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RESEARCH ARTICLE

Greenhouse gas emissions in a subtropical jasmine plantation managed with straw combined with industrial and agricultural wastes

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Abstract

The effects of straw alone or combined with industrial and agricultural wastes as fertilizers on greenhouse gas (GHG) emissions are still poorly known in cropland areas. Here, we studied the effects of 3.5 Mg ha^{-1} straw and 3.5 Mg ha^{-1} straw combined with 8 Mg ha^{-1} of diverse wastes on GHG emission in a subtropical *Jasminum sambac* plantation in southeastern China. There were five treatments in a completely randomized block design: control, straw only, straw + biochar, straw + steel slag, and straw + gypsum slag. Emissions of carbon dioxide were generally higher in the treatments with waste than in the control or straw-only treatments, whereas the contrary pattern was observed in CH_4 and N_2O emission rates. Moreover, the total global warming potentials (GWPs) were no significantly higher in most of the amended treatments as compared to the control and straw-only treatments. In relation to the treatment with only straw, GWPs were 9.4% lower when steel slag was used. This finding could be a consequence of Fe amount added by steel slag, which would limit and inhibit the emissions of GHGs and their transport from soil to atmosphere. Our results showed that the application of slags did not increase the emission of GHGs and that the combination of straw with steel slag or biochar could be more effective than straw alone for controlling GHGs emission and improve soil C and nutrient provision.

Keywords: CH_4; CO_2; N_2O

Introduction

Global warming is caused by emission of large amounts of greenhouse gases (GHGs) to the atmosphere from the combustion of fossil fuels, land-use changes, and other human activities (IPCC, 2014). Global GHG emissions from agricultural activities are about 5.1–6.1 Pg CO_2-eq year^{-1} (Smith *et al.*, 2007), which can contribute to approximately 20% of the current emissions (Hütsch, 2001). The emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from agricultural lands are especially relevant (Myhre *et al.*, 2013). Minimizing the emission of GHGs is an important task for mitigating their adverse impacts on climate change. Many methods

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have been developed to reduce and/or control the emission of GHGs, through water, fertilizers, and tillage management (Gupta *et al.*, 2016; Malhi *et al.*, 2006; Peyron *et al.*, 2016).

Recycling industrial and agricultural wastes is becoming an effective way to solve environmental and resource availability issues, with the application of industrial and agricultural wastes on agricultural lands gradually increasing (Wang *et al.*, 2015a,b). The effects of waste application on soil nutrients and properties (Prendergast-Miller *et al.*, 2014), plant growth (Wang *et al.*, 2015a,b), and GHG emission (Zhang *et al.*, 2012) have been evaluated, and biochar (Zhang *et al.*, 2012) and steel slag (Wang *et al.*, 2012) have been widely studied for increasing crop yield. However, the effect of mixed waste application on the emission of GHGs is more complex and has been rarely and inconclusively studied. Industrial and agricultural wastes contain high concentrations of electron acceptors, such as the active and free oxide forms of iron (Fe), sulfur, nitrogen (N), and phosphorus (P).

Recently, biochar application has been found to significantly increase soil CO_2 fluxes by 22%, while decreasing N_2O fluxes by 31% without any effect in CH_4 fluxes (He *et al.*, 2017). Such effects were dependent on latitude, soil type, and soil use (Fan *et al.*, 2017; He *et al.*, 2017). The use of steel and gypsum slag to reduce GHGs emissions has been less studied, despite reduction in GHGs emissions in rice fields (Susilawati *et al.*, 2015). Accordingly, the combined application of biochar and steel slag has been associated with decreases in GHG emissions in rice fields (Wang *et al.*, 2016; 2017). In general, few studies have provided an overall evaluation of the total global warming potential (GWP) of CO_2, CH_4, and N_2O, the three main GHGs (Wang *et al.*, 2015a,b).

At the best of our knowledge, no information is available on the effects of industrial and agricultural wastes on GHG emissions from subtropical jasmine (*Jasminum sambac*) plantations. More than half of jasmine tea is produced in Fuzhou Province, China (Yang *et al.*, 2008), and developing effective strategies to enhance the yield of jasmine flowers without increasing GHG emissions is considered as an important policy for minimizing future adverse conditions induced by climate change. On the other hand, the use of waste materials for the management of jasmine plantations and GHG emission would be an alternative way to recycle waste without environmental risks.

Here, we evaluated the effects of various waste materials (straw, and straw combined with steel slag, biochar or gypsum slag) as fertilizers on the GHG emissions by jasmine fields, taking into account soil traits and the relationships between CO_2, CH_4, and N_2O emissions and soil traits.

Materials and Methods

Study site and experimental design

An experiment was conducted in a *J. sambac* (L.) field in Fujian Province, China (Supplementary Figure S1, 25°59′10″N, 119°20′7″E), during the growing season from April to October 2015. 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 (Wang et al., 2019). The soil contained 25, 59, and 16% sand, silt, and clay, respectively. Bulk density was 1.2 g cm^{-3}, pH 4.4, salinity of 0.15 mS cm^{-1}, and concentrations of total C, total N, total P, and total K were 11.7, 1.1, 0.5, and 13.3 g kg^{-1}, respectively. The study site has been cultivated with *J. sambac* since 2008. *J. sambac* was cultivated using a ridge and ditch system, with a ridge height of 20 cm, a ridge width of 100 cm, and a ditch width of 30 cm. In April 2008, double-valve jasmine branches (10 cm long) were transplanted by hand at a distance of 3 cm among them along the ridges and 20 cm from the nearest plant in the side ridges. The *J. sambac* was harvested at the end of March or early April each year, when the air temperature was about 20 °C. About 3.5 Mg ha^{-1} of branches and leaves were returned to the field, which was ridged but not plowed each year. The initial growth

Table 1. Elemental concentrations of the different waste amendments in this study

Treatments	Chemical properties										
	Fe_2O_3 (%)	Fe (%)	SO_3 (%)	S (%)	SiO_2 (%)	C (%)	N (%)	P (%)	K (%)	Mg (%)	Ca (%)
Steel slag	4.8	–	–	–	40.7	0.79	0.01	0.01	0.5	0.36	24.9
Biochar	–	0.2	–	0.6	–	56.6	1.4	1.0	1.8	1.0	0.5
Gypsum slag	0.4	–	54.4	–	0.7	0.7	0.01	0.01	0.1	0.3	30.6

period occurs from early April to end May, with flowering occurring from early June to late September, when the final growth period begins. $N:P_2O_5:K_2O$ (16:16:16) was applied to soil 1 day after pruning (130 kg ha^{-1}) and 1 day after harvesting the first flowers (100 kg ha^{-1}).

Triplicate plots (20 m^2 each) were established for five treatments in a completely randomized block design: (i) no straw or waste (control); (ii) straw only (straw); (iii) straw combined with steel slag (straw + steel slag); (iv) straw combined with biochar (straw + biochar); and (v) straw combined with gypsum slag (straw + gypsum slag). Straw was added at 3.5 Mg ha^{-1}, and the biochar and steel and gypsum slags were added at 8 Mg ha^{-1} as granules (2 mm in diameter). The steel slag was collected from the Jinxing Iron & Steel Co., Ltd in Fujian (China). The biochar was collected from the Qinfeng Straw Technology Co., Ltd in Jiangsu Province. The gypsum slag was collected from building waste (from the indoor decoration of buildings). The industrial and agricultural wastes used in this study were rich in Si, Ca, and K, which are essential nutrients for plant growth (Prendergast-Miller *et al.*, 2014) (Table 1). All treatments received the same water management.

Measurement of CO_2, CH_4, and N_2O emissions

The experimental period was from April 2015 to March 2016. Static closed chambers were used to measure CO_2, CH_4, and N_2O emissions, as described by Wang *et al.* (2015a). The chambers were made of rigid Polymer of Vinyl Chloride and consisted of two parts, an upper transparent 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. Three replicate chambers in each treatment were used. A wooden boardwalk was built for accessing the plots to minimize the disturbance of the soil during gas sampling. The chambers had a vent to avoid pressure buildup.

Gas flux was measured for all chambers twice weekly during the growing season and four times a week during the other seasons. The temperature inside chambers was not significantly changed during the sampling process (30 min). 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 evaluation of CO_2, CH_4, and N_2O concentrations.

CO_2, CH_4, and N_2O concentrations were determined by gas chromatography (GC-2010 and GC-2014; Shimadzu, Kyoto, Japan) using a stainless steel Porapak Q column (2-m length, 4-mm External Diameter, 80/100 mesh). A methane-conversion furnace, flame ionization detector, and electron capture detector (ECD) were used for determining CO_2, CH_4, and N_2O concentrations, respectively. The operating temperatures of the column, injector, and detector for quantifying CO_2, CH_4, and N_2O 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. 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. Three injections were used for each analysis. One sample was injected to the Gas Chromatography for each analysis, and the detection limits of the instrument for CO_2, CH_4, and N_2O were 1, 0.1, and 0.05 ppm, respectively.

Global warming potential

GWP is typically estimated using CO_2 as the reference gas, and changes in emission of CH_4 or N_2O are converted to 'CO_2-equivalents' (Hou *et al.*, 2012). The GWP of the combined emission of CH_4 and N_2O was calculated as (Cavigelli and Parkin, 2012; IPCC, 2014): GWP = (cumulative CH_4 emission $\times$ 28) + (cumulative N_2O emission $\times$ 265).

Measurement of soil properties

Three replicates of soil samples were collected from each treatment. 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. Soil pH was measured with a pH/temperature meter (IQ Scientific Instruments, Carlsbad, CA, USA), while salinity was measured using a 2265FS EC meter (Spectrum Technologies Inc., Paxinos, PA, USA) and water content was measured using a Time Domain Reflectometry 300 meter (Spectrum Field Scout Inc., Aurora, CO, USA). Soil samples were collected from the 0- to 15-cm layer from each plot for quantifying ferric, ferrous, and total Fe concentrations. Total Fe concentration was determined by digesting fresh soil samples with 1-M HCl. Ferrous ions were extracted using 1,10-phenanthroline and measured spectrometrically (Lu, 1999). Ferric concentration was calculated by subtracting the ferrous concentration from the total Fe concentration. Sixty days after treatment (DAT), total soil C, N, and P were analyzed. Total soil C and N were determined by an Elementar Vario MAX CN Analyzer (Elementar Scientific Instruments, Hanau, Germany). Total soil P concentration was quantified by perchloric acid digestion followed by ammonium–molybdate colorimetry, using a UV-2450 spectrophotometer (Shimadzu Scientific Instruments, Kyoto, Japan). We calculated the amounts of C, N, and P accumulated in the first 0–30 cm of soil in the different plots by calculating the soil C, N, and P contents (equivalent ha) for each plot.

$$X_{ij} = [X]_{ij} \times \text{Soil mass in the } 0-30 \text{ cm of soil depth by ha,}$$

where $X =$ C, N, or P; $i =$ control or treatments; $j =$ plot.

Statistical analysis

Differences in soil properties and CO_2, CH_4, and N_2O emissions among the treatments were tested for statistical significance by repeated measures analyses of variance. The relationships between mean GHG emissions and soil properties were evaluated by Pearson correlation analysis. These statistical analyses were performed using SPSS Statistics 18.0 (SPSS Inc., Chicago, IL, USA). The effects of treatments on total soil C, N, and P concentrations were analyzed by one-way analysis of variance and Bonferroni *post hoc* test using Statistica 8.0 (StatSoft, Inc., Tulsa, OK, USA).

Results

### Effects of the treatments on soil properties

Soil pH, temperature, water content and ferrous, ferric, and total Fe concentrations varied among the treatments (Figures 1, 2, Supplementary Figures S2 and S3, Supplementary Tables S1 and S2). Soil pH values followed this order: straw + steel slag > straw + biochar = straw + gypsum > straw > control. Soil temperature did not change among treatments and control (Figure 1B.), whereas soil salinity values followed this order: straw + gypsum > straw = straw + steel slag > straw + biochar > control, and soil–water content was higher in straw + biochar treatment with respect to control and straw (Figure 1D). Soil Fe^{2+} concentration followed this order: straw = straw + steel slag > straw + biochar = straw + gypsum slag > control, while Fe^{3+} concentration was higher in control than in straw and straw + biochar treatments (Figure 2A,B). Total soil Fe concentration was higher in the straw + steel slag treatment than in the control, straw, and straw + biochar treatment (Figure 2C).

After 60 days of experimental period, soil total C, N, and P stocks in the first 30 cm of soil depth were higher in treated plots than in control ones (Figure 3). Total soil C and N stocks followed the order: straw + biochar > straw + steel slag = straw + gypsum slag > straw > control (Figure 3A, B). Total soil P stocks values followed the order straw = straw + steel slag > straw + biochar = straw + gypsum slag > control (Figure 3C). This means that treated soils stored higher amounts of C, N, and P than control plots.

CO_2, CH_4, and N_2O emissions and their relationships with soil variables

CO_2 emission varied significantly among sampling dates but not among treatments (Supplementary Tables S3 and S4). In general, CO_2 flux remained low (<1040 mg m^{-2} h^{-1}) during the first 16 DAT and then increased to a seasonal peak (>1610 mg m^{-2} h^{-1}) between 16 and 91 DAT (Figure 4A). *J. sambac* was nearly mature by 106 DAT, with a corresponding decrease in CO_2 emission. No significant changes in CH_4 emissions were found among different treatments, including control (Supplementary Tables S3 and S4). CH_4 flux was low during the whole sampling period (<1.61 mg m^{-2} h^{-1}, on average) (Figure 4B). N_2O emission varied significantly among sampling dates, but not among treatments (Supplementary Tables S3 and S4). Maximum fluxes were earliest in the straw + gypsum treatment at 16 DAT (2.11 mg m^{-2} h^{-1}), and the N_2O flux peaked at 46 DAT in the control (2.56 mg m^{-2} h^{-1}), straw (2.01 mg m^{-2} h^{-1}), straw + biochar (1.78 mg m^{-2} h^{-1}), and straw + steel slag (1.57 mg m^{-2} h^{-1}) treatments (Figure 4C). Then, N_2O emissions from the *J. sambac* plantation presented a decreasing trend until 316 DAT. The flowering period lasted from 91 DAT to the harvest day and the maximum plant height occurred at 91 DAT, with small and nonsignificant changes in plant height from 91 to 286 (harvest) DAT (Figure 4D).

Cumulative CO_2, CH_4, and N_2O emissions were not statistically different among treatments (Figure 5, Supplementary Tables S3 and S4). Seasonal CO_2 and N_2O emissions were correlated positively ($p < 0.01$) with soil temperature (Supplementary Table S5) and negatively with soil Fe^{3+} and total Fe concentrations ($p < 0.01$) in all treatments. CO_2 emissions were also positively correlated with soil salinity (except in straw treatment) and water content (except in straw + biochar and straw + steel slag). Seasonal CH_4 emission was negatively correlated with soil Fe^{2+} concentration ($p < 0.05$) in the straw and straw + steel slag treatments. N_2O emissions were positively correlated with salinity (except in control and straw + steel slag) and water content (except in control and straw + steel slag) ($p < 0.05$). Finally, N_2O emissions were negatively correlated with soil pH in control, straw, and straw + biochar treatments and positively correlated with N_2O in straw + gypsum slag. Total GWP emissions ($CH_4 + N_2O$) were similar among treatments (Table 2).
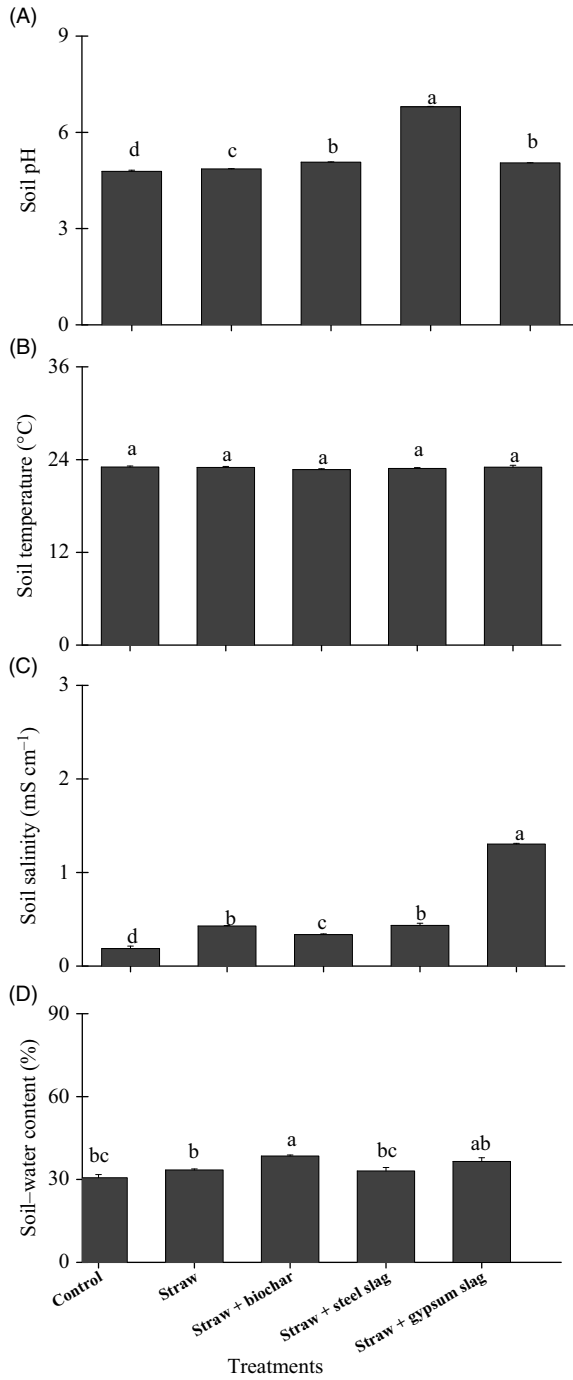
Figure 1. Mean ± S.E. during the studied period of soil pH (A), temperature (B), salinity (C), and water content (D) in the control and treatment. Different letters indicate significant differences ($p < 0.05$) between treatments.
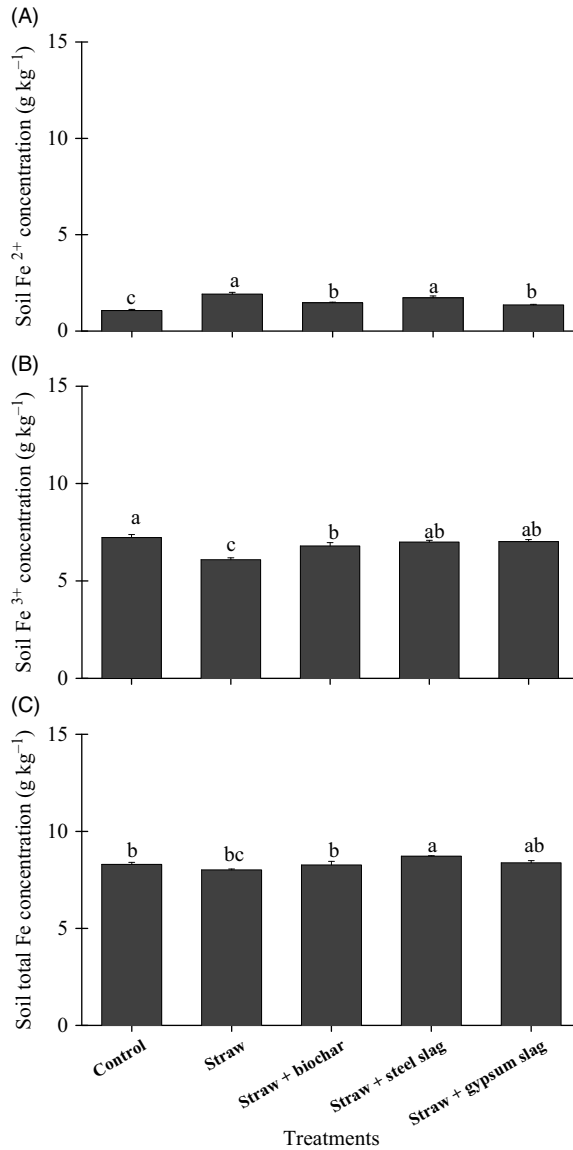
Figure 2. Mean ± S.E. during the studied period of soil Fe^{2+} concentration (A), Fe^{3+} concentration (B), and total Fe concentration (C) in the control and treatment. Different letters indicate significant differences ($p < 0.05$) between treatments.

Discussion

Effects of the treatments on soil properties

Soil pH was higher in the straw + biochar, straw + steel slag, and straw + gypsum slag treatments than in the control and straw treatments (Figure 1), likely due to the high alkalinity of the amendment material. Many cations are released due to the increase of pH (Wang *et al.*, 2015a), and soil salinity was significantly higher in the amended treatments than the control (Figure 1, Supplementary Table S3, $p < 0.05$). The straw, biochar, steel, and gypsum amendment materials used in this study contained some elements such as K and Ca that can easily be released into the soil solution increasing the salinity (Wang *et al.*, 2015a). Soil–water content was also higher in the
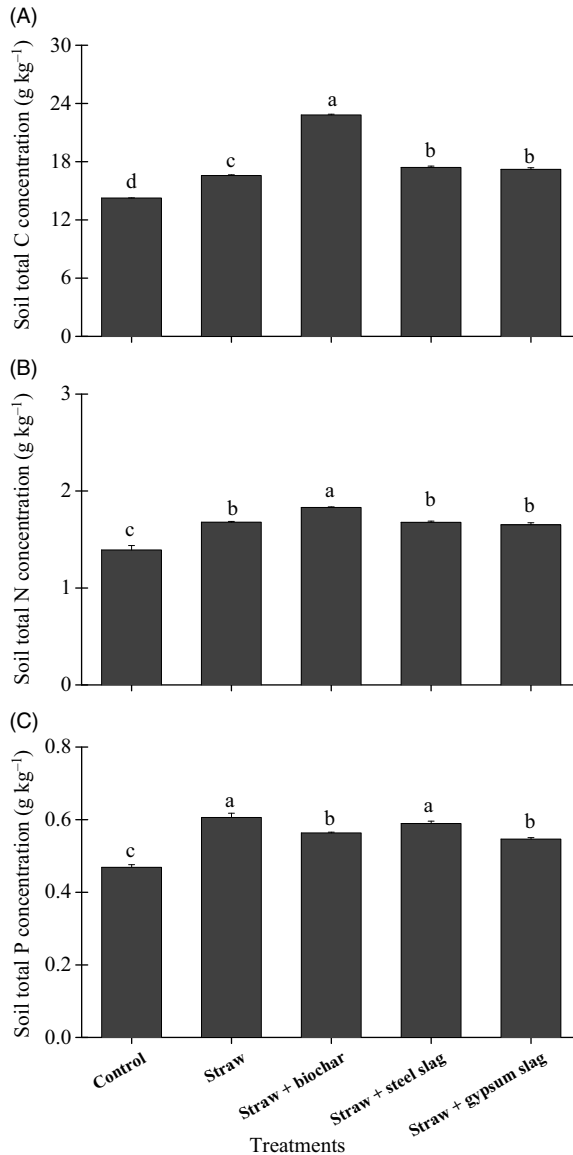
Figure 3. Total soil C (A), N (B), and P (C) stocks (t ha^{-1} at 0–30 cm) observed in each treatment plots after treatments application. Error bars indicate one standard error of the mean of triplicate measurements. Different letters indicate significant differences ($p < 0.05$).

straw + biochar treatment than in the control and straw treatments (Figure 1). Biochar can absorb water because of its high total porosity, and it can thus increase soil–water content (Asai et al., 2009).

Soil Fe^{2+} concentration was significantly higher in all amended treatments than in the control (Figure 2, Supplementary Table S3). The wastes are rich in minerals containing Fe^{3+}, and straw decomposition would add more carbon substrates, such as short-chain fatty acids that can act as electron donors and favor altogether the conditions for Fe^{3+} reduction to Fe^{2+} (Li et al., 2011). At this regard, it is important to highlight the important inputs of Fe by the treatments, that is, 207, 16, and 17 kg ha^{-1}, for steel slag, biochar, and gypsum slag, respectively. Higher soil
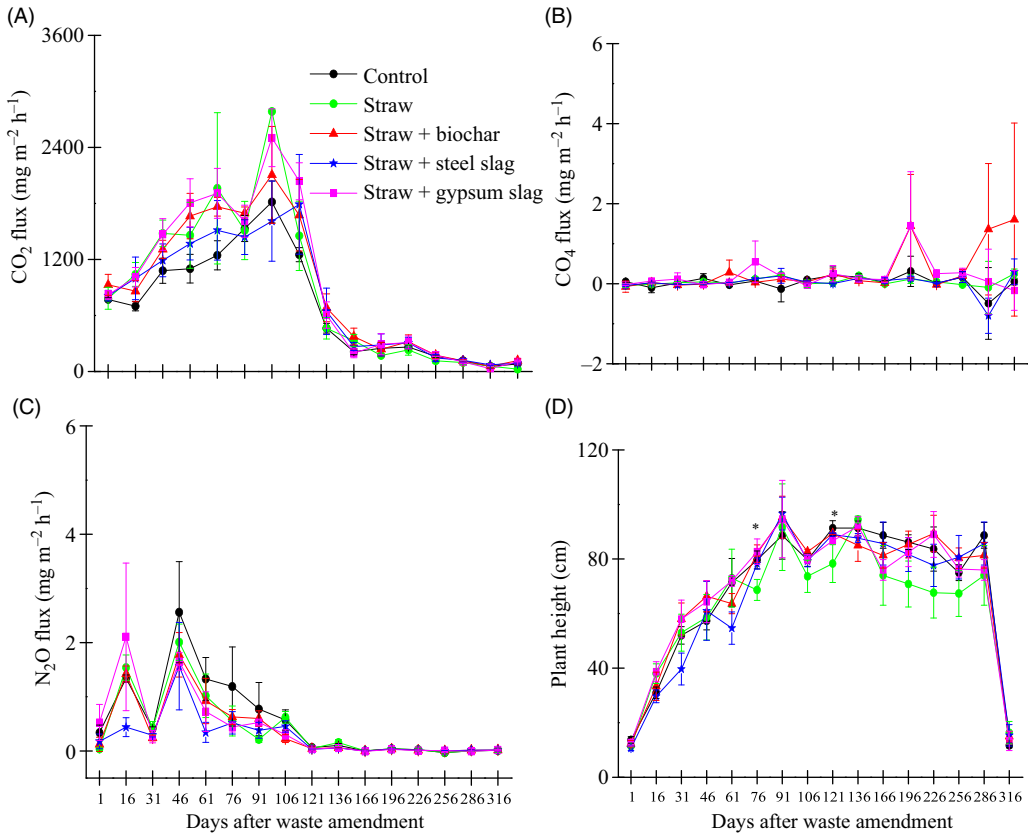
Figure 4. CO_2 (A), CH_4 (B), N_2O (C) emissions, and plant height (D) in the control and treatment. Error bars indicate one standard error of the mean of triplicate measurements. * indicates significant differences ($p < 0.05$) between treatments.

concentrations of organic matter and of Fe^{2+} together with higher CO_2 fluxes in amended soils should also favor methane production (da Silva *et al.*, 2011), mostly in soil–water contents between 40 and 60% as found herein (Figure 1). At this range of soil moisture, several soil meso- and micropores should be flooded, favoring anaerobic conditions and methane production (Wagner, 2017). In our study, the Fe^{3+} concentration was lower in the straw treatment than in the control (Figure 2), supporting the premise that straw or straw combined with waste could increase the reduction of Fe^{3+} to Fe^{2+} and increase the Fe^{2+} concentration.

All treatments increased total soil C, N, and P concentrations as compared to the control after 1 year of application (Figure 3), which suggests an increase of soil nutritional capacity mainly in the soils receiving straw + biochar. The increases in soil N concentrations would be especially important considering that wetlands have been proved to be N-limited (Wang *et al.*, 2015a). According to these results, treatments have increased the amount of C, N, and P stored in the first 30 cm of soil. The amount of C stored within 0–30 cm of soil increased 8.42, 31.06, 11.47, and 10.74 kg ha^{-1} in straw, straw + biochar, straw + steel slag, and straw + gypsum slag, respectively. Our results thus provide soil evidence that these treatments have a considerable capacity to improve N and P storage in soil, with a potential improvement of soil fertility. The increases in C stored in soil constitute, moreover, a good strategy to reduce GWP. This is specially a good potential strategy to reduce GWP because the wastes used as fertilizer materials in this study are abundant for application to agriculture, are low cost, and contribute to the waste recycling.

Table 2. Effect of the amended treatments on the global warming potential of the waste amendments

Treatment	Global warming potential (kg CO_2-eq ha^{-1})		
	CH_4	N_2O	Sum
Control	$2.18 \pm 2.38a$	$36.76 \pm 12.15a$	$38.94 \pm 10.09a$
Straw	$3.39 \pm 3.62a$	$28.07 \pm 4.36a$	$31.46 \pm 0.73a$
Straw + biochar	$20.70 \pm 18.19a$	$25.78 \pm 2.18a$	$46.48 \pm 16.42a$
Straw + steel slag	$1.41 \pm 2.19a$	$18.15 \pm 7.01a$	$19.56 \pm 9.20a$
Straw + gypsum slag	$12.52 \pm 8.54a$	$28.64 \pm 6.31a$	$41.16 \pm 8.13a$

Different letters within a column indicate significant differences between the amended and control treatments ($p < 0.05$) obtained by Bonferroni's *post hoc* test.
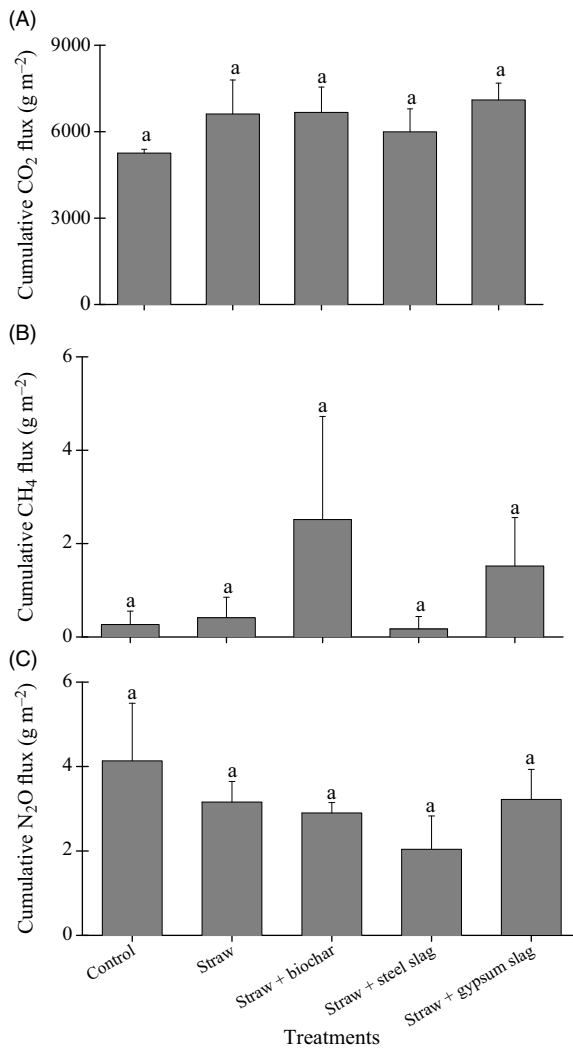
Figure 5. Cumulative emissions of CO_2 (A), CH_4 (B), and N_2O (C) in the amended and control treatments during the study period. Error bars indicate one standard error of the mean of triplicate measurements. Different letters indicate significant differences ($p < 0.05$) between treatments.

CO_2, CH_4, and N_2O emissions and their relationships with soil variables

CO_2 emission changed significantly during the *J. sambac* growing season (Figure 4, Supplementary Table S1). While seasonal CO_2 emission was positively correlated with soil temperature in all treatments, it was negatively correlated with soil Fe^{3+} and total Fe concentrations (Supplementary Table S5). Iron plaques are found around *J. sambac* roots at high Fe concentrations, which would limit the transport of CO_2 from the soil to the atmosphere across the free empty spaces of lacunae parenchyma of plants. Soil–water content was also positively correlated with CO_2 emission (Supplementary Table S5). When soil is not water saturated, soil respiration can increase during wetter periods and soil CO_2 emissions are then positively related to soil–water content (McElligott *et al.*, 2017).

Straw application can increase CO_2 emissions by several mechanisms. First, the decomposition of straw directly releases CO_2 (Curtin *et al.*, 1998). Second, the decomposition of straw adds carbon substrates to the soil, which will increase the amount and activity of soil microbes and then increase CO_2 emission (Curtin *et al.*, 1998). Despite nonsignificant, mean CH_4 emissions were generally higher in the straw, straw + biochar, and straw + gypsum slag treatments than the control (Figure 4), most likely due to the input of carbon substrates from the straw. The decomposition of straw would increase the soil C concentration and promote CH_4 emission (Wang *et al.*, 2015b). Contrarily, mean CH_4 emissions tend to be lower in the straw + steel slag treatment than the control (Figure 4). The steel slag is rich in Fe^{3+} and would increase the concentration of soil Fe^{3+}, which is an alternative electron acceptor that can use C substrates before methanogens (Jiang *et al.*, 2013) and thereby decrease the amount of CH_4 production and emission by competing with methanogens for C substrates (Gauci *et al.*, 2008; Jiang *et al.*, 2013). Mean N_2O emissions tended to be lower in the straw + biochar and straw + steel slag treatments than the straw treatment (Figure 4). Biochar can decrease N_2O emission (Wang *et al.*, 2011) and is rich in alkaline material, so it can increase soil pH, stimulate N_2O reductase activity, and thereby induce the reduction of N_2O to N_2 (Yanai *et al.*, 2007). Biochar may also improve soil aeration and impede the function and diversity of denitrifying bacteria, thereby decreasing N_2O emission (Cavigelli and Robertson, 2001). Steel slag is also rich in Fe^{3+}, and an increase in soil Fe^{3+} concentration could suppress microbial activity, including N_2O production (Noubactep, 2011). In general, the scarce effects on gas emission were consistent with the absence of treatment effects on GWP (calculated from $CH_4 + N_2O$ CO_2-equivalents).

Conclusions

Although all treatments increased total soil C, N, and P concentrations after 1 year, the high increase of total soil N concentration under straw + biochar was especially relevant due to the limiting role of N in these wetlands. Moreover, biochar and steel slag are rich in nutrients, such as Si, Ca, and Mg, which can improve soil fertility. Biochar and steel slag also increased soil–water content, which is specially useful in dry croplands. Our results provide evidence that combining straw with some wastes increases soil capacity to store N and P with a potential improvement of soil fertility. Moreover, it increases the C stored in soil, thus being a potential good strategy to reduce GWP. An important aspect is that the wastes used as fertilizer materials in this study are in abundant supply for application to agriculture, have a low cost, and contribute to the waste recycling. Summarizing our results provides strong evidence for several benefits from the application of these fertilizers in agriculture, while recycling several waste materials and improving soil water, C, and nutrient stocks without affecting GWP emissions.

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