation. Moreover, N<sub>2</sub>O emission was significantly and negatively correlated with soil Fe<sup>2+</sup> and Fe<sup>3+</sup>. This is associated with the role of Fe as the most important cementing material, which can combine organic

matter, including N, by chemical bonds, and thus decreasing N availability, which will then decrease N<sub>2</sub>O production and emission [75].

#### 4.8. Best Management Practices to Improve Soil Properties and Reduce GWP

Our results showed that the straw + standard fertilizer treatment increased average soil water content during the studied year after treatment applications, thus indicating a better soil capacity to retain water, which is very important for a good management of dryland management. More data of other sites and for longer periods including several years are necessary to corroborate this result. The first 15 cm of soil depth, during the crop period there was on average  $683 \times 10^3 \text{ kg}\cdot\text{ha}^{-1}$  of water in straw + standard fertilization treatment whereas in only standard fertilization treatment the water content was  $594 \times 10^3 \text{ kg}\cdot\text{ha}^{-1}$ . The results, despite based only in one-year measurements strongly suggest that straw application could be an effective measure for increasing water storage as well as for conserving soil water. This will be especially important in crops in dry conditions such as Jasmine. Straw can also avoid soil dispersion and sealing by heavy rains in the rainy season of this subtropical zone, thus more nutrients can be stored in the soil and increase *J. sambac* growth. The results thus provide a clear clue that the use of straw has a great potential to enhance soil water content and therefore to improve crop productivity. This could be a relevant improvement since the areas of jasmine cultivation in China are more than 12,000 hm<sup>-2</sup> and they are on expanding (China Tea Circulation Association, 2017). Moreover, China has millions of ha of dry crops, a part of *J. sambac* dry, where straw could be also applied. Water and nutrient increments would increase plant growth in those dryland areas [5,76–78].

Soils amended with straw, alone and in combination with synthetic fertilizer, had higher pH in comparison with soils with only fertilizer treatment. This effect can help to solve the soil acidity problem, which is very important in dryland soils where long-term synthetic N fertilization intensifies soil acidification [79]. Soil acidity reduces yield, root growth, and nutrient uptake [80]. Organic material, such as manure or straw, can improve the soil pH [5,77,79], thus increasing the soil nutrient retention capacity and thus availability for plants, and can therefore increase the crop yield [77].

In the subtropical zone, plant growth is significantly limited by nutrient availability, especially N [81]. In our study, the active Fe decreased after application of fertilizer, straw, and in combination treatments, except in the straw + standard fertilizer treatment. In a previous study, an amendment of steel slag, rich in Fe, in the paddy field increased the rice yield [77], and this may also be possible for *J. sambac* growth and production, especially when combined with straw.

Moreover, in our study, synthetic fertilizer increased the CO<sub>2</sub> emission, but the straw + standard fertilizer treatment decreased it, which revealed that the proper management and optimum combination of straw and fertilizer can provide better control of CO<sub>2</sub> emissions in drylands. However, fertilizer decreased CH<sub>4</sub> and N<sub>2</sub>O emissions, and in the case of these both gasses, the straw + fertilizer treatment increased their emissions. The results of this study are consistent with previous studies showing that the application of straw improves fertilization management by maintaining yield while diminishing GHGs emissions [82]. Moreover, jasmine crops emit less CO<sub>2</sub> and CH<sub>4</sub> and more N<sub>2</sub>O than rice crops in this area of China [83].

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2071-1050/11/4/1092/s1>, Figure S1: Air temperature and air humidity, Figure S2: Plant height in control and distinct treatments, Table S1: RM-ANOVAs of the soil properties, Table S2: Correlation among different soil variables, Table S3: Correlations of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O gas emission with the different soil variables, Table S4: Main effects of the variables in the GDA analysis, Table S5: Test statistics for squared Mahalanobis distances among treatments and control in the GDA analysis.

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