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Original article

Biochar and rice straw have different effects on soil productivity, greenhouse gas emission and carbon sequestration in Northeast Thailand paddy soil

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ABSTRACT

This study aimed to clarify the effects of biochar (BC made from *Eucalyptus camaldulensis Dehnh.*), and rice (*Orysa sativa* L.) straw (RS) amendments on the soil productivity, carbon sequestration (Cseq) and the possibility for mitigating greenhouse gas (GHG) emissions. A field trial was conducted with 10 treatments: the control, chemical fertilizer (CF) and BC or RS each at four rates of L (6.25 t/ha), ML (12.50 t/ha), MH (18.75 t/ha) and H (25.00 t/ha) using a randomized complete block design with four replicates. The results showed that BC and RS not only increased the soil quality but also increased the rice yield (RY). During the growing season, BC and RS applications did not differ in the total CO_2 emission. However, the total CH_4 emission and total global warming potential significantly decreased in the BC application and significantly increased in the RS application, relative to the control. Soil Cseq increased under the BC application by 1.87–13.37 t C/ha, while the RS application reduced Cseq by 0.92–2.56 t C/ha. The high amount of recalcitrant C molecules in BC probably explained the decreases in the GHG-C loss and increases in Cseq. In contrast, RS had high amounts of labile components that enhanced the GHG-C emission and reduced Cseq. Finally, the GHG intensity of rice production was reduced for both BC and RS meaning that these two amendments can be considered as good options for the mitigation of climate change.

Introduction

Long term, poorly managed rice culture in Northeast Thailand has decreased the soil organic carbon (SOC) content resulting in degraded paddy soils with low productivity; to counteract this, leftover rice stubble and straw (RS) is usually incorporated into the soil to improve the fertility and rice yield (RY) and to maintain the SOC (Xiao et al., 2007; Hanafi et al., 2012). RS application increases the SOC as a function of application amounts and duration. For instance, RS added into paddy soils increased seasonal soil carbon sequestration (Cseq) by 0.10 t C/ha and 0.36 t C/ha at an application rate of 2.625 t/ha and 4.5 t/ha, respectively, in a long term field experiment (Xionghui et al., 2012). However, RS is an easily decomposable organic material that provides major substrates for methanogens that contribute to methane (CH_4) and carbon dioxide (CO_2) production resulting in increases in the global warming potential (GWP; Le Mer and Roger, 2001).

Biochar (BC) is a stable, C-rich form of charcoal which can be applied to crop lands as an amendment to improve the soil productivity, reduce greenhouse (carbon) gases (GHG) and enhance soil Cseq (Lehmann, 2007). Assessment of the BC effects in a field trial in China revealed that BC application at rates of 10 t/ha and 40 t/ha improved the rice yield (RY) by 12 percent and 14percent, respectively (Zhang et al., 2012a). Moreover, the initial C loss as CO_2 emission was negligible compared to the amount of intrinsic C stored within the BC itself (Jones et al., 2011). Indeed, BC can remain in soil for hundreds to thousands of years (Sohi et al., 2009; Sparkes and Stoutjesdijk, 2011), providing an alternative for sequestering C in soil (Lehmann et al., 2006; Shen et al., 2014). Accordingly, the possibility to use BC derived from eucalypt trees that grow abundantly in Northeast Thailand should be examined as a potential soil amendment for reducing GHG emissions in paddy soils.

The contrasting chemical characteristics between BC (from eucalypts) and RS may lead to different decomposition rates when

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applied to soils, thus providing crucial implications for improving soil productivity, GHG emissions and Cseq. At present, no knowledge exists in the published literature on the comparative effects of these two organic amendments. Therefore, the aims of this study were to evaluate the soil productivity, GHG emissions and soil Cseq in a paddy field soil in Northeast Thailand amended with BC (eucalypts) and RS.

Materials and methods

Field experimental site, climatic condition, soil, biochar and rice straw amendment

The experiment was conducted from November 2011 to May 2012 in a paddy field of an irrigation project at Na-ngam village, Khon Kaen province, Northeast Thailand (16° 32′ 48.08″ N, 102° 51′ 15.10″ E). Since 1972, the field has been used to grow two rice crops per year. The studied soil is classified as fine, mixed, isohyperthermic Aeric Endoaquepts (United States Department of Agriculture, 1999), and Ratchaburi soil series (Rb) in the Thai soil classification system (Land Development Department, 2005). The physicochemical characteristics of the top soil (0–15 cm) are shown in Table 1. The soil is considered to be unfertile. Particle size distributions contained 50.0 percent sand, 36.7 percent silt and 13.3 percent clay, and was classified as having loamy soil texture. Average climatic conditions during the field trial period varied between 22.31 °C and 34.07 °C and rainfall was on average 1.89 mm/mth.

The BC used in all of the experiments was produced from the branches of eucalypt wood (*Eucalyptus camaldulensis Dehnh.*) aged 5 yr using a pyrolysis process in a conventional kiln at 350 °C for 48 h. It was then ground and passed through a 2 mm sieve. The RS in this study was chopped into 5–10 cm lengths before use. The physicochemical characteristics of the BC and RS are shown in Table 1.

Treatments, rice cultivation, and field management

Each plot size was 4 × 4 m with the adjacent plots sharing a soil boundary of 30 cm in width and 20 cm in height. Ten treatments were arranged in a randomized complete block design with four replications. The treatments were: 1) control (no BC, no RS); 2) chemical fertilizer alone (CF, no BC, no RS); 3) BC 6.25 t/ha (BCL); 4) BC 12.50 t/ha (BCML); 5) BC 18.75 t/ha (BCMH); 6) BC 25.00 t/ha (BCH); 7) RS 6.25 t/ha (RSL); 8) RS 12.50 t/ha (RSML); 9) RS 18.75 t/ha (RSMH); and 10) RS 25.00 t/ha (RSH). All plots, except the control, received CF (grade 16-16-8 of N-P-K) as a basal fertilizer at a rate of 250 kg/ha and a top dressing with urea (46% N) that was applied equally twice to give a total of 187.5 kg/ha.

Table 1
Properties of biochar, rice straw and rice soil prior to field experiment.

Property[a]	Biochar[a]	Rice straw[a]	Rice soil[b]
BD (g/cm^3)	ud	Ud	1.45
pH (1:5)	7.98	7.01	5.0
Total N (%)	0.54	0.65	0.08
Total P (g/kg)	0.22	0.48	ud
Total K (g/kg)	7.63	9.97	ud
Total Ca (g/kg)	23.35	14.59	ud
Total Mg (g/kg)	1.65	2.13	ud
Available P (mg/kg)	ud	ud	74.68
Exchangeable K (mg/kg)	ud	ud	42.39
Exchangeable Ca (mg/kg)	ud	ud	707.23
Exchangeable Mg (mg/kg)	ud	ud	90.58
CEC (cmol/kg)	22.75	16.90	11.50
TOC, SOC (%)	61.43	39.29	0.71
LOC (g/kg)	13.28	66.74	0.36
Cellulose (%)	6.25	50.84	ud
Hemicellulose (%)	1.00	22.19	ud
Lignin (%)	75.69	3.33	ud
Volatile matter (%)	22.86	ud	ud
Ash (%)	2.99	ud	ud
Fixed C (%)	69.56	ud	ud

[a] BD = bulk density; CEC = cation exchange capacity; TOC = total organic carbon; LOC = labile organic carbon; ud = undetermined.
[b] Soil sampling was done at 95 d prior to sowing.

Before commencing the experimental set up, the remaining rice stubble in the field was estimated to be 1.81 t C/ha. This was evenly spread out and then plowed into the moist soil on 10 November 2011, corresponding to 93 d before sowing. The BC and RS were incorporated into the soil on 29 December 2011, corresponding to 44 d before sowing. Rice sprouts (cultivar Pathum Thani 1) were evenly sown in the puddle soil at 125 kg/ha on 11 February 2012 (day 0). Fertilizer top dressing of urea as mentioned above was done at 22 and 46 d after sowing (DAS), except in the control. The water level was maintained at 5–10 cm depth and soil was near saturation from 71 DAS until rice harvest on 1 June 2012 (111 DAS). RY samples were collected inside a quadrant area of 1 × 1 m^2 with two replications per plot.

Field soil sampling, soil, biochar and rice straw analysis

Prior to the experiment, composite samples of the top soil (0–15 cm) were collected from the experimental site (95 d before sowing and 2 d before the remaining rice stubble was incorporated) and post experiment at 111 DAS from individual plots. The soil samples were then air dried and passed through a 2 mm sieve before analysis. Chemical analysis of the soil, BC and RS samples was performed for total organic carbon (TOC) on an Elemental CNS Analyzer (Flash 2000; Thermo Fisher Scientific Inc.; UK). The LOC in soil was determined using the $KMnO_4$ (33 mM) oxidation method (Moody and Cong, 2008). The pH was measured at a sample:water ratio of 1:5 (weight per volume). The total N was determined using the Micro-Kjeldahl method (Bremner, 1965). The available P was measured using the Bray II method (Bray and Kurtz, 1945). The exchangeable K, Ca, Mg and the cation exchange capacity (CEC) were analyzed following Sumner and Miller (1996). At the above sampling times, the soil bulk density (BD, oven dried soil per total soil volume) was determined using a soil core sampler 15 cm long.

The proximate BC properties representing the ash content, volatile matter and fixed C, were determined using the standard techniques of American Standard Test Method (2007). The cellulose, hemicellulose and lignin content in the RS and BC were analyzed according to Aravantinos-Zafiris et al. (1994).

CH_4 and CO_2 gases sampling and analysis

The static, closed chamber method was used to collect gases from the field experiment. Gas sampling was performed weekly from 09:00 h to 11:00 h using a 1 mL syringe to collect gas 0 min, 10 min and 20 min after chamber closure throughout the rice growing season (Saenjan et al., 2002; Ro et al., 2011). The CH_4 and CO_2 concentrations were measured using a gas chromatograph (GC-2014; Shimadzu; Kyoto, Japan) equipped with a flame ionization detector, a methanizer (MTN-1; Shimadzu; Kyoto, Japan) and a stainless steel column packed with unibead C. The column and detector temperatures were 170 °C and 200 °C, respectively. High purity N_2 served as a carrier gas. The retention times of CH_4 and CO_2 were 2.25 min and 3.25 min, respectively. The CH_4 and CO_2 emission rates were calculated from the increases in concentration with time using the volume of the gas chamber, corrected for temperature inside the chamber and the space height from the water level. The TCH_4 and TCO_2 emissions were calculated by summing up the emission quantities between each pair of adjacent measurement intervals (Saenjan et al., 2002). The GWP and the greenhouse gas intensity (GHGI) of rice production were calculated following Zhang et al. (2012b). However, in the present study, only C gases as CO_2 and CH_4 were measured, while N_2O was not included. TGWP-C is the sum of the GWP of CH_4-C and the GWP of CO_2-C.

In this study, SOC stock was considered as soil Cseq during a single rice cropping season and was calculated using Equation (1):

$$C_{seq} = SOC \times BD \times H \times 100 \tag{1}$$

where soil Cseq is measured in tonnes C per hectare, SOC is measured in percent, BD is measured in tonnes per cubic meter or grams per cubic centimeter and H is the plowed layer (0.15 m in depth).

Accordingly, soil Cseq before the experiment obtained from an SOC of 0.71 percent and a soil BD of 1.45 t/m^3 was 15.44 t C/ha (see footnote to Table 4).

Statistical analysis

Data were analyzed for statistically significant differences using ANOVA and Duncan's multiple-range test (SAS version 9.1; SAS Institute, Inc.; Cary, NC, USA). Orthogonal analysis for significant differences between treatment groups of BC and RS was also performed using the MSTAT-C software (version 1.42; Michigan State University; East Lansing, MI, USA). Significant correlation coefficients (Pearson's correlation, r, at $p \leq 0.05$) of the BC and RS rates (x axis) with field soil parameters, and RY; as well as between field soil properties (x axis) and RY from BC and RS amendment (y axis) were analyzed using the Statistix 8 for Windows software (version 8.0; Analytical Software; Tallahassee, FL, USA).

Results

Effects of biochar and rice straw application rates on soil properties

After the rice harvest, the soils with added RS displayed a significant decrease in BD (1.27 g/cm^3 to 1.17 g/cm^3) compared to the control (1.44 g/cm^3) and the CF treatment (1.45 g/cm^3) as shown in Table 2. No significant decrease was observed for the BC applications. No distinctive change in the soil pH was observed for any of the treatments.

The total N in the soil increased significantly with the addition of BC and RS (Table 2). With RS, the total N (0.117–0.127%) was always higher than with BC (0.113–0.119%). The available P in the soil amended with BC and RS increased with application rates, particularly at the highest rates (178.3 mg/kg, 185.8 mg/kg and 188.5 mg/kg for the BCH, RSMH and RSH treatments, respectively). Compared with the control, K increased with the addition of BC and RS and the highest value of 89.4 mg/kg was found in the BCH addition. The Ca contents in the BCML, BCMH and BCH treatments and in the RSH soils were enhanced compared to the control. The BC and RS had higher Mg contents in all treatments relative to the control and CF. The BC application rates boosted the value of the CEC from 14.9 cmol/kg to 16.8 cmol/kg, which was significantly higher than the change from 12.7 cmol/kg to 14.7 cmol/kg in the RS application. Remarkable increases in the SOC were found in both the BC and RS applications relative to the control and the highest SOC value (1.34%) was observed in the BCH treatment. The amounts of LOC in the soil were greater in all RS treatments (0.60–0.75 g C/kg) relative to the control and BC treatments (0.54–0.59 g C/kg).

An orthogonal comparison (Table 2) showed significantly higher mean BD in the BC soil group (1.41 g/cm^3) and the RS soil group (1.22 g/cm^3). The BC and RS treatment groups resulted in no significant differences in the soil pH mean values. The RS application group had a significantly higher mean total N (0.123%) and available P (159.2 mg/kg) relative to the BC application group. The mean K, Ca, Mg and CEC levels in the soils were enhanced within the BC group (77.8 mg/kg, 1328 mg/kg 108.1 mg/kg and 16.0 cmol/kg, respectively) and the mean K and CEC values were significantly higher than those of the RS treatment group. The mean BC SOC (0.98%) was significantly higher than for RS (0.74%). Conversely, the LOC for the BC treatment group (0.56 g C/kg) was significantly lower than for the RS group (0.71 g C/kg).

No significant relationship between the BC application rate and soil BD was found (Table 3). However, the RS application rate showed a strong negative relationship with soil BD. The medium to high correlations for the BC and RS application rates (r = 0.50 to 0.94) were significant for soil N, P, K, Ca, Mg, CEC, SOC and LOC.

Table 2
Field soil properties after rice harvest at 111 d after sowing.

Treatment[a]	BD[b]	pH	SOC[b]	LOC[b]	Total N	Avia P	K	Ca	Mg	CEC[b]
	g/cm^3		%	g C/kg	%	mg/kg				cmol/kg
Control	1.44a	4.6	0.61e[c]	0.54d	0.085d	90.2d	50.4c	1026e	91.6d	11.2h
CF	1.45a	4.7	0.59e	0.53d	0.092d	114.7c	58.4c	1082de	94.8d	12.1g
BCL	1.40ab	4.9	0.82c	0.55cd	0.113c	118.2c	68.4b	1171b-e	100.9c	14.9d
BCML	1.40ab	4.8	0.78cd	0.54d	0.119bc	122.3c	76.4b	1341abc	107.7ab	15.7c
BCMH	1.41ab	5.0	0.99b	0.59bc	0.115c	149.1b	77.0b	1376ab	110.1ab	16.4b
BCH	1.43a	5.1	1.34a	0.56cd	0.117bc	178.3a	89.4a	1420a	113.6a	16.8a
RSL	1.27bc	4.7	0.76cd	0.60b	0.125ab	119.8c	68.4b	1121cde	101.5c	12.7f
RSML	1.25c	5.1	0.72d	0.74a	0.117bc	142.7b	71.7b	1180b-e	104.3bc	13.3e
RSMH	1.19c	4.8	0.73cd	0.73a	0.124ab	185.8a	73.4b	1266b-e	107.5ab	13.4e
RSH	1.17c	4.8	0.73cd	0.75a	0.127a	188.5a	73.7b	1319a-d	112.6a	14.7d
F-test	***[c]	ns[c]	***	***	***	***	***	**[c]	***	***
CV (%)	6.7	5.0	7.94	5.3	4.3	5.9	9.0	11.9	3.7	2.0
Mean (BC)	1.41	4.9	0.98	0.56	0.116	142.0	77.8	1328	108.1	16.0
Mean (RS)	1.22	4.9	0.74	0.71	0.123	159.2	71.8	1222	106.5	13.5
Ortho	***	ns	***	***	***	***	***	ns	ns	***

[a] BCL = biochar (BC) 6.25 t/ha + CF (chemical fertilizer); BCML = BC 12.50 t/ha + CF; BCMH = BC 18.75 t/ha + CF; BCH = BC 25.00 t/ha + CF; RSL = rice straw (RS) 6.25 t/ha + CF; RSML = RS 12.50 t/ha + CF; RSMH = RS 18.75 t/ha + CF; RSH = RS 25.00 t/ha + CF; CF = chemical fertilizer 16-16-8 (N-P-K) at 250 kg/ha (basal) and 46% N at 187.5 kg/ha (top at 22 and 46 d after sowing).

[b] BD = bulk density; SOC = soil organic carbon; LOC = labile organic carbon; CEC = cation exchange capacity.

[c] Different lowercase online letters indicate a significant difference among treatments; ns = not significant;$^{**}p \leq 0.01$;$^{***}p \leq 0.001$; $n = 4$.

Table 3
Pearson's correlation (r) of biochar and of rice straw rates with field soil properties and rice yield (upper), and between rice yield and soil properties (lower).

	BD[b]	SOC[b]	LOC[b]	Total N	Avail[b] P	K	Ca	Mg	CEC[b]	RY[a]
Amendment rates versus Soil properties										
BC[a]	−0.08 ns[c]	0.90***[c]	0.50**[c]	0.78***	0.92***	0.87***	0.69***	0.89***	0.91***	0.92***
RS	−0.85***	0.46	0.90***	0.79***	0.94***	0.86***	0.71***	0.89***	0.54***	0.91***
Rice yield versus Soil properties										
RY (BC)	−0.04 ns	0.89***	0.36***	0.76***	0.90***	0.92***	0.69***	0.81***	0.87***	–
RY (RS)	−0.76***	0.45	0.79***	0.75***	0.82***	0.74***	0.69***	0.88***	0.90***	–

[a] BC = biochar; RS = rice straw; RY = rice yield.
[b] BD = bulk density; SOC = soil organic carbon; LOC = labile organic carbon; Avail = available; CEC = cation exchange capacity.
[c] ns = not significant;$^{*}p \leq 0.05$;$^{**}p \leq 0.01$;$^{***}p \leq 0.001$; $n = 20$.

Table 4
Total CH_4 (TCH_4), CO_2 (TCO_2) emission, total global warming potential C (TGWP-C), rice yield (RY), greenhouse gas intensity of rice production (GHGI) and carbon sequestered (Cseq) for treatments.

Column[a]	1	2	3	4	5	6	7
						Cseq	
Treatment[b]	TCH_4 t CH_4/ha	TCO_2 t CO_2/ha	TGWP-C t C/ha	RY t/ha	GHGI t C/t RY	After exp. t C/ha	Change t C/ha
Control	0.26de	0.27	1.84de	1.77g	1.08a	13.22e	−2.22e
CF	0.17fg	0.26	1.26fg	2.46f	0.51d	12.86e	−2.58e
BCL	0.17fg	0.31	1.27fg	3.47de	0.37de	17.31c	1.87c
BCML	0.18fg	0.26	1.29fg	4.03cd	0.37de	16.45cd	1.01cd
BCMH	0.22ef	0.30	1.57ef	4.55bc	0.35de	20.96b	5.52b
BCH	0.14g	0.27	1.05g	6.05a	0.19e	28.81a	13.37a
RSL	0.29d	0.27	2.06d	2.95ef	0.81c	14.52de	−0.92de
RSML	0.49c	0.29	3.38c	4.02cd	0.86c	13.56e	−1.88e
RSMH	0.62b	0.26	4.25b	4.12bcd	1.03ab	13.07e	−2.37e
RSH	0.70a	0.25	4.78a	4.74b	1.01ab	12.88e	−2.56e
p-value[c]	***	ns	***	***	***	***	***
CV (%)	15.39	10.68	14.56	11.10	23.74	11.02	195.57
Mean BC	0.18	0.29	1.30	4.53	0.32	20.88	5.44
Mean RS	0.52	0.26	3.62	3.96	0.93	13.51	−1.93
Orthogonal	***	ns	***	***	***	***	***

[a] Column 3 = [(column 1 × 25) + (column 2 × 1)] × 12/44, column 5 = column 3/column 4, column 7 = column 6 − SOC before experiment (15.44 t C/ha).
[b] CF = chemical fertilizer; BCL = biochar (BC) 6.25 t/ha + CF; BCML = BC 12.50 t/ha + CF; BCMH = BC 18.75 t/ha + CF; BCH = BC 25.00 t/ha + CF; RSL = rice straw (RS) 6.25 t/ha + CF; RSML = RS 12.50 t/ha + CF; RSMH = RS 18.75 t/ha + CF; RSH = RS 25.00 t/ha + CF; CF = chemical fertilizer 16-16-8 (N-P-K) at 250 kg/ha (basal) and 46% N at 187.5 kg/ha (top at 22 and 46 d after sowing).
[c] Different lowercase online letters indicate a significant difference among treatments; ns not significant;$^{***}p \leq 0.001$; $n = 4$.

Rice yield and its correlation with biochar and rice straw application rates and soil properties

The RY increased with increasing rates of BC and RS, in the ranges 3.47–6.05 t/ha and 2.95–4.74 t/ha, respectively (Table 4). All rates of BC and RS yielded significantly greater RY than the control (1.77 t/ha) and the CF application (2.46 t/ha). Furthermore, orthogonal analysis revealed a significantly higher RY in the BC treatment group. A significant positive relationship between application rates of BC and RS was also found with RY (r = 0.92 and 0.91) as shown in Table 3. In addition, RY was positively and significantly correlated with the total N, P, K, Ca, Mg, CEC, SOC and LOC (r = 0.36–0.92) as shown in Table 3.

CH_4 and CO_2 emissions and climate change parameters correlation with biochar and rice straw application rates

The BC application treatments had low CH_4 emission rates over the growing season in the range 132.05–200.06 mg CH_4/m^2/d (Fig. 1A). In contrast, all RS-treated soils displayed very high CH_4 emission rates with maximum values at 19 DAS (2633.50 mg CH_4/m^2/d) as shown in Fig. 1B, which then rapidly decreased at 71 DAS, as the soil moisture was near saturation to field capacity, until rice harvest. In all BC application levels and in CF, TCH_4 decreased to low values (0.14–0.22 t CH_4/ha) compared to the control (0.26 t CH_4/ha) as shown in Table 4. There were no differences among the BC levels. In contrast, RS applications resulted in increases in TCH_4 (0.29–0.70 t CH_4/ha) with increasing application levels. Moreover, the orthogonal analysis showed that the BC treatment group contributed to a significant decrease in TCH_4 (0.18 t CH_4/ha) whereas the RS group increased TCH_4 (0.52 t CH_4/ha).

In the field soils, the CO_2 emission rates fluctuated across the BC and RS treatments with a tendency to be higher with higher application levels (Fig. 1C–D). With BC, small peaks in the CO_2 emission rates were visible during the period of moist soil (71–106 DAS) compared to RS (Fig. 1C–D). TCO_2 was generally low with no differences among the 10 treatments (Table 4).

TGWP-C showed similar trends to TCH_4 (Table 4). Decreasing TGWP-C was observed for both BC and CF (1.05–1.57 t C/ha) but an increasing trend was observed for RS (2.06–4.78 t C/ha). In addition, a reduction of GHGI was shown in all BC treatments and in the RSL, RSML and CF applications (0.19–0.86 t C/t RY) when compared to the control (1.08 t C/t RY). However, the high applications of RS (RSMH and RSH) were not significantly different from the control. Comparisons between the BC and RS groups showed that the BC amendment decreased TCH_4, TGWP-C and GHGI, but the RS amendment enhanced these parameters. Moreover, significant negative correlations (data not shown) were found for the BC application rates with TCH_4, TGWP-C and GHGI ($r = -0.588$, -0.594 and -0.763, $p \leq 0.01$, respectively). The RS application rates displayed significantly high and positive correlations with TCH_4 and TGWP-C (both $r = 0.871$, $p \leq 0.01$).

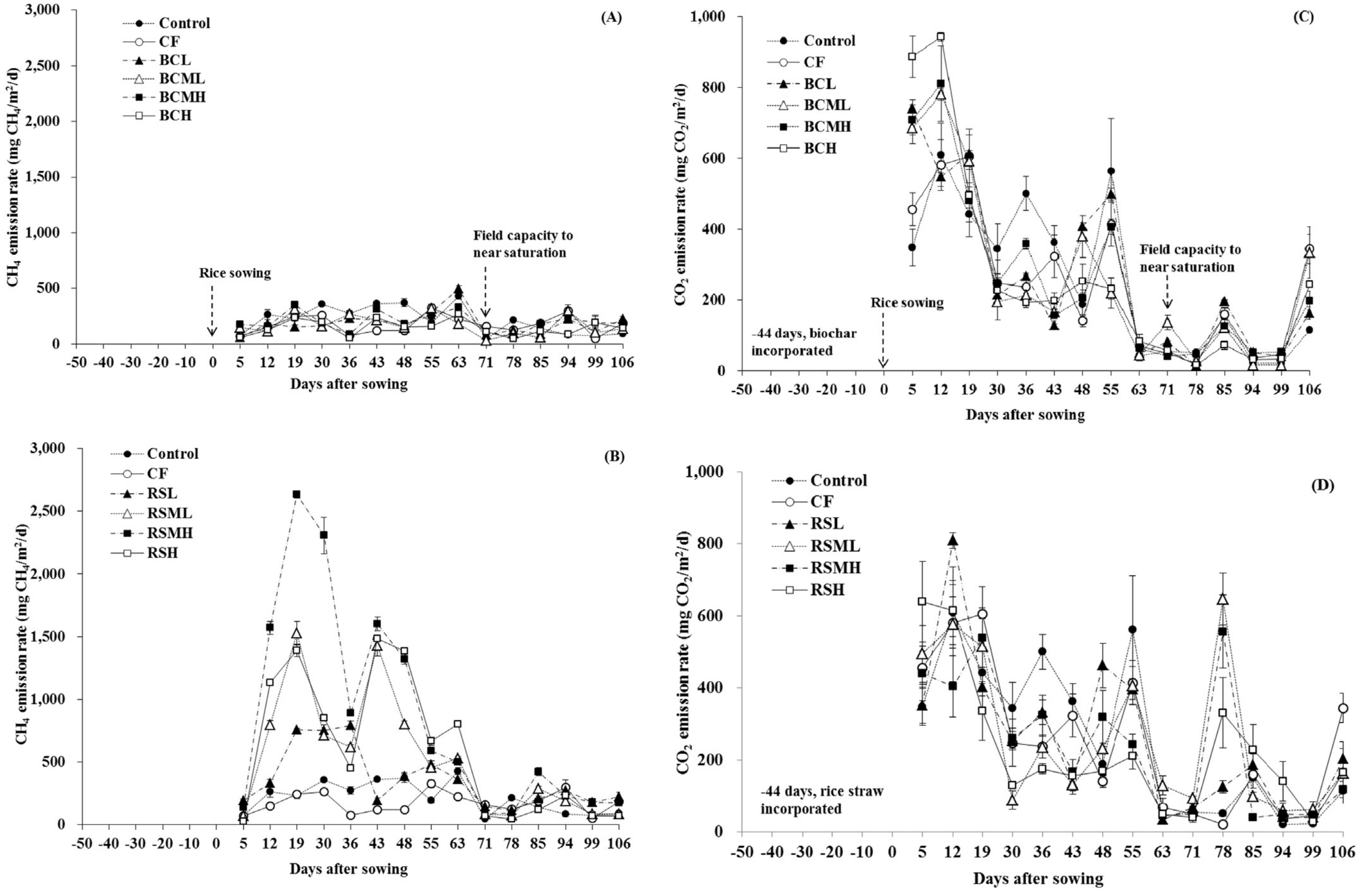

Fig. 1. CH_4 (A, B) and CO_2 (C, D) emission rates from rice field soil with biochar (BC) and rice straw (RS) applications. BCL = BC 6.25 t/ha + CF; BCML = BC 12.50 t/ha + CF; BCMH = BC 18.75 t/ha + CF; BCH = BC 25.00 t/ha + CF; RSL = RS 6.25 t/ha + CF; RSML = RS 12.50 t/ha + CF; RSMH = RS 18.75 t/ha + CF; RSH = RS 25.00 t/ha + CF; error bars show SE, *n* = 4.

Organic C input and soil C sequestration

In the present experiment, organic C added into the soil ranged from 3.84 t C/ha to 15.43 t C/ha for the BC group and from 2.46 t C/ha to 9.82 t C/ha for the RS group as the TOC content was higher in BC (61.43%) compared to RS (39.29%) (Table 1). Based on the soil organic C content before the experiment (15.44 t C/ha), the BC applications increased soil Cseq by 1.87–13.37 t C/ha; whereas the RS applications, CF and the control decreased Cseq indifferently by 0.92–2.58 t C/ha (Table 4), indicating that the RS application eventually had no significant effect on Cseq. Moreover, the orthogonal analysis indicated that the BC group increased soil Cseq (5.44 t C/ha) but the RS group decreased soil Cseq (−1.93 t C/ha).

Discussion

Biochar and rice straw application influence on soil productivity

The study identified no decrease in the soil BD with BC addition (maximum rate of 25 t/ha) as shown in Table 2. This was in contrast to previous work that found a decrease in the BD at higher addition rates of BC of 40–116 t/ha (Jones et al., 2011; Zhang et al., 2012a; Mukherjee and Lal, 2013). Therefore, if the objective is to reduce the soil BD, then additional BC should be applied. In contrast, RS application decreased the soil BD probably due to the adherence of straw particles to the soil matrix which increased the space volume:soil aggregation ratio by organic cementing agents derived from RS decomposition by soil microorganisms (Saddiq and Al-Ameer, 2011) and also due to active rice root occupation in the soil.

The application of BC and RS led to a significant increase in the SOC (Table 2). The higher SOC in the BC-applied soils was due to the high amounts of stable C components in the BC, such as lignin and fixed C (Table 1), which were resistant to microbial degradation. On the other hand, the lower SOC in the RS-amended soils was probably due to higher amounts of labile C, that is, cellulose, hemicellulose and LOC in the RS (Table 1), which stimulated C loss as CO_2 and CH_4 gases (Zhang et al., 2012b). This suggests that BC amendments limit the C mineralization and thereby increase the SOC accumulation in agreement with a report by Bruun and El-zehery (2012).

Significant increases in the LOC were found in RS relative to the control and BC-amended soils (Table 2) due to the high LOC content in the RS material (Table 1). The BC and RS applications also displayed significant increases in total N relative to the control. This phenomenon could have been due to: 1) chemical fertilizer application; 2) decomposition of labile organic N compounds from BC and RS; or 3) the high CEC characteristics of BC and RS that can absorb NH_4^+ ion in soils (Yao et al., 2012; Saothongnoi et al., 2014). Enhanced available P was also found in the BC and RS applications (Table 2). This was also probably due to the reasons cited above. Furthermore, the decomposition of labile organic compounds to organic acids, in the case of RS and the water soluble organic compounds in BC (for example, acetic, citric, oxalic, tannic, and gallic acids and catechol) can chelate with soil Al and Fe and thereby release P into the soil solution (DeLuca et al., 2009; Butnan et al., 2015).

The BC and RS applications both resulted in greater amounts of K, Ca, Mg, and CEC than in the control (Table 2). This was due to the mineralization of nutrients from the decomposition of BC and RS. Higher values were found in the BC-amended soils because they were in the form of dissolvable salts in BC and were thus rapidly released to the soil. From these results, it might be concluded that BC is a soil conditioner that increases CEC (Glaser et al., 2000, 2002) as the highest CEC was found in the BC application as a consequence of the negative charges on the BC surface which increased the number of absorption sites. Liang et al. (2006) stated that a higher soil CEC favors higher cation adsorption in the soil. The addition of BC to the soil therefore served two benefits as a direct source of fertilizer and as an absorber of nutrient cations (Lehmann et al., 2002). The ability of RS to increase the soil CEC was less than that of BC probably due to the much lower cation absorption capacity of RS.

BC and RS application to paddy soil improved the soil fertility and resulted in increases in RY (Table 4) with the BC applications producing significantly higher RY than the RS applications. This can be explained by the fact that BC possessed some ash-derived nutrients, especially K, Ca and Mg (Joseph et al., 2009). The results of the post-harvest soil analysis showed increases in the concentrations of these nutrients (Table 2). Nonetheless, the increase was only significant for K. This encouraged a higher RY with BC than with RS. However, the high positive correlations of the BC and RS applications with soil properties confirmed that amendment with either BC or RS increased the soil fertility (Table 3).

Contrasting effect of biochar and rice straw on CH_4 and CO_2 emission and climate change parameters

Even though TCO_2 emission showed no significant differences among treatments with BC and RS applications, the RS amendment led to increased TCH_4 emission and TGWP-C while the BC amendment led to decreases in these parameters (Table 4). These results were due to the different characteristics of the two organic materials. RS has a high amount of easily decomposable fractions, such as LOC, cellulose and hemicellulose (Table 1) that increased in the TCH_4 emission and led to high TGWP-C. In contrast, the high amounts of recalcitrant molecules in BC such as lignin and fixed C (Table 1) led to a reduction in TCH_4 emission which in turn led to decreases in TGWP-C (Table 4). This concurs with the results of Haefele et al. (2011) and Wu et al. (2012). In addition, Dempster et al. (2012) demonstrated that eucalypt wood BC applied to soil led to a decrease in the microbial community and C biomass due to inhibition of microbial activity. Shen et al. (2014) also reported a decrease in CH_4 emission under BC application and an increase in CH_4 emission after RS application. In addition, significant decreases of TCH_4 and TGWP-C were observed in the CF treatment compared to the control. Zanatta et al. (2010) also found that N fertilizer application depressed TCH_4; however, it should be borne in mind that N fertilizer application may lead to the production of non-C greenhouse gases such as N_2O.

A significant decrease in the intensity of greenhouse gases (GHGI) from rice production was observed in all BC application rates. Even though RS application contributed to an increase in TCH_4 and TGWP-C, it is interesting to note that GHGI was reduced at low application rates of RS and that no significant differences compared with the control were found at the highest application rate (Table 4). These findings suggest that incorporating RS would not influence the radiative forcing (or GWP) of rice production in terms of per unit of RY relative to the control. The reduction of GHGI of rice production under BC and RS application therefore, is a good option for the mitigation of climate change (Zhang et al., 2012b).

Contrasting effects of biochar and rice straw on soil C sequestration

Bot and Benites (2005) demonstrated that in well-managed soil, when C inputs (organic amendments, crop residues and litter, among others) exceed C outputs such as harvested materials, and C gases are emitted to the atmosphere ($TCH_4 + TCO_2$), then soil Cseq occurs. In the current study, BC increased soil Cseq with increasing application rates, while RS application decreased soil Cseq to levels lower than before the experiment (Table 4). The decreased soil Cseq in RS applications was probably due to high C mineralization and greenhouse gas production. In contrast, the increased Cseq under BC was probably due to the chemical recalcitrance of BC. This is in agreement with the results of Bruun and El-zehery (2012) who found that only 1.8–1.9 percent of the C contained in BC was mineralized, while 45–47 percent was mineralized from RS when it was applied to soil.

BC and RS application improves the soil quality and increases RY. Moreover, BC substantially limited C mineralization, thus reducing the GHG C loss to the atmosphere as TCH_4 and TGWP-C, which in turn increased soil Cseq. In contrast, the high amounts of readily decomposable fractions in RS contributed to the high GHG C emission and to TGWP-C and reduced soil Cseq. In addition, from a sustainability viewpoint, the GHGI of rice production decreased under BC and the low rate of RS application. These results therefore suggest that BC application could be a potentially useful agricultural practice for mitigating global warming and climate change in tropical rice cultivation in Northeast Thailand.

Conflict of interest

None.

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