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RESEARCH ARTICLE

Impacts of eucalyptus biochar application on greenhouse gas emission from an upland rice–sugarcane cropping system on sandy soil

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Summary

An on-farm field experiment was conducted in northeastern Thailand to assess the effects of different eucalyptus biochar (BC) application rates, in combination with mineral fertilizers, on upland rice and a succeeding crop of sugarcane on sandy soil. Soil mineral N and greenhouse gas emissions were also evaluated. The field experiment consisted of three treatments: no biochar (BC0), 3.1 Mg ha^{-1} of biochar (BC1), and 6.2 Mg ha^{-1} of biochar (BC2). All treatments received the same recommended fertilizer rate. Soil mineral N, and emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were monitored after BC application. The results revealed that the BC2 treatment caused lower soil mineral N content than that of the BC0 treatment during the upland rice period. During the sugarcane period, the BC2 treatment induced a greater soil mineral N content than the BC1 treatment but had no significant difference from the BC0 treatment. The BC2 treatment resulted in significantly lower cumulative CH_4 and N_2O emissions than the BC0 treatment during the upland rice period. In conclusion, we found that the BC2 treatment alleviated the global warming potential from CH_4 and N_2O emissions throughout the experiment, causing slight changes in soil N availability in the upland rice–sugarcane cropping system.

Keywords: Methane; Global warming potential; Soil mineral N

Introduction

The increasing concentration in the atmosphere of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) due to anthropogenic activity, is the major cause of global climate warming (IPCC, 2007). Globally, agriculture has been one of the major sources of GHGs (Maraseni *et al.*, 2009). While CO_2 production by microbe activity and carbon from crop straw decomposition can provide more substrate for microbe respiration (Paul and Clark, 1989), biomass burning is one of the main sources of CO_2 emissions. A previous study reported that burning sugarcane straw released 941 kg CO_2 ha^{-1} (De Figueiredo and La Scala, 2011). Moreover, land use change is a major cause of anthropogenic GHG emissions, driving global carbon dynamics and climate change (Lam *et al.*, 2021). Methane production occurs in anaerobic conditions via CO_2 reduction and the transmethylation of acetic acid or methyl alcohol. Thus, high moisture content with high carbon substrate may accommodate methane production. Nitrous oxide is a powerful GHG that has a global warming potential (GWP) that is 310 times that of CO_2 (IPCC, 2017). The increased use of nitrogen fertilizers in agricultural soil increases mineral

N availability, which can lead to increased emission of N_2O via nitrification and denitrification (Baggs, 2011); thus, soils are considered the largest source of N_2O emissions.

Sugarcane is one of the major cash crops of Thailand and its ratooning systems with a preceding upland rice crop have been acknowledged to be suitable for northeastern Thailand (Thawaro *et al.*, 2017). Nevertheless, the soils of northeastern Thailand are mainly sandy, with low fertility and low soil organic matter (OM), which results in low average sugarcane yields and only 1–2 ratoon canes. A substantial exchange of CH_4 between the sugarcane crop and the atmosphere may occur, with CH_4 emission rate reaching 19.9 kg ha^{-1} (Denmead *et al.*, 2010). Nitrogen fertilizer application under high temperature and soil moisture in a temperate region can stimulate nitrogen loss via denitrification, and crop production systems have been recognized as important sources of N_2O (Wang *et al.*, 2021a). Fertilized sugarcane soils without a trash cover emit 17 kg N_2O ha^{-1} $year^{-1}$ (Weier, 1998). An approach to ameliorate N availability while suppressing N loss via denitrification may be a promising practice for sugarcane cultivation in sandy soils with poor fertility.

Biochar (BC) is an important choice for the improvement of soil physicochemical conditions, increasing nutrient cycling (Steiner *et al.*, 2008) and biological properties (Lehmann *et al.*, 2011). BC is an important source of nutrient, which depends on the plant type, soil conditions, and combustion temperature. While wheat BC contains 0.89 g P kg^{-1} and 48.9 g K kg^{-1}, corn stalk BC contains 2.5 g P kg^{-1} and 13.4 g K kg^{-1} (Xie *et al.*, 2013). Moreover, sugarcane bagasse and peanut hull BC have higher Ca but lower N contents after pyrolysis (Yao *et al.*, 2012). Eucalyptus (*Eucalyptus camaldulensis,* Dehnh) in northeastern Thailand is currently an important resource to satisfy the energy demands of many rapidly developing countries in the Asia-Pacific region (Nansaior *et al.*, 2013). Eucalyptus BC application in upland rice–sugarcane crop system has been reported to enhance soil fertility and crop yield on degraded sandy soils (Butphu *et al.*, 2020).

As BC contains pores that can be occupied by water, its application improves the soil moisture content and stimulates conditions suitable for CH_4 and N_2O production (Graber *et al.*, 2010). Bruun *et al.* (2011) found that the effects of BC on N_2O emissions depend on the dose used: low dose (1% by mass) can increase, and high doses (3%) can attenuate N_2O emissions from loamy soil. Low eucalyptus BC rate (1–2%, w/w) was used under loamy sand conditions and found to have a positive effect on plant growth (Butnan *et al.*, 2015). Eucalyptus BC application reduced N_2O and CO_2 emissions at sugarcane harvest under an incubation experiment (Kaewpradit and Toomsan, 2019). However, there is a need to understand how N_2O emissions respond to soil management, a critical step towards developing mitigation strategies (Rees *et al.*, 2013).

The objective of this study was to assess the effects of eucalyptus BC combined with mineral fertilizers on soil mineral N and GHG emissions in an upland rice–sugarcane rotation under poor sandy soil. It was hypothesized that the application of eucalyptus BC would enhance soil mineral N and mitigate GHG emissions in an upland rice–sugarcane crop system.

Materials and Methods

Field experiment

An on-farm field experiment was conducted in Khon Kaen Province of northeastern Thailand (latitude 16.210982, longitude 102.815315). The soil (Grossarenic Haplustalfs, Nam Phong series; WRB: Arenosols) was sandy (proportions of sand, silt, and clay were 96%, 3%, and 1%, respectively), as is typical for the region. The maximum and minimum air temperature and total rainfall are presented in Supplementary Material Figure S1. The field experiment consisted of an upland rice–sugarcane rotation system. Upland rice was established during the common time gap between two sugarcane cropping cycles in June 2013 and harvested in October 2013. Sugarcane was planted in November 2013 and harvested in November 2014.

Table 1. Some soil physico-chemical properties used in the experiment

Soil properties	0–15 cm[a]	15–30 cm
Organic matter (g kg^{-1})	3.4	3.8
Total N (g kg^{-1})	0.01	0.04
Available P (mg kg^{-1})	22.5	27.3
Exchangeable K (mg kg^{-1})	34.0	45.6
Exchangeable Ca (mg kg^{-1})	70.0	65.0
pH (1:5 H_2O)	5.7	5.5
Electrical conductivity (1:5 H_2O; mS cm^{-1})	0.02	0.02
Cation exchange capacity (cmol kg^{-1})	0.79	0.62
Sand (%)	96	93
Silt (%)	3	5
Clay (%)	1	2

[a]From Butphu *et al.* (2020).

BC application

Eucalyptus BC (*Eucalyptus camaldulensis*, Dehnh) was applied in May 2013 at three rates: no biochar (BC0); 3.1 Mg ha^{-1} (BC1); and 6.2 Mg ha^{-1} (BC2) and incorporated to a soil depth of 15 cm, 30 days prior to the sowing of upland rice. The three treatments were arranged in a randomized complete block design, using four replications.

Upland rice cultivation

Upland rice (*Oryza sativa* L. cv., Siewmaejun) was planted with 25 × 25 cm spacing, 30 days after BC application (DAA) in mid-June 2013. The plot size was 9.6 × 6 m, and the harvest area was 9 m^2 in the center of each plot. Mineral fertilizers were applied at the recommended rates. Basal fertilizers (25 kg N ha^{-1}, 14 kg P ha^{-1} and 16 kg K ha^{-1}) were broadcasted 20 days after planting (DAP), and 7 kg N ha^{-1} (as urea) was top-dressed at panicle initiation (PI).

Sugarcane cultivation

Sugarcane (*Saccharum* spp., variety Khon Kaen 3) was planted (using two single budded healthy cane setts) in late November 2013 with a spacing of 120 × 30 cm. Mineral fertilizer was applied in the planting row at the time of planting at rates of 47 kg N ha^{-1}, 21 kg P ha^{-1}, and 39 kg K ha^{-1}. Six months after planting (MAP), 72 kg N ha^{-1} was applied by banding.

Soil and BC analyses

Physico-chemical properties of the BC and soil

Soil samples were collected in each plot and composed by four subsamples, at depths of 0–15 and 15–30 cm. Chemical analyses were performed before the experiment at the final upland rice and sugarcane harvest. The physico-chemical properties of the soil are presented in Table 1. The methods used for evaluating the physico-chemical characteristics of soil and BC properties are presented in Butphu *et al.* (2020). The eucalyptus BC contained 718 g C kg^{-1}, 3.3 g N kg^{-1}, 987 mg P kg^{-1}, 3.5 g K kg^{-1}, 5.7 g Ca kg^{-1}, pH (1:10 H_2O) 6.7, EC (1:10 H_2O) 0.3 mS cm^{-1}, CEC 26.4 cmol kg^{-1}, 32% volatile matter, and 3.3% ash.

Soil sampling during the crop period

During the upland rice period, soil samples were taken at auger depths of 0–15 cm and 15–30 cm; 0, 15, 30, 60, 90, and 119 (harvest) DAP. During the sugarcane growth period, soil samples were taken at 2, 4, 6, 8, and 10 months after planting (MAP). Soil moisture was determined after drying samples (105°C for 24 h). Mineral N (NH_4^+ and NO_3^-) was determined immediately after

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collecting the soil samples with 100 mL of 1 M KCl (Thawaro *et al.*, 2017), using a flow injection analyzer (Tecator, 1984). Microbial biomass N (MBN) was measured in the fresh soil immediately after sampling through chloroform fumigation. Chloroform was washed and distilled before use to remove ethanol, and the samples were incubated for 36 h. MBN was determined by the ninhydrin-reactive N method, in which 10 g of fumigated and unfumigated soils were extracted and supplemented with 50 mL of 1 M KCl. The differences in MBN between the fumigated and unfumigated values were calculated using a k_{EN} factor of 0.32 (Amato and Ladd, 1988).

Crop yield

At upland rice harvest, grain yield from the harvest area (9 m^2) was determined. At the final sugarcane harvest, the stalk weight was recorded. Total N uptake was calculated from the dry matter yield and N content.

GHG analysis

Gas samples were collected from acrylic chambers (50 × 50 × 60 cm) placed on acrylic channel bases (50 × 50 × 15 cm) and inserted permanently into the soil (Figure S2). During the upland rice period, the chamber was placed over four rice canopies and sealed by pouring water into the channels. In the sugarcane period, a chamber was placed between rows of sugarcane. Gas samples were collected at 40, 47, 54, 60, 70, 78, 84, 91, 104, 113, 122, 136, and 149 days after BC application (DAA) during the upland rice period. Then, gas samples were collected at 184, 198, 215, 237, 260, 280, 297, 315, 329, 346, 363, 379, 396, 413, 433, 452, and 514 days after BC application (DAA) during the sugarcane period. After pretests, 10 mL gas samples were collected in 0-, 10-, and 20-min increments for CH_4 and CO_2 and after 30 min for N_2O. Samples were stored in a 10-mL vacuum vial with a rubber stopper and aluminum cap. CH_4 and CO_2 were determined by injecting 1 mL gas samples into a Shimadzu 14B gas chromatograph equipped with a packed column (Porapak N, 80/100 mesh) and a flame ionization detector. The column temperature was set at 60°C, and both the injection and detector temperatures were set at 100°C. Determination of N_2O concentrations was carried out on a gas chromatograph (Agilent Model 6890, Agilent Technologies, USA) equipped with a packed column (Porapak Q, mesh 80/100) and a microelectron capture detector.

Statistical analysis

Data were subjected to a randomized complete block analysis of variance, with four replications. Statistical analyses were conducted using MSTAT-C (Version 1.42, Crop and Soil Science Division, Michigan State University, USA). One-factor ANOVA was used to analyze the main effect of treatments and standard error of the difference (SED) for comparing treatment means. A principal component analysis (PCA) biplot was applied to assess the relationship between cumulative GHG and some soil properties, crop N uptake, and crop yield.

Results

Soil N dynamics and moisture content during the upland rice–sugarcane period

During the upland rice period and at 0–15 cm soil depth, the BC2 treatment provided a soil ammonium content lower than that of the BC1 treatment at 91 DAA (Figure 1A), while the BC0 treatment gave a greater nitrate content than both BC treatments (Figure 1B). In addition, the BC1 treatment caused significantly lower soil nitrate (Figure 1A) and mineral N contents (Figure 1C) than the other treatments at 122 DAA ($P \leq 0.05$). At 15–30 cm soil depth, the BC2 treatment provided a soil ammonium content lower than that of the BC0 treatment at 47

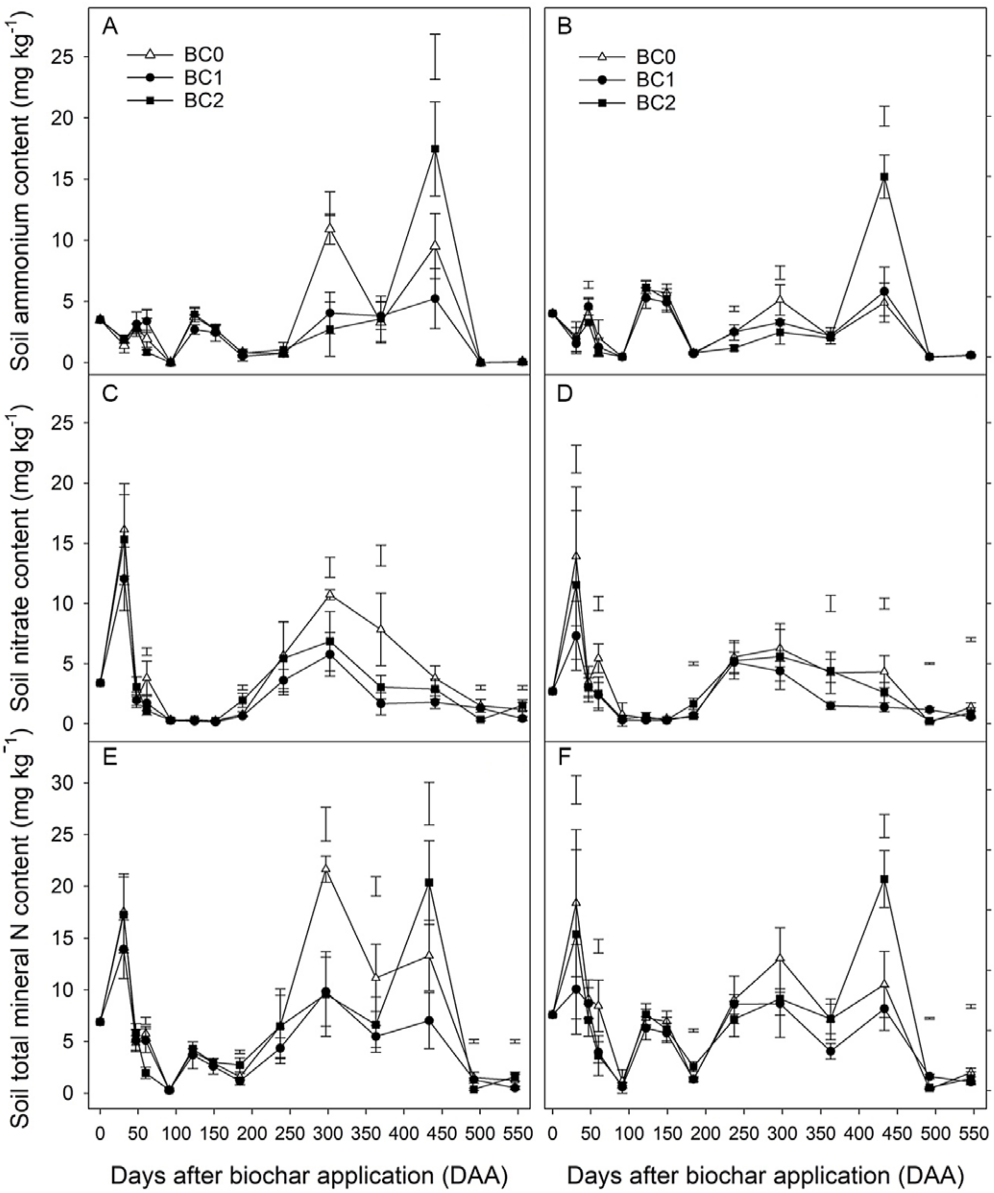

Figure 1. Dynamics of soil ammonium (A, D), nitrate (B, E), and total mineral nitrogen (C, F) at 0–15 (A–C) and 15–30 cm (D–F) soil depths as affected by biochar application: no biochar application (BC0); 3.1 Mg ha^{-1} (BC1); and 6.2 Mg ha^{-1} (BC2). Error bars indicate standard deviations (n = 4), and vertical bars represent the SED. All treatments received the same recommended fertilizer rate.

DAA ($P \leq 0.05$) (Figure 1D). Moreover, both BC treatments caused significantly lower soil nitrate and mineral N contents than the BC0 treatment at 60 DAA (Figure 1E, F).

During the sugarcane period, the BC2 treatment increased soil nitrate (Figure 1A) and mineral N content as compared with the BC0 treatment (0–15 cm) at the planting date. At 297 DAA, both BC treatments resulted in significantly lower soil ammonium, nitrate, and mineral N contents than the BC0 treatment (Figure 1A-C). Moreover, such treatment still provided lower nitrate and mineral N contents at 363 DAA (Figure 1B, C). The BC1 treatment not only reduced the

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soil ammonium, nitrate, and mineral N contents at 433 DAA but also the nitrate and mineral N contents at the final sugarcane harvest (Figure 1A-C), while the BC2 treatment reduced nitrate and mineral N contents at 496 DAA (Figure 1B, C). However, the MBN did not differ among treatments throughout the experiment (data not shown). The BC2 treatment increased soil moisture content as compared with the BC0 treatment throughout the experiment at both soil depths (Figure S3).

GHG emissions

The CO_2 emission rate was not significantly different among the treatments during the upland rice period (Figure 2A). However, during the sugarcane period, the BC1 treatment caused higher CO_2 emission rate than the other treatments at 346 and 379 DAA ($P \leq 0.05$). The CH_4 emission rate was significantly low at 84 DAA, with the BC1 treatment inducing a higher CH_4 emission rate than the other treatments ($P \leq 0.01$) (Figure 2B). The BC2 treatment reduced ($P \leq 0.05$) N_2O emission rate as compared with BC0 treatment at 70, 91, and 122 DAA (Figure 2C).

Cumulative GHG and GWP

Cumulative CO_2 emissions were not significantly different among the upland rice and sugarcane treatment periods (Table 2). However, the BC2 treatment resulted in significantly lower cumulative CH_4 ($P \leq 0.01$) and N_2O emissions ($P \leq 0.05$) than the BC0 treatment during the upland rice period, while there was no significant difference among treatments during the sugarcane period. Moreover, the BC2 treatment mitigated not only cumulative CH_4 but also N_2O emissions ($P \leq 0.05$) throughout the experiment. Similar GWP from CO_2 emission was found among treatments (Table 3).

Yield and total N uptake of upland rice and sugarcane

At upland rice harvest, there was no significant difference among treatments in terms of grain yield and total N uptake (Figure 3A). However, the greatest yield and total N uptake of sugarcane were found in BC2 treatment ($P \leq 0.01$), with no differences between BC1 and BC0 treatments (Figure 3B).

Correlation among emission of GHGs and some soil properties, crop N uptake, and crop yield

At upland rice harvest, there were strong correlations between cumulative N_2O emission, cumulative CH_4 emission, soil bulk density (BD), OM, cation exchangeable capacity (CEC), total N uptake, and upland rice yield, as indicated by significant biplot PCA and confirmed by Pearson's correlation coefficient ($P \leq 0.05$, Figure 4A). The first and second principal components (PCA1 and PCA2) explained 84.2% of the total variability of the dataset. Cumulative N_2O emissions have a significant negative correlation with OM, CEC, total N uptake, and upland rice yield, while a significant positive correlation was found with BD (Figure 5A). Cumulative CH_4 emissions have a significant negative correlation with OM. The increase in OM not only reduced N_2O emissions but also CH_4 emissions.

At sugarcane harvest, there were strong correlations between cumulative N_2O emissions, total N uptake, and sugarcane yield (Figure 5F, H), while BD, OM, and CEC showed no correlation with cumulative N_2O and CH_4 at the sugarcane harvest, as indicated by PCA and Pearson's correlation coefficient. The first and second principal components (PCA1 and PCA2) explained 67.9% of the total variability of the dataset (Figure 4B).

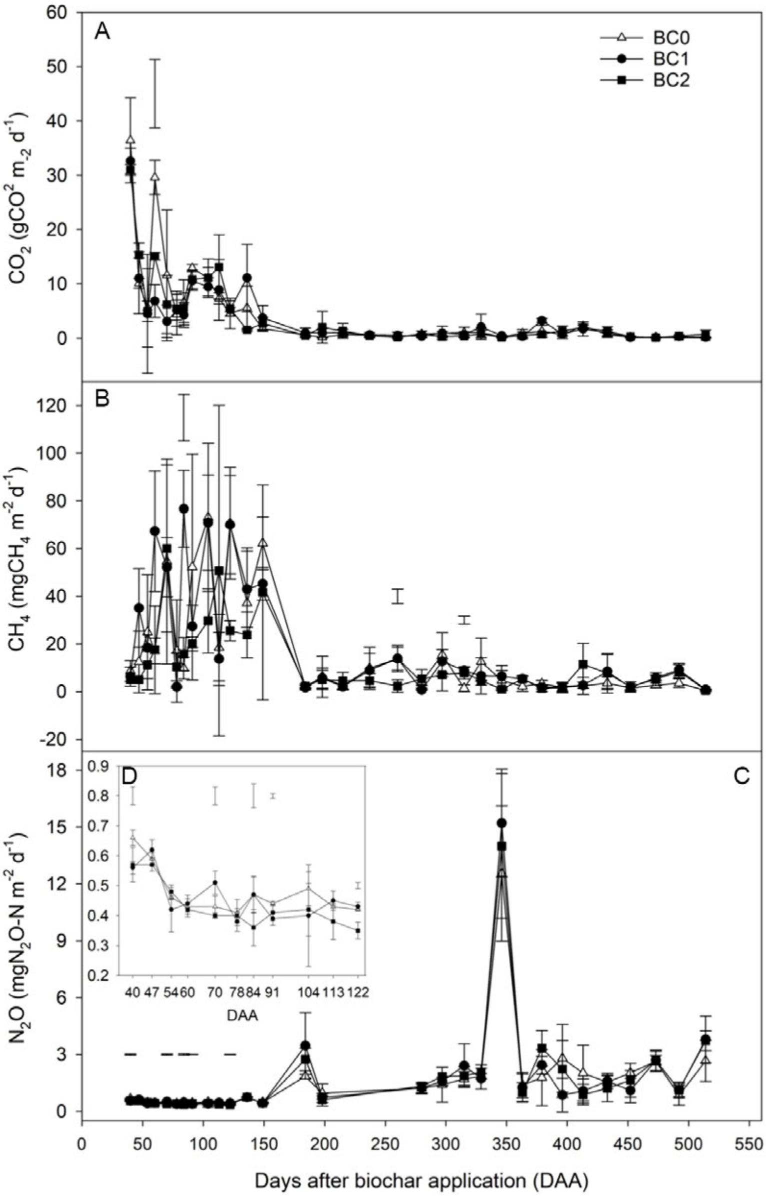

Figure 2. CO_2 (A), CH_4 (B), and N_2O (C) emission rates as affected by biochar application in an upland rice–sugarcane cropping system: no biochar application (BC0); 3.1 Mg ha^{-1} (BC1); and 6.2 Mg ha^{-1} (BC2). N_2O emission rate during the upland rice period (from 40 to 122 DAA) is shown in (D). Error bars indicate standard deviations (n = 3), and vertical bars represent the SED. All treatments received the same recommended fertilizer rate.

Discussion

Trade-off between N availability and cumulative N_2O emissions in upland rice–sugarcane cropping systems

Fertilizers are one of the major sources of soil mineral N, and fertilization treatments have a significant impact on N_2O emissions (Koga, 2013; Gonzaga *et al.*, 2018). The highest nitrate and mineral N contents occur during the upland rice period (Figure 1B, C) at the first time of

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Table 2. Cumulative CO_2 (g CO_2 m^{-2}), CH_4 (g CH_4 m^{-2}), and N_2O (g N_2O-N m^{-2}) emissions[a] during upland rice, sugarcane, and the total period as affected by biochar application: no biochar application (BC0); 3.1 Mg ha^{-1} (BC1); and 6.2 Mg ha^{-1} (BC2)

	BC0	BC1	BC2	SED
Upland rice period				
CO_2	1251.8 (±77)	1095.0 (±74)	1258.9 (±198)	120.00^{ns}
CH_4	4.75a (±0.57)	5.06a (±0.32)	3.34b (±0.18)	0.27**
N_2O	1.46a (±0.02)	1.41b (±0.05)	1.35c (±0.03)	0.01*
Sugarcane period				
CO_2	210.8 (±21.1)	265.9 (±5.3)	240.3 (±29.8)	21.27^{ns}
CH_4	1.67 (±0.46)	1.92 (±0.26)	1.55 (±0.49)	0.22^{ns}
N_2O	0.80 (±0.09)	0.84 (±0.05)	0.66 (±0.05)	0.66^{ns}
Upland rice–sugarcane system				
CO_2	1466.6 (±77.5)	1361.0 (±75.9)	1499.2 (±227.6)	136.73^{ns}
CH_4	6.42a (±0.49)	6.99a (±0.53)	4.89b (±0.44)	0.41*
N_2O	2.26a (±0.08)	2.25a (±0.09)	2.01b (±0.07)	0.07*

[a]Mean values ± standard deviation (n = 3). In each line, numbers followed by same letters are not significantly different according to Least Significant Difference with $\alpha = 0.05$. *$P \leq 0.05$; $^{ns}P > 0.05$. All treatments received the same recommended fertilizer rate. SED = standard error of the difference between treatment means.

Table 3. Global warming potential[a] (GWP) [CO_2 = 1, CH_4 = 21, N_2O = 310 (IPPC 2017)] of CO_2, CH_4, and N_2O emissions during the upland rice and sugarcane periods and the total period as affected by biochar application: no biochar application (BC0); 3.1 Mg ha^{-1} (BC1); and 6.2 Mg ha^{-1} (BC2)

	BC0	BC1	BC2	SED
Upland rice period				
CO_2	1251.8 (±77)	1095.0 (±74)	1258.9 (±198)	120.00^{ns}
CH_4	99.7a (±11.9)	106.3a (±6.6)	70.1b (±3.7)	5.70**
N_2O	451.5a (±5.5)	437.5a (±14.3)	418.9b (±8.2)	4.33**
Total	1803.1 (±79.6)	1638.9 (±80.1)	1748 (±190.5)	119.00^{ns}
Sugarcane period				
CO_2	210.8 (±21.1)	265.9 (±5.3)	240.3 (±29.8)	21.27^{ns}
CH_4	35.1 (±9.7)	40.4 (±5.5)	32.6 (±10.3)	4.67^{ns}
N_2O	248.1 (±28.6)	260.1 (±14.5)	203.9 (±15.0)	19.00^{ns}
Total	494.0b (±10.3)	566.5a (±19.7)	476.7b (±13.6)	13.37**
Upland rice–sugarcane system				
CO_2	1466.6 (±77.5)	1361.0 (±75.9)	1499.2 (±227.6)	136.73^{ns}
CH_4	134.88a (±10.2)	146.71a (±11.2)	102.73b (±9.3)	8.5*
N_2O	699.6a (±25.5)	697.7a (±28.6)	622.8b (±20.4)	21.7*
Total	2297.1 (±79)	2205.4 (±96)	2224.7 (±199)	129.13^{ns}

[a]Mean values ± standard deviation (n = 3). In each line, numbers followed by same letters are not significantly different according to Least Significant Difference with $\alpha = 0.05$. *$P \leq 0.05$; $^{ns}P > 0.05$. All treatments received the same recommended fertilizer rate. SED = standard error of the difference between treatment means.

application while it was only observed when fertilizer was applied at the second time of application during the sugarcane period (Figure 1F). Moreover, our results revealed different relationships between ammonium-nitrate (0–30 cm depth) and cumulative N_2O emissions (Table 4). A significant positive correlation was found between soil ammonium and cumulative N_2O emissions during the dry season at 2 MAP (Figure S1), while a negative correlation occurred when there was no rainfall during the wet season (8 MAP). In contrast, the correlation between soil nitrate and cumulative N_2O emissions was negative under the dry season (sugarcane planting date) and positive under moist conditions (10 MAP).

Nitrification is one of the main sources of N_2O in soils, providing nitrate – an initial substrate for N_2O production via denitrification (Katharina *et al.*, 2021). Nitrate is a substrate of

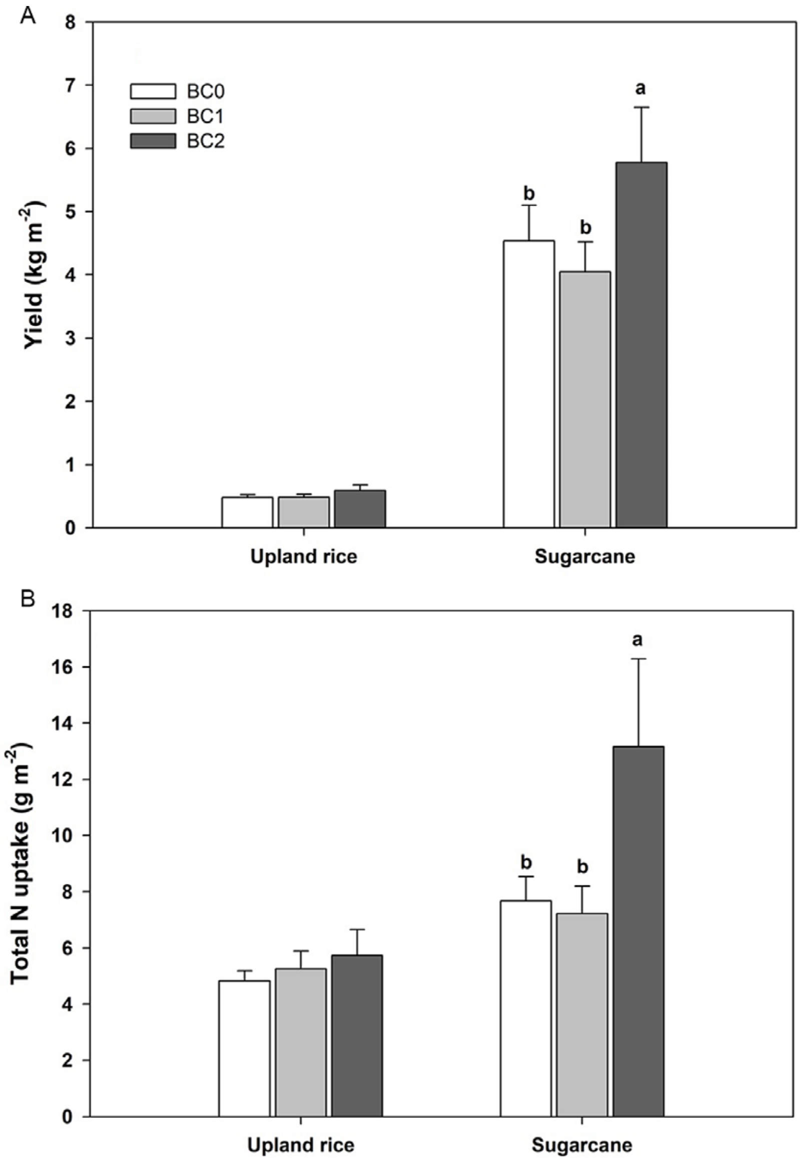

Figure 3. Crop yield (A) and total N uptake (B) of upland rice and sugarcane as affected by biochar application: no biochar application (BC0); 3.1 Mg ha^{-1} (BC1); and 6.2 Mg ha^{-1} (BC2). Different letters indicate significant differences among treatments ($P \leq 0.05$). Error bars indicate standard deviations ($n = 4$). All treatments received the same recommended fertilizer rate.

denitrification under anaerobic conditions, and such reducing condition caused a positive correlation between nitrate and N_2O emission. Accordingly, low soil moisture reduces denitrification and suppress N_2O emissions. On the other hand, aerobic conditions led ammonium to nitrification, resulting in nitrate. Thus, a significant positive correlation between soil ammonium and cumulative N_2O emissions was revealed under low soil moisture. Under anaerobic conditions, ammonium is the main mineral N form that does not enter denitrification, and hence, a negative correlation was presented (Table 4).

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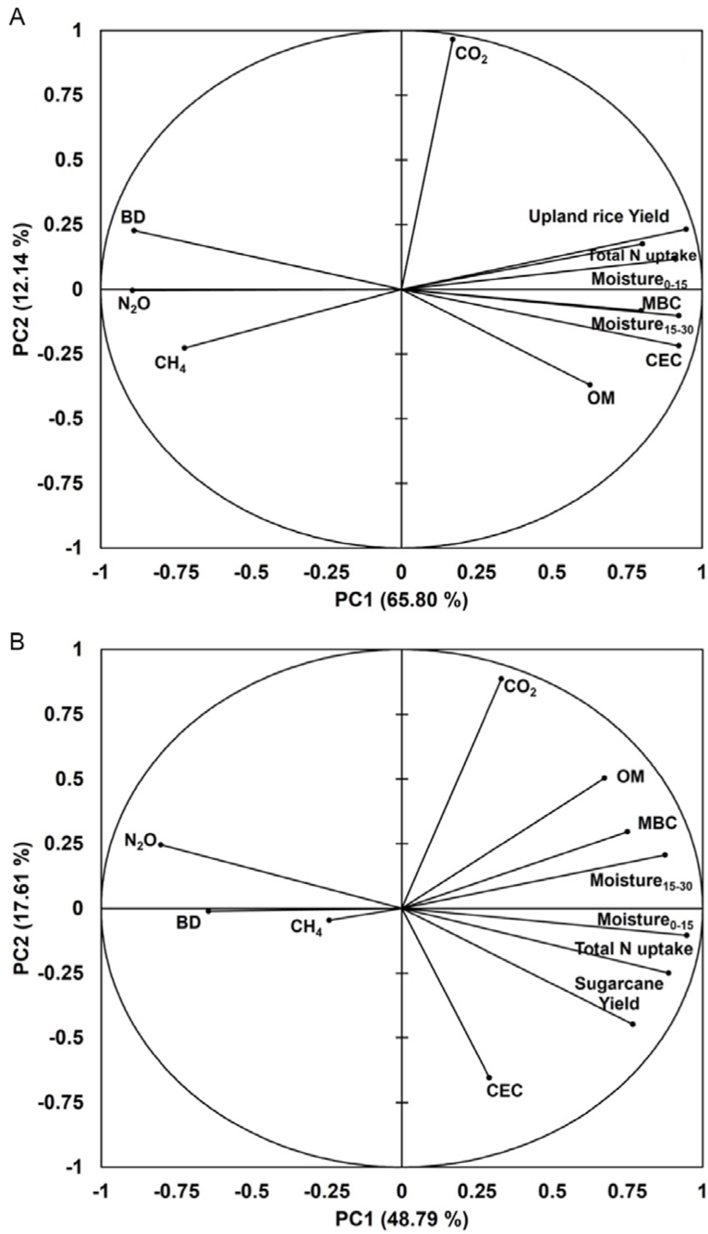

Figure 4. Principal components analysis (PCA) biplot showing the relationship among cumulative CO_2, N_2O, CH_4 emissions, soil bulk density (BD), organic matter (OM), cation exchangeable capacity (CEC), crop total N uptake (Total N), microbial biomass carbon (MBC), soil moisture content at 0–15 cm ($Moisture_{0-15}$) and 15–30 cm ($Moisture_{15-30}$) soil depth at upland rice harvest (A) and sugarcane harvest (B).

Several studies have suggested that BC application not only ameliorates soil fertility (Petter *et al.*, 2016) but also reduces the concentrations of nutrients and labile C by sorption and sequestration (Lou *et al.*, 2011; Ippolito *et al.*, 2012; Xu *et al.*, 2012; Luo and Gu, 2016) and leads to microbial abundance. However, some experiments have shown a negative or null effect of BC on N availability. Bargmann *et al.* (2014) demonstrated that BC amendments suppressed soil

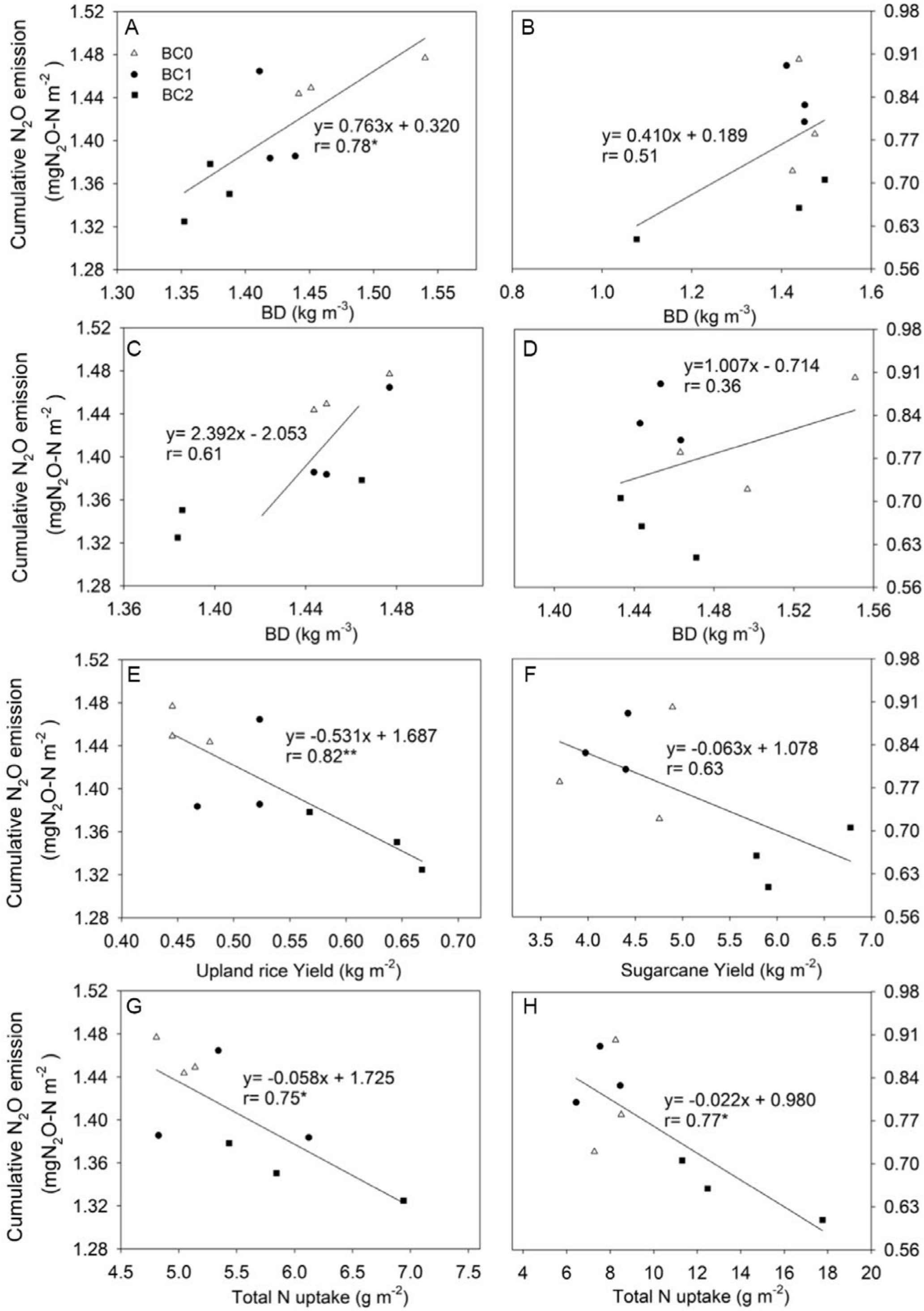

Figure 5. Relationship between cumulative N_2O emission and soil bulk density (BD) at 0–15 cm (A, B) and 15–30 cm (C, D) soil depth at upland rice harvest (A, C) and sugarcane harvest (B, D), between cumulative N2O emission and upland rice yield (E) or sugarcane yield (F), and between cumulative N_2O emission and total N uptake by upland rice (G) and sugarcane (H). $^*P \leq 0.05$; $^{**}P \leq 0.01$. Symbols represent biochar treatments: no biochar application (BC0); 3.1 Mg ha^{-1} (BC1); and 6.2 Mg ha^{-1} (BC2).

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Table 4. Correlations between ammonium and nitrate at 0–30 cm soil depth and cumulative N_2O emission along the experimental period for upland rice and sugarcane cultivation

Upland rice	Ammonium	Nitrate
Planting date	-0.059^{ns}	0.109^{ns}
15 DAP[a]	0.446^{ns}	0.030^{ns}
30 DAP	0.494^{ns}	0.704*
60 DAP	Nd	-0.312^{ns}
90 DAP	-0.248^{ns}	-0.145^{ns}
Harvest	-0.588^{ns}	0.630^{ns}
Sugarcane	Ammonium	Nitrate
Planting date	-0.263^{ns}	−0.729*
2 MAP[b]	0.745*	-0.085^{ns}
4 MAP	0.324^{ns}	0.031^{ns}
6 MAP	-0.381^{ns}	-0.001^{ns}
8 MAP	−0.823**	-0.169^{ns}
10 MAP	Nd	0.699*
Harvest	-0.021^{ns}	-0.530^{ns}

Nd, not detectable; *$P \leq 0.05$; **$P \leq 0.01$; $^{ns}P > 0.05$. [a]DAP = days after upland rice planting, [b]MAP = months after sugarcane planting.

mineral N content via immobilization and absorption by an inner surface. Furthermore, there were no significant effects of BC applications on mineral N content (Wang *et al.*, 2021b) and MBN (Zavalloni *et al.*, 2011). Similarly, there was no effect of BC on MBN which N content in microbial biomass in our study (data not shown) while BC increased mineral N availability (Figure 1). The possible explanation is that mineral N was trapped by BC surface charge, resulting in zero effect on MBN due to the inaccessibility of microbes. In addition, the BC application changes microbial community composition, such as that of denitrifiers (Gomez *et al.*, 2014). High BC doses decreased N_2O emissions (Bruun *et al.*, 2011), whereas the BC addition in combination with chemical fertilizers improves the agronomic efficiency of nitrogen use in upland rice (Petter *et al.*, 2016). In contrast, low BC doses (< 3 Mg ha^{-1}) had no effect on GHG emission in an incubation experiment (Romero *et al.*, 2021).

Our study revealed a negative effect of BC application on N_2O emissions while a positive effect on mineral N content. BC contains surface charge and pores where mineral N (substrate for denitrification and immobilization) can be absorbed, suppressing not only denitrification but also immobilization. N_2O emission is one fertilizer N loss pathway, leading to low crop productivity and such emissions from sugarcane fields were between 7.4 and 72.1 kg N_2O ha^{-1} in Australia (Denmead *et al.*, 2010). However, Kaewpradit and Toomsan (2019) found a mitigation of N_2O emission when using BC at 6.25 Mg ha^{-1}, with increased N availability in short-term incubation. Our results confirm that eucalyptus BC application at 6.25 Mg ha^{-1} not only reduces N_2O emissions but also increases N availability in the upland rice–sugarcane cropping system.

How do some soil properties and crop yield affect cumulative GHG emissions?

Our results revealed greater CO_2 and CH_4 emissions during the rice growing season (Figure 2A,B) and it is known that microbial respiration is a source of CO_2 and activated by rice root exudate (Le Mer and Roger, 2001). Accordingly, BC – a material with high carbon content – stimulated microbial activity, given by increases in β-glucosidase activity (Kaewpradit and Toomsan, 2019). As an extracellular enzyme involved in carbon mineralization, β-glucosidase activity increases carbon availability for microbes. A close correlation between β-glucosidase activity and labile SOC components was demonstrated under sandy soil in northeastern Thailand (Phukongchai *et al.*, 2022).

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Table 5. Correlations between CO_2, CH_4, and N_2O emissions with some soil properties, crop yield, and total N uptake during the upland rice and sugarcane cultivation

Soil and crop variables	Upland rice			Sugarcane		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Soil						
Bulk density (0–15 cm soil depth)	0.033^{ns}	0.440^{ns}	0.780*	0.195^{ns}	0.198^{ns}	0.514^{ns}
Bulk density (15–30 cm soil depth)	0.226^{ns}	0.640^{ns}	0.600^{ns}	0.550^{ns}	-0.474^{ns}	0.360^{ns}
Microbial biomass N (MBN)	0.163^{ns}	-0.360^{ns}	-0.276^{ns}	-0.351^{ns}	0.090^{ns}	0.570^{ns}
Microbial biomass C (MBC)	0.005^{ns}	-0.350^{ns}	−0.829**	0.486^{ns}	-0.235^{ns}	-0.279^{ns}
Organic matter (OM)	-0.170^{ns}	−0.72*	-0.500^{ns}	0.620^{ns}	0.040^{ns}	-0.349^{ns}
Cation Exchange Capacity (CEC)	-0.066^{ns}	-0.609^{ns}	−0.726*	0.390^{ns}	0.429^{ns}	0.268^{ns}
Mineral N (0–15 cm soil depth)	-0.020^{ns}	0.005^{ns}	-0.314^{ns}	0.736^{ns}	0.577^{ns}	0.250^{ns}
Mineral N (15–30 cm soil depth)	0.296^{ns}	-0.303^{ns}	-0.306^{ns}	-0.268^{ns}	0.301^{ns}	0.350^{ns}
Mineral N (0–30 cm soil depth)	0.038^{ns}	0.190^{ns}	0.090^{ns}	−0.687*	0.241^{ns}	0.020^{ns}
Available P	0.013^{ns}	-0.432^{ns}	-0.511^{ns}	0.297^{ns}	0.402^{ns}	0.100^{ns}
Exchangeable K	0.066^{ns}	-0.520^{ns}	-0.406^{ns}	0.69*	-0.260^{ns}	-0.470^{ns}
Exchangeable Ca	-0.160^{ns}	-0.136^{ns}	-0.612^{ns}	0.475^{ns}	0.289^{ns}	0.001^{ns}
Soil moisture (0–15 cm soil depth)	0.054^{ns}	-0.400^{ns}	−0.550*	0.060^{ns}	-0.004^{ns}	−0.69**
Soil moisture (15–30 cm soil depth)	0.004^{ns}	-0.430^{ns}	−0.730**	0.250^{ns}	-0.010^{ns}	0.500^{ns}
Crop						
Yield	0.440^{ns}	−0.66*	-0.638^{ns}	-0.316^{ns}	-0.234^{ns}	−0.710*
Total N uptake	0.567^{ns}	−0.734*	−0.785*	-0.044^{ns}	-0.459^{ns}	−0.730*

*$P \leq 0.05$; **$P \leq 0.01$; $^{ns}P > 0.05$.

This results in higher CO_2 and CH_4 emissions during the rice growing season in a rainy period (Figure S1), when anaerobic conditions are suitable for CH_4 production. However, the effect of BC on CO_2 emission was not detected in the sugarcane field experiment (Table 2). Soil compaction and less oxygen led to anaerobic conditions and then affect N_2O emissions (Skiba and Smith, 2000; Ruser *et al.*, 1998). Thus, a positive correlation between soil bulk density and cumulative N_2O emissions was revealed (Figure 5A-D). However, this did not occur in the sugarcane period, which was likely associated with a large root system reducing soil bulk density and providing better aerobic conditions (Smith *et al.*, 2005). Nutrients applied in the BC amendment treatment are known to enhance sugarcane growth (Butphu *et al.*, 2020), resulting in more roots and more micropores for oxygen after former primary root decomposition.

In addition, BC micropores can be occupied by water (Graber *et al.*, 2010). The application of BC increased total soil pores, leading to higher water availability (Agbede *et al.*, 2020; Masulili *et al.*, 2010). While BC improves soil moisture content, a negative correlation between soil moisture and N_2O emissions was observed at upland rice and sugarcane harvests (Table 5). As BC contains water in micropores, soil water available was increased and mitigation of N_2O emissions can be explained by a negative correlation between the soil cation exchange capacity (CEC) and cumulative N_2O emissions at upland rice harvest. Ammonium can be converted to nitrate or absorbed at negatively charged positions of BC, which reduces N_2O emission. This mineral N pool may preserve microbial biomass and evidence is the negative correlation between the carbon contain in microbial biomass and the cumulative N_2O emissions at upland rice harvest (Table 5). A negative correlation between the total N uptake by upland rice and sugarcane and N_2O emissions indicates that N uptake increased when N_2O emission was low (Figure 5G, H). In fact, eucalyptus BC application seems to be a promising practice not only to mitigate N_2O emissions but also to improve the soil N pool and N uptake by crops like rice and sugarcane.

Conclusion

Our study found that eucalyptus BC application at 6.2 Mg ha^{-1} in combination with mineral NPK fertilizers increased soil N availability and mitigated N_2O emissions. The increase in soil mineral N

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content and decreased N loss via denitrification favored N uptake and crop yield. Moreover, a decrease in cumulative N_2O emissions leads to decreased GWP. Thus, BC amendment to upland rice not only enhances soil–crop N availability and crop yield but also contributes as an environmentally friendly strategy for crop production in upland rice–sugarcane rotations on degraded sandy soils.

Supplementary Material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0014479722000254

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