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Rice husk biochar and crop residue amendment in subtropical cropping soils: effect on biomass production, nitrogen use efficiency and greenhouse gas emissions

Dai H. Nguyen, Clemens Scheer✉, David W. Rowlings, Peter R. Grace

Queensland University of Technology, 2 George St. Brisbane 4001, Australia.

✉ Corresponding author e-mail: clemens.scheer@qut.edu.au

Abstract

We investigated the effect of maize residues and rice husk biochar on biomass production, fertiliser nitrogen recovery (FNR) and N_2O emissions for three different subtropical cropping soils. Maize residues at two rates (0 and 10 t ha^{-1}) combined with three rates (0, 15 and 30 t ha^{-1}) of rice husk biochar were added to three soil types in a pot trial with maize plants. Soil N_2O emissions were monitored with static chambers for 91 days. Isotopic ^{15}N labelled urea was applied to the treatments without added crop residues to measure the FNR. Crop residues incorporation significantly reduced N uptake in all treatments but did not affect overall FNR. Rice husk biochar amendment had no effect on plant growth and N uptake but significantly reduced N_2O and CO_2 emissions in two of the three soils. The incorporation of crop residues had a contrasting effect on soil N_2O emissions depending on the mineral N status of the soil. The study shows that effects of crop residues depend on soil properties at the time of application. Adding crop residues with a high C/N ratio to soil can immobilise N in the soil profile and hence reduce N uptake and/or total biomass production. Crop residues incorporation can either stimulate or reduce N_2O emissions depending on the mineral N content of the soil. Crop residues pyrolysed to biochar can potentially stabilise native soil C (negative priming) and reduce N_2O emissions from cropping soils thus providing climate change mitigation potential beyond the biochar C storage in soils. Incorporation of crop residues as an approach to recycle organic materials and reduce synthetic N fertiliser use in agricultural production requires a thorough evaluation, both in terms of biomass production and greenhouse gas emissions.

Keywords: Crop residues; greenhouse gas; N_2O; nitrogen fertiliser recovery; rice husk biochar

INTRODUCTION

Agriculture is a major emitter of greenhouse gases (GHGs) to the atmosphere. Globally, it is estimated that there are about 5.1 to 6.1 billion tonnes CO_2-eq yr^{-1} GHG emissions from agriculture, which contributed 10 – 12% of the total anthropogenic GHG emissions in 2005 (Smith et al. 2007). Croplands are responsible for 60% of total anthropogenic nitrous oxide (N_2O) emissions which is a potent GHG with a global warming potential of nearly 300 times that of CO_2 and also the primary contributor to stratospheric ozone depletion (Ravishankara et al. 2009; Smith et al. 2007). Nitrous oxide emissions are affected by a number of factors such as soil organic C (SOC), N fertilisation, and fertiliser N rates. When SOC decomposes, it is emitted as carbon dioxide (CO_2) into the atmosphere. On the other hand, agriculture has a significant climate change mitigation potential which could change the position of agriculture from the second largest emitter to a much smaller emitter or even a net sink of GHGs with the greatest mitigation contribution originating from soil C sequestration, but also methane and nitrous oxide emissions can be considerably reduced (Bellarby et al. 2008).

Globally, 3.8 billion tonnes of crop residues are produced annually from cereal, sugar, legumes, tuber and oil crops (Lal 2005). The management of crop residues in cropping systems has a significant impact on soil quality and resilience, agronomic productivity, and GHG emissions from soil to the atmosphere (Lal 1997). Maintaining crop residues on the soil surface after harvesting reduces water loss, limits weed growth and can improve the physico-chemical properties of soil. Retention of crop residues on cropping soils offers the potential of soil C sequestration and may lead to C sequestration at the rate of 0.2 billion tonnes yr^{-1} or 5.0 billion tonnes of cumulative C sequestration in the world by the year 2020 (Lal 1997). However, this potential C sequestration can be offset if crop residues amendment substantially increases the emissions of other GHGs like N_2O or CH_4. To date, the effect of crop residues incorporation on soil GHG fluxes is not clear and both positive and negative effects have been observed depending on the N content of the crop residues (Chen et al. 2013). The incorporation of crop residues with a high C/N ratio may result in net N immobilisation during crop residue decomposition leading to reduced N_2O emissions. Conversely, it has been shown that crop residues can stimulate N_2O emissions in soils; (i) mineralisable N transformed into mineral N can provide additional substrate for nitrification and denitrification; (ii) mineralisable C from crop residues can stimulate heterotrophic denitrification activity generating N_2O emissions from soil mineral N and crop residue N; and (iii) increased oxygen consumption from C mineralisation can create anaerobic soil condition and stimulate N_2O loss from denitrification (Velthof et al. 2002).

In recent years, biochar production via pyrolysis of crop residues and its application to soil has been proposed as novel approach to sequester atmospheric CO_2 in terrestrial ecosystems, increase crop yields and reduce GHG emissions from soil (Lehmann et al. 2006). Organic materials which are pyrolyzed to biochar have a reduced capacity to be oxidised to CO_2 and thus offer a significant, long-term term C sink (Lehmann 2007). It has been shown that biochar addition can improve plant growth and soil quality (Chan et al. 2007; Chan et al. 2008; Major et al. 2010). These positive yield responses of biochar addition were related to improved water holding capacity (Iswaran et al. 1980), increased N uptake (Wardle et al. 1998), liming values (van Zwieten et al. 2010a) and soil physical properties (Asai et al. 2009; Major et al. 2010). Some studies also observed negative reponses to crop growth due to pH induced micro-nutrient deficiency (Kishimoto and Sugiura 1985). Several studies have shown that biochar can alter microbial communities and biogeochemical processes in soils (Pereira et al. 2015; Song et al. 2014), however, there is still contradiction over the effect of biochar on soil GHG fluxes. Several studies demonstrated reduced N_2O emissions (Liu et al. 2011; Singh et al. 2010b; van Zwieten et al. 2010b; Wang et al. 2011; Yanai et al. 2007) and increased CH_4 uptake (Karhu et al. 2011) associated with the effects of biochar on soil aeration, N availability and pH, while other studies have shown no effects (Pereira et al. 2015; Scheer et al. 2011; Suddick and Six 2013) or increased emissions in others (Clough et al. 2010; Singla et al. 2014).

Little is known on the combined effect of biochar and crop residue amendment on GHG fluxes from cropping soils and no study is available to evaluate the effect of biochar application in soils which are incorporated with crop residues in relation to fertiliser N recovery (FNR). Therefore, the objective of this study was to evaluate the effect of crop residue and rice husk biochar amendment on biomass production, N losses and N_2O emissions from three different subtropical cropping soils in Australia. We hypothesised that crop residue addition would increase N immobilisation and in combination with rice husk biochar reduce N loss, improve FNR and reduce N_2O emissions from the investigated sugarcane soils.

MATERIALS AND METHODS

Rice husk biochar and crop residues

Rice husk biochar was produced from rice husk by thermal pyrolysis at 350 – 500ºC and sieved to <2 mm before application to soils. It had a pH 9.1, 0.4% total N, 46.4% total C and 6.8 % moisture (Table 1).

The crop residues used in this experiment was maize straw (*Zea mays* L.) collected from a previous field experiment planted in October 2011. The maize received 200 kg N ha^{-1} as urea and was harvested after 114 days. The maize straw was chopped and dried at 60 °C for 72 h and ground to pass a 2 mm stainless steel screen. Characteristics of the crop residues are 1.1% total N and 43.0% total C (Table 1).

Soil preparation

Three soils were collected from the coastal humid subtropical cropping region in eastern Australia. Surface soil (0 – 20 cm) from a sandy loam (Soil 1) and a clay (Soil 2) were both collected from established (6 months) sugarcane fields near Broadwater, New South Wales (NSW) (29º00'S 153º25'E), and a sandy loam from a recently planted field near Rocky Point, Queensland (27º46'S 153º18'E). Rice husk biochar and crop residues were thoroughly mixed with 7.35 kg (oven-dry weight base) soil sieved to 2 mm into a 7.8 L, 250 mm diameter plastic pot. Chemical fertiliser was applied identical as a basal requirement for maize industry in NSW (Garcia undated) (0.981 g N and 0.20 g P and 0.8 g K pot^{-1}, equivalent 200 kg N, 40 kg P and 160 kg K as urea, K_2HPO_4 and K_2SO_4 ha^{-1}, respectively). All P and 50% K and 40% N were applied just before sowing, 20% N was applied at 35 days after sowing and the remaining 50% K and 40% N were applied after 50 days. Treatments without crop residues were fertilised with ^{15}N labelled (5.23 % atom excess) urea. Characteristics of soils, crop residues and rice husk biochar are shown in Table 1.

Experimental design

Three rates of rice husk biochar (RB0, RB1, RB2) were compared with and without (CR0, CR10) the addition of crop residues for each soil. RB was applied at the equivalent of 0, 15 and 30 t ha^{-1} (0, 31.8 and 63.6 g C pot^{-1} respectively) and maize residues were added at the rate of 10 t dry matter ha^{-1} (equivalent to 19.6 g C pot^{-1}). The pots were arranged as a randomised complete block design with four replicates per treatment.

The crop cultivar used was maize *cv*. Pioneer 31H50, a silage variety. Three maize plants were sown in each pot and after 10 days thinned to one. The trial was irrigated with an automated drip system set to minimise leaching from the pots. In the first 30 days, 100 mL water were automatically irrigated twice a day. In the following 30 days the amount of water applied was increased to 200 ml and irrigated twice a day and in the last 31 days, 300 ml water was applied three times a day. Soil moisture varied between 55% and 80% water-filled pore space (WFPS) over the experiment. A plate was placed underneath the pot for collecting leachate which was returned to the pot. The trial was undertaken in a climate controlled glasshouse with day/night temperatures of 30/18 ºC.

Gas sampling

A chamber (140 mm headspace and 100 mm diameter) with rubber septa lid was inserted into each pot next to the plant to collect gas samples (Figure 1). Gas samples were taken 20 times over the 91 day trial at 5 day intervals, with more intensive sampling following fertilisation. Headspace samples were collected at 0, 30 and 60 minute intervals after closure and analysed for N_2O concentration using a Shimadzu GC-2014 gas chromatograph equipped with an ECD ^{63}Ni detector.

Fluxes of GHG (N_2O, CO_2 and CH_4) emissions from the static chambers were calculated from the slope of the linear increase or decrease of the three concentrations measured over the closure time as described by Scheer et al. (2014). Flux rates (F) of N_2O were calculated using Eq. 1 and 2.

$$F = \frac{b * V_{CH} * MW * 60 * 10^6}{A_{CH} * MV_{corr} * 10^9} \qquad \text{(Eq. 1)}$$

where: *b* is the increase in headspace concentration (ppb min^{-1}); A_{CH} is the basal area of the measuring chamber (m^2); MW_{N2O-N} the molecular weight of N_2O-N (28 g mol^{-1}); MW_{CO2}: Molecular weight of CO_2-C (12 g mol^{-1}); MW_{CH4}: Molecular weight of CH_4-C (12 g mol^{-1}); $MV_{corr.}$: Temperature corrected molecular volume (m^3 mol^{-1}); V_{CH}: Volume of the measuring headspace chamber (m^3); 60 converts from minutes to hours; 10^6 converts from g to µg, and 10^9 converts from ppb to µL m^{-3}.

$$MV_{corr} = 0.02241 * \frac{273.15 + T}{273.15} \qquad \text{(Eq. 2)}$$

where: $MV_{corr.}$: is defined as above; 0.02241: 22.41 L mol volume (m^3 mol^{-1}); T: Air temperature during the measurement (°C).

Soil and plant sampling

Soil sub-samples (100 g) were collected from 3 of the replicates every four weeks using a two cm diameter, stainless steel auger for mineral N analysis. Soil sampling did not disturb in the area of gas sampling. Soil bulk density after the experiment was measured by using a soil ring to take 100 cm^3 soil that was dried at 105 ºC for 24 h. Water-filled pore space (WFPS) was determined every fortnight by sub-sampling 50 gram soil, dried at 105 ºC for 24 h and calculated by following formula Eq. 3.

$$WFPS(\%) = \frac{GWC * BD}{1 - \frac{BD}{2.65}} \qquad (Eq.\ 3)$$

where:

- GWC: gravimetric water content (%)
- BD: soil bulk density (g cm^{-3})
- 2.65 assumes the soil particle density (g cm^{-3})

Maize plants were harvested after 91 days and the roots separated and washed in deionised water until clean. Both roots and above the ground biomass were dried in an oven at

70 ºC for 72 hours. Samples were fine ground and analysed using an isotope ratio mass spectrometer (20-22 IRMS, Sercon Ltd, Crewe, UK).

Fresh soil samples (20 g soil) were extracted with 100 mL 2.0 M KCl in 120 mL plastic vials and analysed for NH_4^+ and NO_3^- colourmetrically (AQ2$^+$, SEAL Analytical WI, USA). Total N in plant and soil was determined by dry combustion (Leco Trumac Series Macro Determinator, St. Joseph, MI, USA).

Fertiliser ^{15}N recovery (FNR) was calculated as described by Bronson et al. (1991). All ^{15}N samples were analysed with a SerCon Isotope Ratio Mass Spectrometer.

Statistical analysis

All statistical analyses were completed using R Commander Package statistical software 2.13.2 (R Development Core Team 2008). Three-way analysis of variance (ANOVA) was used to determine the difference between treatments. Multiple comparisons were run in IBM SPSS 21. Differences were considered significant when P values were lower than 0.05.

RESULTS

Biomass production and soil mineral N

Total biomass production from three soils is presented in Figure 2. Above and belowground biomass production (root and straw) in treatments with crop residue incorporation ranged from 105 to 118 g pot^{-1} with a mean of 112 g pot^{-1}. This was generally lower than in treatments without crop residues where above and belowground biomass ranged from 101 to 135 g pot^{-1} with a mean of 121 g pot^{-1}. Results of dry biomass production indicated both positive and negative responses to rice husk biochar additions. In Soil 1, there was no significant difference in biomass production for the different rice husk biochar rates. The nil crop residue treatments yielded ca. 112 g straw pot^{-1}, 10% higher than the crop residues incorporated treatments. In Soil 2, there was no significant difference after crop residue or rice husk biochar addition in straw and total biomass production. Mean straw yield in the treatments with incorporated crop residues decreased by 7% compared to the nil crop residue treatments. In Soil 3, a significant difference in biomass production was found at different rates of rice husk biochar and interaction of rice husk biochar and crop residues, but no significant difference in the absence of crop residues was found. Overall, there was no significant effect of rice husk biochar on biomass production except for Soil 3 while crop residues significantly reduced biomass production in all soils.

Mineral N (e.g. NH_4^+ and NO_3^-) was not significantly affected by the application of rice husk biochar and crop residues. Nitrate in Soil 3 was significantly higher than in Soil 1 and Soil 2. The high rice husk biochar added soils showed a higher N availability, but the difference was not significant (Figure 3).

Total N uptake and fertiliser N recovery

Crop residue addition significantly decreased total plant N uptake in Soil 1 and Soil 3 (Table 2). Increased biochar rates had no significant effect on N uptake except for Soil 3 where N uptake was increased. Nitrogen uptake ranged from 0.77 to 0.99 g N pot^{-1} in Soil 1 and from 0.90 to 1.19 g N pot^{-1} in Soil 3. No influence of the amendments on N uptake in maize straw was observed in Soil 2, which ranged from 0.74 to 1.13 g pot^{-1}.

Rice husk biochar addition and soil types had no significant influence on the fertiliser ^{15}N recovery (%, FNR) in the soil or plant (Table 3). Fertiliser N recovery in soils varied between 16.7% and 29.2% (average 25.1%). Plant FNR ranged from 68.7% to 81.0% (average 71.4%) with the highest mean FNR in Soil 2 (75.0%) while Soil 1 and Soil 3 were almost identical at 70%. An average of 3.5% of added fertiliser over three soils could not be recovered in the soil or in plant. Highest N losses were from Soil 3, with almost twice as much N lost compared to Soil 1 and Soil 2.

Greenhouse gas emissions

The incorporation of crop residues significantly increased CO_2 emissions in all three soils (Table 4). Adding rice husk biochar generally reduced CO_2 emissions, except for the nil crop residues in Soil 1 and with crop residues in Soil 3. The percentages of CO_2 reduction varied from 15.4% in the nil crop residues plus RB1 in Soil 3 to 42% in the nil crop residues plus RB2 in Soil 2.

Maximum emissions of N_2O occurred in the first three days after maize sowing (Figure 4). The addition of the rice husk biochar significantly decreased N_2O emissions from Soil 1 and Soil 2 under both the nil residue and crop residue treatments. Daily N_2O emissions were the lowest in the Soil 2 and the highest in Soil 3 where crop residue incorporation increased emissions over the first 60 days. Total N_2O emissions during growing time (91 days) were significantly affected by the addition of rice husk biochar (P<0.001), except in Soil 3, but there was no significant interaction between the two sources of amendments (Table 4). Total N_2O emissions decreased with increasing rice husk biochar rates in the three soils. Crop residue incorporation decreased N_2O emissions in Soil 1, but significantly increased N_2O emissions in Soil 3 (Table 4). Average N_2O emissions over the experimental period varied from 0.012 to 0.075 mg N_2O pot^{-1} d^{-1} in treatments without crop residues and from 0.017 to 0.108 mg N_2O pot^{-1} d^{-1} in treatments incorporated with crop residues.

Methane fluxes were measured and low fluxes were observed, which were not significantly different from the fluxes in the control for each soil. Cumulative CH_4 emissions varied from 0.007 mg C pot^{-1} to 0.20 mg C pot^{-1}. Since, there were no significant difference between rice husk biochar rates and crop residue incorporation, the data is not shown here.

DISCUSSION

Effect of RB and crop residues on maize growth and N uptake

There was no significant effect of rice husk biochar rates on biomass production which is contrast to the literature where it is frequently suggested that biochar applications to soil can increase agricultural productivity (Blackwell et al. 2009). However, plant response to biochar addition only has been shown to vary according to biochar characteristic, soil type and plant species. Improved crop growth after biochar addition has been explained by mechanisms such as changed microbial activity, soil physical properties, pH, and CEC (Chan et al. 2007; Rondon et al. 2007; Yamato et al. 2006). We assume that in our study biochar did not affect maize growth probably due to the adequate supply of mineral N fertiliser and irrigation water to the experimental pots in all treatments. Another reason for this result could be that the short period of 91 days in this study was not long enough for the biochar to establish change in the microbial activity of the soils. Other studies reported an effect of biochar on biomass production only one year after application suggesting that biochar application to soil can provide increasing benefits over time (Kimetu et al. 2008; Major et al. 2010; Steiner et al. 2007).

Biochar had no effect on soil mineral N content but biochar application significantly increased N uptake in maize in Soil 3 which is most likely attributed to the higher mineral N content at the start of the experiment. The increased N uptake in the rice husk biochar treatments is consistent with earlier finding of Zhang et al. (2012) who found that increased biochar rates significantly increased N uptake in maize. Results of this study suggest that the increased N uptake in Soil 3 applied with biochar can partly be explained by reduced gaseous N losses and increased N retention.

The effects of crop residues on biomass production depended on soil properties. It reduced biomass production in all three soils after its incorporation into the soil. This was most likely caused by N immobilisation over the cropping season, although this effect was no longer apparent in the mineral N content after harvest (Figure 3). Organic matter with a C/N ratio higher than 30 generally results in N immobilisation (Alexander 1977). We assume that the high C/N ratio of the maize residues (C/N =38.4) used in this study immobilised soil mineral N and resulted in low N uptake.

Effect of RB on fertiliser N recovery in soil and in plant

The amount of fertiliser ^{15}N recovery in the soils varied between 16.7% and 29.2% with a higher amount of residual ^{15}N found in Soil 1 and Soil 3 where high SOC content promoted N immobilisation. Total ^{15}N recoveries were not significantly different, despite differences in total soil N in all three soils when ^{15}N was added (Table 1 and 3). These results suggest that initial SOC content had little effect on total N retention in the cropping system.

There was no significant response of biochar amendment on plant FNR. Our hypothesis that rice husk biochar will increase FNR was not supported by this experiment where FNR in Soil 1 and Soil 3 was identical (70%), but lower than that in Soil 2 (75%). Our results showed a relatively high FNR because leaching was minimised as leachate water was collected and returned to the pot, which reduced N leaching losses from the root zone. The current results are, therefore, at the upper level of FNR reported for agricultural crops varying between 30% and 78% (Broadbent and Carlton 1978; Kirda et al. 2001).

After balancing the fertiliser N proportions between plant and soils, on average 3.5% fertiliser N was lost. Soil 3 had the highest N loss accounting for 5.25% of N lost. Although this soil had a sandy texture combined with high N levels and low CEC, these losses couldn't have resulted through leachate which was returned to the pots with a negligible amount. The N was, therefore, most likely lost via gaseous N emissions such as N_2 and N_2O. The observed emissions of N_2O only accounted for 0.4% of fertiliser N added (Table 4). Whilst gaseous N emissions of N_2 were not specifically monitored in this study, it has been shown that gaseous N losses can constitute the largest part of N losses in sugarcane systems with up to 100 times as much N loss as N_2 than as N_2O (Weier 1999). Since the soil pH during the experiment was below 5.5 (data not shown) also NH_3 volatilisation can be considered negligible. Consequently, we hypothesise that the majority of N loss in this study was emitted as N_2 from denitrification.

Effect of RB and crop residues on GHG emissions

All treatments amended with crop residues increased CO_2 emissions but the magnitude varied according to soil types and interaction with rice husk biochar rates. The increased CO_2 emissions in the crop residue treatments confirmed that the added C substrate is immediately broken down by soil microbes after incorporation (Muhammad et al. 2011); (Lehtinen et al. 2014). Furthermore, soil moisture in this study was maintained between 55% – 80% WFPS by irrigation which stimulated microbial activity and mineralisation because microbial activity is optimised at, or near field capacity, equivalent to 60% WFPS (Hofman and Van Cleemput 2004).

There was a significant reduction of soil CO_2 emissions in treatments where rice husk biochar had been added. Increasing rates of rice husk biochar addition also had an influence on the magnitude of the CO_2 reduction. Such a "negative priming effect" of biochar addition on SOM degradation has been reported by other (Spokas et al. 2009; Zimmerman et al. 2011). The exact cause of this reduction is not known. One potential explanation is that application of biochar affects soil physical properties such as soil structure, soil porosity, thereby changing oxygen content, water holding capacity and microbial activities (Downie et al. 2009). It can also reduce bioavailability of soluble organic substrate by OM sorption to biochar and physical protection which slows down mineralisation and decomposition of SOM. Moreover, a change in microbial abundance and community structure due to biochar presence may affect not only biochar mineralisation itself but also mineralisation of existing soil C (Lehmann et al. 2011). The results of this short term study suggest that rice husk biochar has the potential to enhance SOC preservation by retarding its mineralisation (negative priming) and thus could stabilise existing SOC in cropping soils.

The effect of crop residues on N_2O emissions varied depending on soil chemical properties, in particular on the initial mineral N levels of the soil. The increase of N_2O emissions after incorporating crop residues in Soil 3 was depending on the addition of mineral N fertiliser and organic matter substrate, stimulating denitrification capacity (Baggs et al. 2003). A recent meta-analysis of agricultural soils in Europe showed that N_2O emissions are 12 times higher following crop residue incorporation due to increased denitrification stimulated by the added substrate and the creation of anaerobic micro sites by increased soil respiration (Lehtinen et al. 2014). In Soil 3, a high initial NO_3^-, high decomposable C and suitable moisture regulated the denitrification process to produce more N_2O. In contrast to the findings of Soil 3, we found a significant reduction in N_2O emissions in Soil 1. This contrast likely depended on the low NO_3^- content in the initial soil (Table 1) and after the experiment (Figure 3) which limited available NO_3^- for the denitrification process. The results suggest that under low soil mineral N levels in Soil 1 the addition of crop residues increased the immobilisation of available NO_3^- which in turn led to reduced N_2O emissions.

The hypothesis that the application of biochar would reduce N_2O emissions was confirmed in this pot trial and confirmed what was already reported (Nguyen et al. 2014; Singh et al. 2010a; Yanai et al. 2007). Nitrous oxide emissions from treatments applied with RB decreased by increasing rice husk biochar rates in all three soils with or without incorporation of crop residues confirming results of previous studies (Rondon et al. 2005; Wang et al. 2012; Zhang et al. 2010). Suppression of N_2O emissions in treatments amended with biochar may result from increased soil aeration which inhibited denitrification rates. Biochar can also alter the soil microbial communities (Song et al. 2014) and promote microbial immobilisation of the available N in soil (Rondon et al. 2005; Singh et al. 2010a), although this effect was not apparent in the plant N uptake. The fact that both CO_2 and N_2O

production were reduced also suggests that biochar amendment might suppress microbial activities.

CONCLUSIONS

To our knowledge this is the first study that investigates the combined effect of biochar and crop residue amendment on soil GHG emissions and plant FNR. Applications of rice husk biochar and crop residues significantly influenced overall N_2O emissions but did not affect biomass production and FNR. This study highlights that incorporation of crop residues as an approach to recycle organic materials and reduce synthetic N fertiliser use in agricultural production requires a thorough evaluation, both in term of biomass production and GHG emissions. In order to optimise the benefits of crop residue incorporation soil properties need to be taken into account. The study also showed that application of rice husk biochar could potentially stabilise native and added soil C and reduce N_2O emissions from these subtropical cropping soils at the same time. Thus crop residues pyrolysed to biochar as a soil amendment has a climate change mitigation potential beyond the biochar C storage in soils. However, this study only investigated a short time frame right after the addition of rice husk biochar and did not show a positive effect on crop growth and FNR. Future work is needed to assess if biochar can improve agricultural productivity and provide a long lasting mitigation as it has been indicated in current results.

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Tables

Table 1 Properties of organic amendments and soils

	Crop residues	Rice husk biochar	Sandy loam Broadwater (Soil 1)	Clay Broadwater (Soil 2)	Sandy loam Rocky Point (Soil 3)
pH (1:5 H_2O)	-	9.00	4.7	5.18	4.42
CEC (cmol$^{(+)}$ kg^{-1})	-	5.65	8.9	11.0	7.6
Moisture (%)	7.1	6.80	-	-	-
Total C (g C kg^{-1})	430	464	36.4	22.8	32.2
Total N (g N kg^{-1})	11.2	4.0	2.9	1.8	2.5
C/N ratio (%)	38.4	116.1	12.7	12.7	13.1
NH_4^+ (mg kg^{-1} soil)	-	-	12.8	5.5	17.3
NO_3^- (mg kg^{-1} soil)	-	-	19.9	19.8	31.0
Soil bulk density (g cm^{-3})	-	-	1.12	1.05	1.08
Texture (USDA)	-	-	Sandy loam	Clay	Sandy loam
Sand (%)	-	-	75.4	17.2	64.9
Silt (%)	-	-	12.6	33.1	21.3
Clay (%)	-	-	12.0	49.7	13.8

Table 2 Nitrogen uptake (g N pot^{-1}) in maize in the three different soils after maize harvest

	Soil 1		**Soil 2**		**Soil 3**	
	Straw	Root	Straw	Root	Straw	Root
Nil crop residues (CR0)						
RB0	0.97±0.03	0.11±0.01	0.99±0.03	0.12±0.01	1.08±0.01	0.12±0.01
RB1	0.99±0.04	0.11±0.01	1.13±0.10	0.08±0.01	1.19±0.06	0.13±0.01
RB2	0.93±0.07	0.14±0.01	0.98±0.10	0.10±0.01	1.14±0.04	0.08±0.01
With crop residues (CR10)						
RB0	0.79±0.02	0.09±0.01	0.74±0.10	0.06±0.01	0.90±0.01	0.09±0.01
RB1	0.83±0.08	0.07±0.01	0.95±0.08	0.09±0.02	1.04±0.03	0.09±0.01
RB2	0.77±0.08	0.07±0.01	1.05±0.06	0.07±0.01	1.07±0.01	0.10±0.01
Significance test (P value)						
For RB	0.600	0.340	0.107	0.720	0.003	0.123
For CR	0.005	0.001	0.089	0.013	0.001	0.116
For RBxCR	0.969	0.048	0.149	0.040	0.215	0.057

Table 3 Fertiliser N recovery (FNR) in soils and in plant and N loss in different rates of rice husk biochar in different soils after maize harvest

Treatments	FNR in soil (%)	FNR in plant (%)	N loss (%)
Soil 1	27.4	70.0	2.63
RB0	28.7±1.0	69.0±2.4	2.28±1.6
RB1	24.3±4.0	73.8±3.8	1.87±0.5
RB2	29.2±8.5	67.0±7.4	3.76±1.1
Soil 2	22.3	75.0	2.71
RB0	27.5±0.9	70.2±1.4	2.32±0.6
RB1	16.7±4.8	81.0±6.9	2.35±2.2
RB2	22.8±3.8	73.8±5.5	3.45±1.9
Soil 3	25.6	69.2	5.25
RB0	24.9±1.1	69.4±0.9	5.62±0.6
RB1	27.1±3.6	68.7±3.2	4.18±2.1
RB2	24.7 ± 4.1	69.3±4.2	5.96±0.6
Mean of 3 soils	**25.1**	**71.4**	**3.53**
Significance test (P value)			
For RB	0.451	0.358	0.396
For Soils	0.341	0.257	0.057
For RBxSoils	0.619	0.743	0.983

Table 4 Effects of rice husk biochar and crop residues on total N_2O and CO_2 emissions from three different soils.

Treat-ments	**Soil 1**		**Soil 2**		**Soil 3**	
	N_2O*	CO_2§	N_2O	CO_2	N_2O	CO_2
Nil crop residues (CR0)						
RB0	5.0±0.9	8.7±1.6	2.8±0.2	10.5±1.4	6.8±0.8	9.1±0.6
RB1	2.2±0.2	11.3±1.4	1.8±0.3	7.4±1.2	5.7±0.6	7.7±0.5
RB2	1.6±0.2	8.7±0.9	1.0±0.1	6.1±0.3	6.7±1.0	5.2±0.8
Mean	2.9	9.6	1.9	8.0	6.4	7.3
With crop residues (CR10)						
RB0	2.9±0.4	14.2±2.2	3.0±0.1	11.0±2.0	9.9±1.6	11.6±2.1
RB1	1.6±0.1	11.2±0.8	2.3±0.3	13.4±1.7	8.1±1.3	12.7±2.2
RB2	1.6±0.2	9.8±0.2	1.9±0.3	8.4±1.4	6.4±0.5	12.5±1.8
Mean	2.0	12.0	2.4	11.0	8.1	12.2
Significance test (P value)						
For RB	0.001	0.018	0.001	0.005	0.222	0.299
For CR	0.023	0.002	0.009	0.002	0.051	0.001
For RBxCR	0.078	0.017	0.403	0.043	0.245	0.095

* mg N_2O-N, §g CO_2-C pot^{-1}, respectively

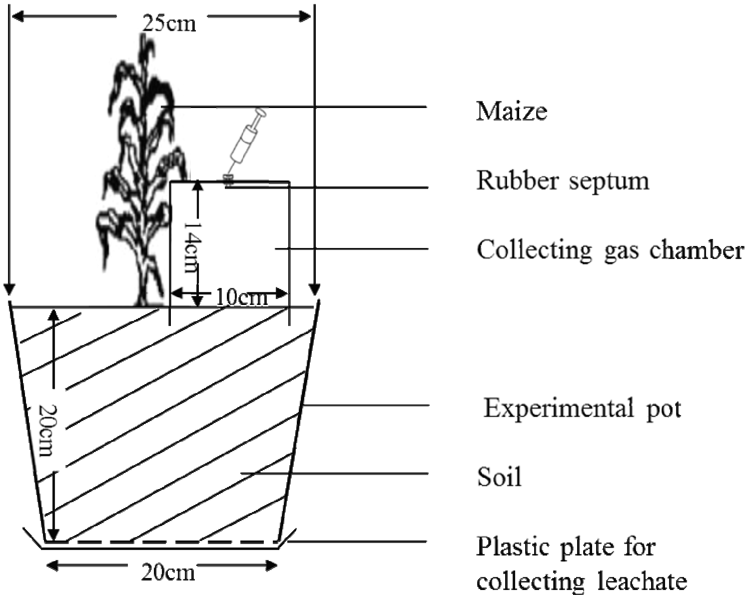


Figure 1 Simple apparatus for collecting gas samples

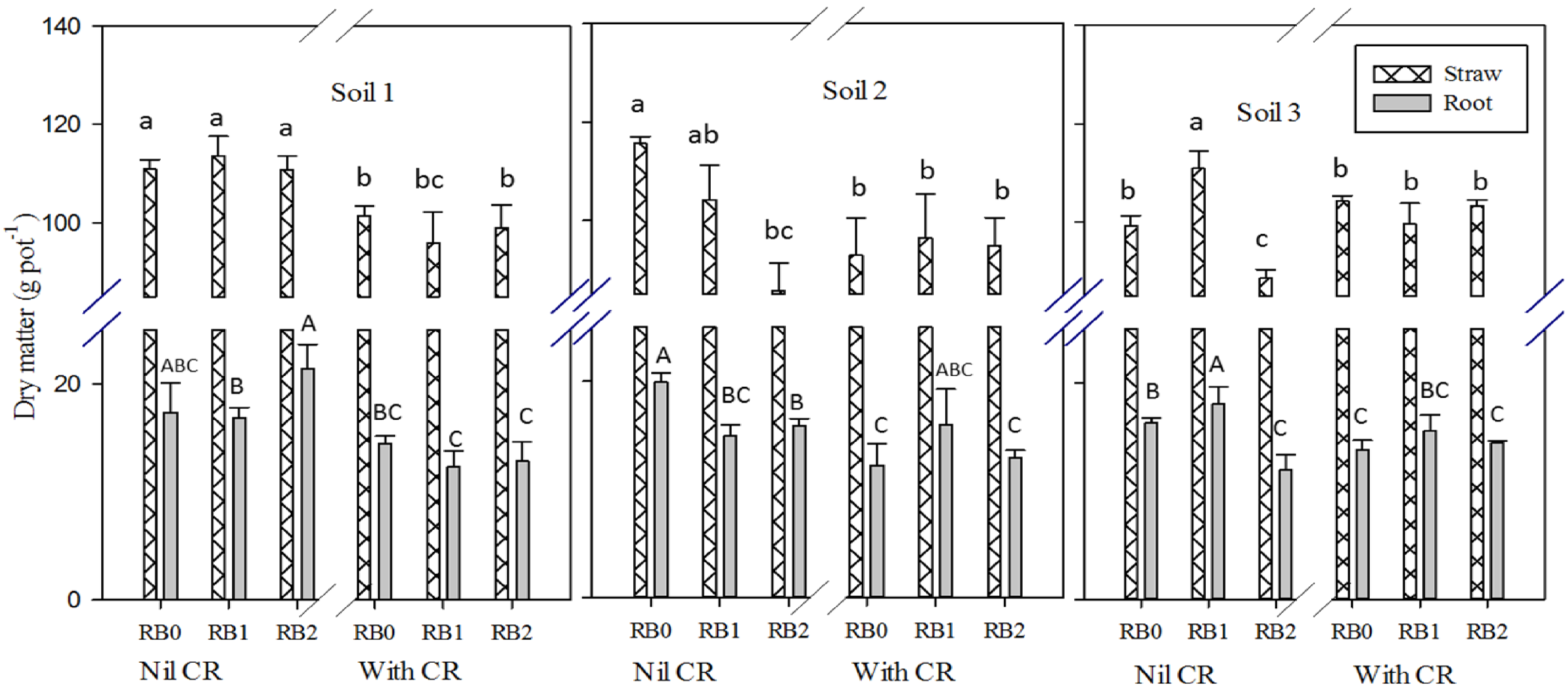


Figure 2 Effects of rice husk biochar (RB) and crop residues on biomass production in different soils. Vertical bars represent standard error. Different letters above the bars indicate significant difference between treatments in each soil (P<0.05). Lowercases refer for straw biomass and uppercases refer for root biomass. CR is crop residues.

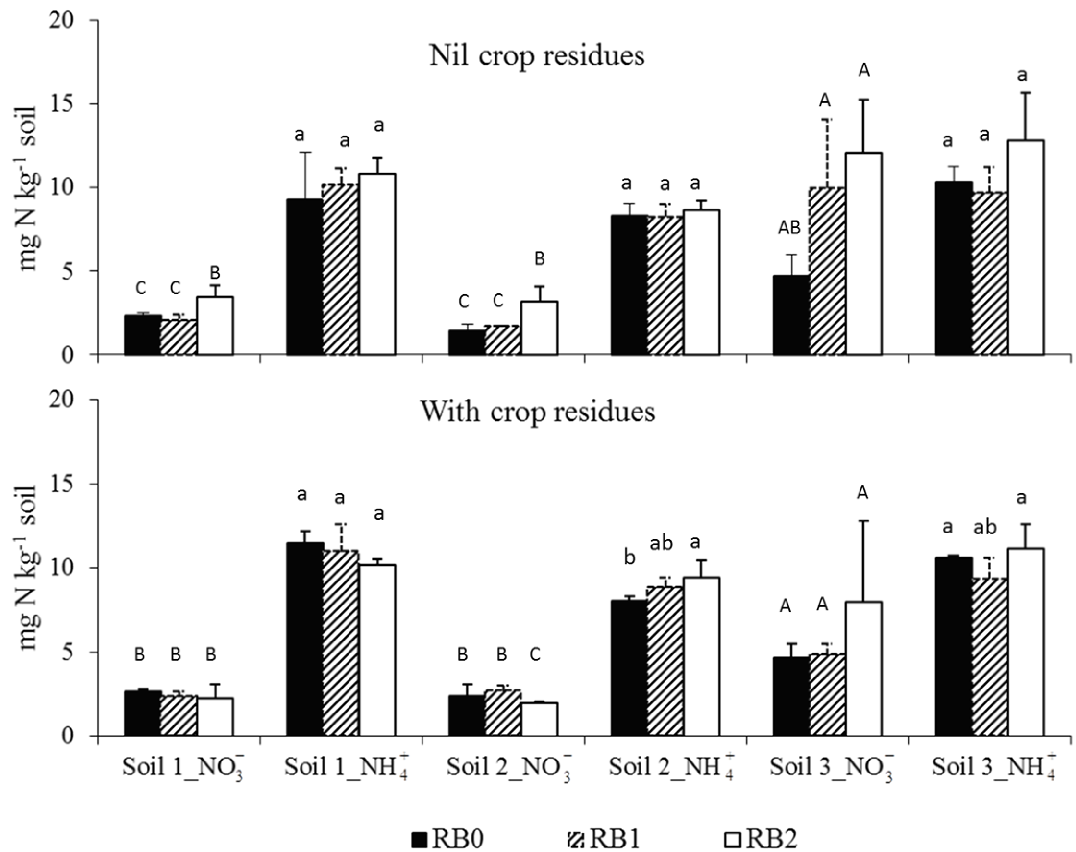
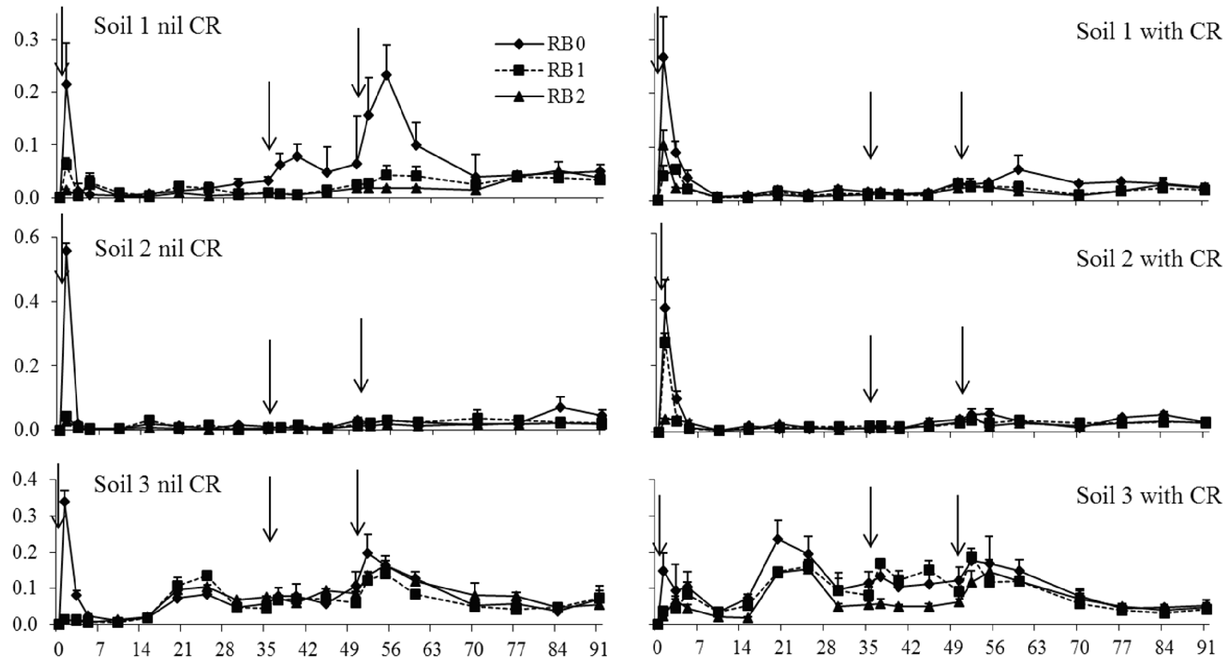


Figure 3 Effects of rice husk biochar (RB) and crop residues on NO_3^- and NH_4^+ contents of three soils after maize harvest. Vertical bars represent standard error. Different letters above the bars indicate significant difference between treatments in the categories of nil or with CR (P<0.05). Lowercases refer for NO_3^- and uppercases refer for NH_4^+.



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543 **Figure 4** Daily fluxes of N_2O emissions during the experiment growing time under different
544 management of rice husk biochar (RB) rates and crop residues. Vertical bars represent
545 standard error. Arrows indicate time of N fertilisation. CR is crop residues.

546