Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol

Dengxiao Zhang, Genxing Pan, Gang Wu, Grace Wanjiru Kibue, Lianqing Li, Xuhui Zhang, Jinwei Zheng, Jufeng Zheng, Kun Cheng, Stephen Joseph, Xiaoyu Liu

1. Introduction

Rainfed agriculture refers to farming practices that rely on rainfall for water. Globally, rainfed agriculture covers 75% of the land area and a great part of this land has a relatively low soil fertility, while still producing 58% of the world’s food (Rosegrant et al., 2002; Portmann et al., 2010). China needs to improve crop productivity in order to feed its large population which will continue to grow in the coming decades. Consequently, there is a need to increase crop production in rainfed areas (Godfray et al., 2010). Maize is now the most extensively cultivated staple crop in China (National Bureau, 2013). A high proportion of the maize growing area is located in the rainfed region of North and Northeast China. The demand for maize will continue to increase because the proportion of meat in the diet of the Chinese people is increasing (Liu et al., 2008), and more maize will be needed to feed the animals.

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Fertilizer is important to ensure high crop yields, particularly in rainfed agriculture (Chu et al., 2007; Zhang et al., 2007; Chen et al., 2011). To maintain the high-yielding maize producing systems, more chemical fertilizers are consumed every year (Ju et al., 2009). The nitrogen (N) fertilizer application rate is as high as 400 kg N/ha/year in some rainfed maize producing areas (Chen et al., 2013; Cui et al., 2013). The N partial factor productivity (in kilograms of grain per kilogram of nitrogen applied) can be greatly improved under balanced fertilization (BF, 59 kg/kg) to the conventional system (CF, 37 kg/kg) with a surplus of 140 kg N per hectare (Chen et al., 2014). A national priority is to maintain high maize yield production while reducing the rate of fertilizer application. In rainfed areas, the pursuit of high maize yields is changing from managements with high fertilizer inputs to those using high yielding cultivars and improved fertilization regimes, and improving water management (Deng et al., 2006; Wu et al., 2009; Rockström et al., 2010; Chen et al., 2010, 2013; Grassini and Cassman, 2012). There is an urgent need to match the fertilizer formulations and application rates with the soil nutrient status and crop nutrient requirements (Chen et al., 2014). Achieving this results in a balanced fertilization regime (BF). Previous studies have shown that changing fertilization practice in this way can result in high maize yields within the rainfed areas (Chu et al., 2007). The most important aspect of optimizing the fertilization rate, is reducing the N inputs while increasing the phosphorus (P) uptake efficiency. However, it will be necessary to convince farmers to change their existing practice (Chu et al., 2007).

Biochar soil amendment is an effective method for increasing soil carbon storage (Lehmann et al., 2006; Sohi, 2012). Biochar has been tested as a possible method to increase crop yield by improving soil fertility (Jeffery et al., 2011; Liu et al., 2013; Biederman and Harpole, 2013) and as a method to decrease the N fertilizer induced N₂O emissions from agricultural land (Cayuela et al., 2014). Thus biochar has the potential to increase maize yield and reduce N₂O emission in rainfed areas. If crop productivity improvement and N₂O reduction could be achieved at the same time, biochar production and implementation would gain farmers’ attention. However, few studies have investigated the effect of biochar on maize production and greenhouse gases emissions (Zhang et al., 2012). This limits our understanding of the role of biochar in low carbon agriculture, especially for the rainfed regions with higher chemical fertilizer inputs.

In the current study, a two-year field experiment was conducted in a rainfed area to ascertain (1) if high productivity could be achieved under BF; (2) if biochar could further increase maize production by improving N use efficiency under BF; (3) if a high-yielding maize producing system could be realized in rainfed areas under BF and biochar amendment while also reducing greenhouse gases emissions.

2. Materials and methods

2.1. Experiment site

The experimental site was located in Gaopu village [38°29′8″N, 112°72′2″E], Douluo Town, Xinzhou Municipality, Shanxi Province, China. Lying in the northeastern part of the arid loess plateau of China, this area is controlled by a temperate continental monsoon climate. The soil is derived from loess deposits, and is a calcareous inceptisol (Soil Survey Staff, 2010) poor in soil organic carbon and soil nutrients. The cropland in the area has typically produced low yields with a mean maize yield of 4.4 t/ha during 2000–2012 (China Statistical Yearbook). During 1990–2010, the local area had a mean annual temperature of 8.0–10.5 °C, 145–165 frost-free days and a mean annual precipitation ranging from 345 to 588 mm. The mean temperature during the experiment was about 20.7 °C with no difference between the two years. However, the total precipitation in 2011 (325 mm) was lower than in 2012 (377 mm) with less rainfall during the early stage of maize growth (Fig. 1). A single maize crop has been conventionally produced in the area annually with sowing generally occurring in mid-May and harvesting in late September. The basic properties of the topsoil (0–0.15 m) are: pH (H₂O) 8.4, soil organic carbon (SOC) 4.3 g/kg, total N 0.4 g/kg, available N 35 mg/kg, available P 11.46 mg/kg, available K 159.8 mg/kg.

2.2. Biochar for soil amendment

Biochar used for the field experiment was made from wheat straw provided by Sanli New Energy Company, Henan province, China. The biochar was produced in a vertical kiln at a pyrolysis temperature of around 450 °C (Pan et al., 2011). About 30% of the feedstock biomass was converted to biochar with 250 kg of bio-liquid (Wood vinegar and pyrolysis oil) and 800 m³ syngas per tonne of feedstock. Biochar was ground to pass through a 2 mm sieve and homogenized before applying to soil. The biochar’s properties were characterized following the protocol described by Lu (2000). The total organic C and N were determined with an Elementar Vario max CNS Analyser (German Elementar Company, 2003). The available P was extracted with 0.5 mol/l sodium bicarbonate solution and measured using a colorimetric method. The total K content was determined by acid digestion and elemental analysis by atomic adsorption spectroscopy. The dissolved organic carbon (DOC) was extracted from 5 g of biochar with an addition of 25 ml of deionized water and the total carbon was determined by automated TOC Analyzer (Multi N/C 2100, German Analytik Jena Company, 2006). The pH was measured for a 1:5 char/water suspension with a compound glass electrode (Seven Easy Mettler Toledo, China, 2008). The specific surface area of the biochar material was tested using the Brunauer-Emmett-Teller (BET) method of which the N adsorption–desorption isotherms at 77 K were measured by an automated gas adsorption analyzer ASAP2000 (Micromeritics, Norcross, GA) with +5% accuracy. Basic biochar properties were: Organic C content 46.7%, total N 0.59%, K 2.6%, available P 80 mg/kg, DOC 0.53 mg/kg, pH (H₂O) 10.4, and surface area 8.92 m²/g.

2.3. Field experiment design

The field trial was established in May, 2011. It was a two-factor experiment with fertilization nested with biochar soil amendment. The soil was first treated with biochar (BC) amended at 3 application rates of 0, 20, 40 t/ha (C0, C1 and C2), respectively. The maize crop was treated with two fertilization regimes: the local conventional fertilization as a control (CF), and balanced fertilization (BF). The CF and BF treatments differed in both the total amount and the nutrient ratio of the fertilizer applied. Using CF, farmers apply a high amount of total N and a lower amount of P without considering their optimal ratio. In contrast, in BF the total amount of N used is lower, the P is higher and the N/P ratio is 3.5 which is an optimal value for maize production (Chu et al., 2007). In the field trial there were 6 treatments (3 levels of BC treatments and 2 fertilization regimes (as described below)) with triplicates. All plots were 4 m x 7 m in area and were arranged in a random block design.

2.4. Field operation and crop management

Before maize sowing in May 2011, biochar was spread on the soil surface and was incorporated into the soil by plowing with a spade, and then thoroughly mixing the soil with a rake by hand to a depth about 0.15 m. No more biochar was added in the following years. For the CF treatment, N fertilizer (urea) was applied at

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293 kg N/ha with P (calcium superphosphate) at 69 kg P₂O₅/ha as basal fertilizer, with additional N at 139 kg N/ha as dressing at the maize elongation stage. For the BF treatment, N fertilizer (urea) was applied at 217 kg N/ha with P (calcium superphosphate) at 145.5 kg P₂O₅/ha as basal fertilizer without any further fertilizer dressing over the growing period. These fertilization treatments were consistent over the two years of the experiment.

Maize was sown on the 11th May and 6th May, and harvested on the 26th September and 28th September, respectively, in 2011 and in 2012. Maize seedlings were thinned about two weeks after sowing to reach a row spacing of 0.50 m and intra-row spacing of 0.30 m in both years. In the CF treatment only, N fertilizer dressing was added when the maize was in the elongation stage on 28 June, 2011 and on 6 July, 2012. The other management practices such as applying pesticides for weed control were consistent across all plots over the two years.

2.5. Yield measurement, soil sampling and analysis

Grain yield was estimated by manually harvesting all the plants in a single plot. Firstly, the total yield of maize ears for each plot was weighed. Secondly, a total of 20 maize ears were randomly selected and were air-dried. The mass ratio of maize seed and cob of these ears was determined. Thirdly, the grain yield was estimated by multiplying the air-dried weight by the mass ratio of maize seed and cob at each plot.

Topsoil (0–0.15 m) samples were collected after the maize harvest for both years. A composite sample of 3 randomly chosen soil cores was taken with an Eijkelkamp soil core sampler in each plot. The sample was placed in a re-sealed plastic bag and shipped to the laboratory for further analysis. The samples were ground to pass a 0.15 mm sieve for soil organic C and moisture measurement was simultaneously conducted with green-house gases sample collection. Soil physico-chemical properties were determined following the protocol described in Lu (2000). Soil pH was measured in distilled water (soil/water ratio of 1:2.5 in mass) with a pH meter (Seven Easy Mettler Toledo, China, 2008). Available K was extracted with 1.0 mol/l ammonium acetate solution (pH 7.0) and determined with a flame photometer (FP 6410, Company of Shanghai Jingke, China). Soil bulk density was measured using a 100 cm³ cylinder. The other properties were measured following the same protocol as for biochar.

2.6. Greenhouse gases emission monitoring

Gas sampling was performed at 7-day intervals at 8:00–10:00 a.m. throughout the maize growing season. A static closed chamber-GS method was used to monitor the greenhouse gases fluxes (Zhang et al., 2010). Briefly, the gas samples were collected at 0, 10, 20 and 30 min after the closure of the chamber. The gas sample was then injected into a special vacuum glass vial (No. 5, Japan Maruenu Corporation, Japan, 2010) and immediately shipped to the lab for analysis. The concentrations of CO₂, CH₄ and N₂O in the gas sample were simultaneously analyzed with a gas chromatograph (Agilent 7890D, America) equipped with a flame ionization detector (FID) and an electron capture detector (ECD). The conditions for the analysis were kept consistent with those described in the work by Zhang et al. (2010). Gas flux was determined from the accumulation rate of greenhouse gas concentration in the four sequential samples, taken at 0, 10, 20, and 30 min after chamber closure. The total emissions of CO₂, CH₄ and N₂O over the whole maize growing season were calculated from the emissions averaged over every two adjacent intervals of all the monitored fluxes. The detailed calculation of a flux using these sequential samples was described in detail by Zou et al. (2005).

2.7. Calculation and statistics

For assessing treatment effects on enhancing crop productivity, partial nutrient productivity (PNUP) of both N and P fertilizers was calculated with the grain yield divided by the total amount of N and P input, where

\[
\text{PNUP}_{\text{kg grain/kg}} = \frac{Y}{F}
\]

where \(Y\) represents the grain yield (kg/ha) under a certain treatment, and \(F\) is the corresponding total N (kg N/ha) and P (kg P₂O₅/ha) input.

Meanwhile, the N fertilizer-induced emission factor of N₂O (EF) was calculated using the equation:

\[
\text{EF}_{\text{g N₂O–N/kg}} = \frac{E_{\text{N₂O}}}{N}
\]

where \(E_{\text{N₂O}}\) is the seasonal total emission of N₂O–N (kg/ha) monitored in a single maize cycle, and \(N\) is the N fertilizer applied over the whole maize growing season.

In addition, the global warming potential (GWP) was calculated using the following equation:

\[
\text{GWP}_{\text{kg CO₂/ha}} = 28 \times E_{\text{CH₄}} + 265 \times E_{\text{N₂O}}
\]

where \(E_{\text{CH₄}}\) and \(E_{\text{N₂O}}\) are, respectively, the total seasonal emissions of CH₄ and N₂O (kg/ha) monitored over a single maize cycle. The
global warming potential of CH₄ and N₂O are 34 and 298 times greater than that of CO₂ over a 100-year horizon (IPCC, 2013).

The greenhouse gases emission intensity (GHGI) was calculated using the equation:

\[ \text{GHGI}_{\text{kg CO}_2-e/t} = \text{GWP}/Y \]  

(4)

where GWP is the sum of CH₄ and N₂O (kg CO₂-e/ha) emissions, and Y is the grain yield (t/ha).

A net carbon budget in the life cycle of maize production was calculated over the two-year field experiment using the following equation. Here, the net carbon budget included direct carbon emission, indirect carbon emission (biochar application, fertilization application, pesticides), and soil organic carbon accumulation.

Net carbon emission (Mg CO₂-e/ha)

\[ = \sum(Ai \times f) + \text{GWP} + \text{C}_{\text{seq}} \]  

where \( Ai \) is the agricultural input (fertilizer, herbicide and biochar production); \( f \) is the emission factor; \( \text{GWP} \) is the total amount of carbon emission across two years; \( \text{C}_{\text{seq}} \) is the accumulate soil organic carbon. The emission factors for N, P, K and herbicide are greater than that of CO₂.

\[ \frac{3.38, 0.73, 0.55 	ext{ and } 17.24}{\text{Mg CO}_2-e/t} \text{, respectively} (Lu et al., 2008; Dubey and Lal, 2009; West and Marland, 2002). \]

Biochar emission factor is 0.167 Mg CO₂-e/t (fresh matter) including feedstock collection, transportation, and nutrient lost and so on (unpublished).

All data were presented as the mean plus or minus standard deviation. Statistical analysis was performed using SPSS16.0 software. Analysis of variance (ANOVA) considered three factors including fertilizer regimes, biochar amendment rates and experimental year. Year was included in the ANOVA as a fixed effect. Multiple-factor repetitive measurement and analysis of variance (MANOVA) were performed for soil moisture analysis. Least significant difference (LSD) was used to compare means at a level of 0.05.

3. Results

3.1. Crop yield

Maize yield was affected by fertilization regimes (P = 0.02) and biochar amendment (p = 0.01) for both years with the yield under BF 5.8% and 23.7% greater than under CF in years 2011 and 2012, respectively (Tables 1 and 2). Biochar amendment significantly increased maize yield in both years, especially under BF treatments. Under CF, biochar increased maize yield by 12.9% under C2 in 2011 while the yield increase was not statistically significant in 2012. Under BF, however, biochar increased maize yield consistently over two years with 11.9% and 35.4% increase under C2 for 2011 and 2012, respectively. The partial nutrient productivity was significantly higher under BF than under CF, and biochar amendment further improved the PNUP under both fertilization regimes in 2011 (P < 0.01).

3.2. Soil properties

A three-way ANOVA showed that many soil properties were influenced by either the fertilizer regime or by biochar amendment (Tables 3 and 4). The mean concentrations of soil-available P were 16.2 and 16.4 mg/kg under BF for 2011 and 2012, respectively, which were higher (P < 0.01) than that under CF. Biochar increased the concentration of SOC and TN by 25–54% and 4–12% respectively, whereas it had no effect on soil pH and available N. Biochar increased soil-available P in 2011, but not in 2012. Soil bulk density decreased by about 0.18 t/m² in the first year of the experiment (2011), but this effect disappeared in the second year. Soil moisture contents were similar between treatments, while biochar increased soil moisture content significantly over the two years following a repeated ANOVA (Fig. 2, P < 0.01).

3.3. Greenhouse gases emission

The emission of CO₂ and CH₄ was not influenced by fertilization regimes and biochar amendment, whereas the accumulated N₂O emissions differed between fertilization regimes, biochar amendment rates, and years (Tables 1 and 2). More N₂O was emitted in 2012 than in 2011. N₂O emission decreased by 59–70% in 2011 and 54–67% in 2012 under BF compared to CF. Under BF, biochar amendment significantly decreased N₂O emission by 34.3–37.9% and 30.8–33.5% in 2011 and 2012, respectively (Table 1). However, biochar did not affect N₂O emission under BF in either year and therefore a significant F × C interaction effect was observed (Table 2). The EF decreased from 4.77 g N₂O–N/kg N under CF to 2.82 g N₂O–N/kg N under BF in 2011 in the absence of biochar, and from 6.01 g N₂O–N/kg N to 3.97 g N₂O–N/kg N in 2012.

Table 1

<table>
<thead>
<tr>
<th>Fertilization</th>
<th>CF</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochar</td>
<td>C0</td>
<td>C1</td>
</tr>
<tr>
<td>Yield (t/ha)</td>
<td>2011</td>
<td>8.71 ± 0.55c</td>
</tr>
<tr>
<td>2012</td>
<td>8.50 ± 0.82b</td>
<td>8.49 ± 1.71b</td>
</tr>
<tr>
<td>P</td>
<td>2011</td>
<td>17.38 ± 1.10c</td>
</tr>
<tr>
<td>2012</td>
<td>16.95 ± 1.63</td>
<td>16.95 ± 3.40d</td>
</tr>
<tr>
<td>N₂O–N (kg/ha)</td>
<td>2011</td>
<td>1.31 ± 0.26a</td>
</tr>
<tr>
<td>2012</td>
<td>2.60 ± 0.23a</td>
<td>1.80 ± 0.36b</td>
</tr>
<tr>
<td>CO₂–C (kg/ha)</td>
<td>2011</td>
<td>1894 ± 74b</td>
</tr>
<tr>
<td>2012</td>
<td>1289 ± 63a</td>
<td>1392 ± 151a</td>
</tr>
<tr>
<td>CH₄–C (kg/ha)</td>
<td>2011</td>
<td>0.47 ± 0.23a</td>
</tr>
<tr>
<td>2012</td>
<td>0.37 ± 0.06a</td>
<td>0.45 ± 0.10a</td>
</tr>
<tr>
<td>GWP (kg CO₂/ha)</td>
<td>2011</td>
<td>529 ± 99a</td>
</tr>
<tr>
<td>2012</td>
<td>1069 ± 99a</td>
<td>734 ± 103b</td>
</tr>
<tr>
<td>GHGI (kg CO₂-e/t)</td>
<td>2011</td>
<td>60.5 ± 7.4a</td>
</tr>
<tr>
<td>2012</td>
<td>1269 ± 21.2a</td>
<td>89.4 ± 26.9b</td>
</tr>
<tr>
<td>EF (g N₂O–N/kg N)</td>
<td>2011</td>
<td>4.77 ± 0.93a</td>
</tr>
<tr>
<td>2012</td>
<td>6.01 ± 0.54a</td>
<td>4.17 ± 0.59b</td>
</tr>
</tbody>
</table>

PNUP: partial nutrient productivity; GWP: global warming potential; GHGI: greenhouse gases emission intensity; EF: N₂O emission factor; CF: conventional fertilization practiced by the local farmers; BF: balanced fertilization. Lowercase letters represent the difference between treatments at p < 0.05 within a single year, the same below.

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2012. Under CF, mean EFs under biochar amendment were reduced by 36% and 32% for 2011 and 2012, respectively.

The overall GWP and GHGI were significantly affected by fertilization regime, biochar and their interaction in both years (Tables 1 and 2). In the absence of biochar, the GHGI was greatly reduced from 60.5 kg CO₂-e/t under CF to 15.3 kg CO₂-e/t under BF in 2011 and from 126.9 to 37.4 kg CO₂-e/t in 2012. The GHGI under BF was further reduced by 11.8–28.8% and 19.8–27.8% with biochar amendment for 2011 and 2012, respectively.

Table 2
A three-way ANOVA for the effects of biochar (C), fertilization (F) and year (Y) on maize yield and greenhouse gas emissions.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Yield</th>
<th>N₂O</th>
<th>CH₄</th>
<th>CO₂</th>
<th>GWP</th>
<th>GHGI</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>P</td>
</tr>
<tr>
<td>Model</td>
<td>11</td>
<td>2.39</td>
<td>0.04</td>
<td>9.40 &lt;0.01</td>
<td>47.07 &lt;0.01</td>
<td>1.14 0.38</td>
<td>14.08 &lt;0.01</td>
<td>49.79 &lt;0.01</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>5.05</td>
<td>0.01</td>
<td>85.77 &lt;0.01</td>
<td>254.21 &lt;0.01</td>
<td>3.82 0.06</td>
<td>0.78 0.39</td>
<td>270.43 &lt;0.01</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>4.69</td>
<td>0.02</td>
<td>15.89 &lt;0.01</td>
<td>0.45 0.64</td>
<td>2.98 0.07</td>
<td>16.74 &lt;0.01</td>
<td>12.4 &lt;0.01</td>
</tr>
<tr>
<td>Y</td>
<td>1</td>
<td>0.26</td>
<td>0.61</td>
<td>0.53 0.47</td>
<td>175.73 &lt;0.01</td>
<td>0.65 0.43</td>
<td>146.36 &lt;0.01</td>
<td>184.87 &lt;0.01</td>
</tr>
<tr>
<td>F × C</td>
<td>2</td>
<td>0.79</td>
<td>0.47</td>
<td>1.23 0.31</td>
<td>13.3 &lt;0.01</td>
<td>2.49 0.1</td>
<td>0.58 0.57</td>
<td>14.15 &lt;0.01</td>
</tr>
<tr>
<td>F × Y</td>
<td>1</td>
<td>3.13</td>
<td>0.09</td>
<td>2.86 0.1</td>
<td>25.07 &lt;0.01</td>
<td>0.08 0.78</td>
<td>0.38 0.53</td>
<td>25.82 &lt;0.01</td>
</tr>
<tr>
<td>C × Y</td>
<td>2</td>
<td>0.85</td>
<td>0.44</td>
<td>1.1 0.35</td>
<td>0.21 0.82</td>
<td>0.06 0.94</td>
<td>1.19 0.32</td>
<td>1.38 0.25</td>
</tr>
<tr>
<td>F × C × Y</td>
<td>2</td>
<td>0.57</td>
<td>0.57</td>
<td>0.63 0.54</td>
<td>1.09 0.35</td>
<td>0.83 0.45</td>
<td>0.07 0.94</td>
<td>1.19 0.32</td>
</tr>
</tbody>
</table>

Table 3
Topsoil properties (mean ± standard deviation, n = 3) under different treatments after maize harvest in two years. C0, C1 and C2 indicate biochar amendment rate of 0, 20 and 40 t/ha, respectively.

<table>
<thead>
<tr>
<th>Biochar</th>
<th>CF</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C0</td>
<td>C1</td>
</tr>
<tr>
<td>Bulk density (t/m³)</td>
<td>2011</td>
<td>1.29 ± 0.04a</td>
</tr>
<tr>
<td>pH (H₂O)</td>
<td>2011</td>
<td>8.07 ± 0.08a</td>
</tr>
<tr>
<td>SOC (g/kg)</td>
<td>2011</td>
<td>4.19 ± 0.20c</td>
</tr>
<tr>
<td>Total N (g/kg)</td>
<td>2011</td>
<td>0.57 ± 0.01a</td>
</tr>
<tr>
<td>Available N (mg/kg)</td>
<td>2011</td>
<td>34.44 ± 1.68a</td>
</tr>
<tr>
<td>Available P (mg/kg)</td>
<td>2011</td>
<td>9.76 ± 1.96b</td>
</tr>
</tbody>
</table>

Table 4
A three-way ANOVA for the effects of biochar (C), fertilization (F) and year (Y) on soil physical and chemical properties.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Bulk Density</th>
<th>pH</th>
<th>SOC</th>
<th>TN</th>
<th>Available N</th>
<th>Available P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>F</td>
</tr>
<tr>
<td>Model</td>
<td>11</td>
<td>2.39 0.04</td>
<td>10.32 &lt;0.01</td>
<td>10.19 &lt;0.01</td>
<td>2.38 0.04</td>
<td>1.96 0.08</td>
<td>3.88 &lt;0.01</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>10.04 &lt;0.01</td>
<td>0.04 0.85</td>
<td>0.37 0.37</td>
<td>0.04 0.85</td>
<td>1.07 0.31</td>
<td>16.34 &lt;0.01</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>28.98 &lt;0.01</td>
<td>0.61 0.55</td>
<td>45.80 &lt;0.01</td>
<td>10.81 &lt;0.01</td>
<td>0.54 0.59</td>
<td>3.84 0.04</td>
</tr>
<tr>
<td>Y</td>
<td>1</td>
<td>44.36 &lt;0.01</td>
<td>105.93 &lt;0.01</td>
<td>16.63 &lt;0.01</td>
<td>1.03 0.32</td>
<td>11.19 &lt;0.01</td>
<td>0.00 0.99</td>
</tr>
<tr>
<td>F × C</td>
<td>2</td>
<td>2.37 0.12</td>
<td>0.87 0.43</td>
<td>0.11 0.89</td>
<td>0.01 0.99</td>
<td>0.64 0.54</td>
<td>0.15 0.86</td>
</tr>
<tr>
<td>F × Y</td>
<td>1</td>
<td>0.02 0.88</td>
<td>0.60 0.45</td>
<td>0.01 0.92</td>
<td>1.59 0.22</td>
<td>0.55 0.47</td>
<td>0.01 0.93</td>
</tr>
<tr>
<td>C × Y</td>
<td>2</td>
<td>6.08 &lt;0.01</td>
<td>1.33 0.28</td>
<td>1.09 0.35</td>
<td>0.60 0.56</td>
<td>2.30 0.12</td>
<td>5.86 &lt;0.01</td>
</tr>
<tr>
<td>F × C × Y</td>
<td>2</td>
<td>1.61 0.22</td>
<td>0.65 0.53</td>
<td>0.53 0.60</td>
<td>0.33 0.72</td>
<td>0.88 0.43</td>
<td>3.31 0.05</td>
</tr>
</tbody>
</table>

Fig. 2. Dynamics of soil water content under fertilization and biochar treatments during two maize growing seasons (mean value ± standard deviation). CF and BF indicate the fertilization treatment of conventional fertilization and balanced fertilization, respectively. C0, C1 and C2 indicate biochar amendment rate of 0, 20 and 40 t/ha, respectively. The ANOVA P-values are reported in the upright box following a repeated measures analysis of variance.

2012. Under CF, mean EFs under biochar amendment were reduced by 36% and 32% for 2011 and 2012, respectively.

The overall GWP and GHGI were significantly affected by fertilization regime, biochar and their interaction in both years (Tables 1 and 2). In the absence of biochar, the GHGI was greatly reduced from 60.5 kg CO₂-e/t under CF to 15.3 kg CO₂-e/t under BF in 2011 and from 126.9 to 37.4 kg CO₂-e/t in 2012. The GHGI under BF was further reduced by 11.8–28.8% and 19.8–27.8% with biochar amendment for 2011 and 2012, respectively.

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4. Discussions

4.1. Improved maize production with BF and biochar

The current study showed that maize yield was increased when BF was applied compared to CF even though the N application rate of BF was cut down to almost a half that of CF. Under CF, to maintain high maize yields, farmers use more N but less attention is paid to P nutrition, although the advantages of balanced fertilization has been well established (Chu et al., 2007). Yield increase under BF resulted from the increase in soil-available P supply. This was in agreement with Chu et al. (2007), who also suggested the importance of P nutrition in the same geographical area.

Biochar amendment increased maize yield consistently over the two year experiment, under both CF and BF. This is in agreement with other results from field studies in the same region (Zhang et al., 2012) and in other locations (Major et al., 2010). Yield increases in the current study were probably due to the addition of the nutrients along with biochar and soil structure and moisture improvement. The greater availability of P may contribute to maize yield increase, especially in the first year following biochar amendment. Major et al. (2010) also suggested that biochar improves maize growth by supplying some limiting soil nutrients, such as calcium and magnesium. The improvement of soil nutrient supply was exhibited in previous studies of both flooded rice and non-irrigated dry crops (Huang et al., 2013). Soil moisture improvement may be another contributor to maize yield increase on water stressed farmlands as observed in the current work. It has been shown that biochar amendment can improve soil water holding capacity (Karhu et al., 2011; Saarnio et al., 2013; Rogovska et al., 2014). Crop productivity improvement was observed in line with the increase in soil water availability (Saarnio et al., 2013; Rogovska et al., 2014). Liu et al. (2013) suggested the importance of soil water improvement on crop yield increase after biochar amendment and this was evidenced by the finding that the crop yield increase was significantly higher in water limited dry cropland than in rice paddies.

4.2. Cutting down greenhouse gases emission through BF and biochar

Nitrogen fertilizer is the main contributor to N₂ O emission in agricultural soils. It is estimated that about 1% of the applied N (emission factors, EF) is emitted from soil as N₂ O; the EF is about 1.8% in dry land crops in China (Lu et al., 2006). Therefore, cutting down the N fertilizer application rate is an efficient way to reduce greenhouse gases emission, particularly N₂ O (Kaiser et al., 1998). In the current study, N₂ O emission decreased by about 70% under BF compared to under CF.

As previously reported, biochar amendment can reduce N₂ O emissions from agricultural soils (Cayuela et al., 2014). The result observed in the current study is in accordance with previous studies (Zhang et al., 2010; Taghizadeh-Toosi et al., 2011; Liu et al., 2012). A significant reduction of N₂ O emission was also observed in the second year after biochar amendment under CF. The reduced N₂ O emission was possibly due to biochar amendment promoting the reduction of N₂ O to N₂ (Cayuela et al., 2013). Biochar can also reduce the N availability to microorganisms by absorption (Singh et al., 2010). This further accounts for the unchanged N₂ O emission with increasing biochar rate under BF, since the N supply under BF was limited for the microbial denitrification or nitrification. This resulted in a lower N₂ O emission under BF, compared to CF. Hoben et al. (2011) also reported that N₂ O flux was not linearly proportional with N fertilization rates in a maize field.

4.3. Establishing low carbon agriculture with BF and biochar in rainfed area

The conventional N fertilization rate in the studied area is far more than the plants need. This not only causes a direct emission of N₂ O from the field, but also leads to a tremendous waste of energy. It is estimated that about 6.38 and 0.73 Mg CO₂-e are emitted when producing one tonne of nitrogen (N) and phosphorous (P) fertilizer, respectively (Lu et al., 2008; Dubey and Lal, 2009). Thus, about 2.70 Mg CO₂-e emissions are avoided, per hectare, under BF than under CF over the two years (Fig. 3c).
considered the carbon emission of fertilizer, pesticides and biochar production. As mentioned above, BF further promoted maize yield and decreased greenhouse gases emission from agricultural fields directly with GWP, reduced by 70% (Fig. 3b). If practiced with biochar amendment, there will be 50% SOC increase under biochar application rate of 40 t/ha, which equals to a net withdraw of 19.7 Mg CO₂-e/ha from the atmosphere (Fig. 3c). This demonstrated that the combination of biochar amendment and BF in total contributed to a net carbon gain of around 14.5 Mg CO₂-e/ha over two years, which is significantly higher than the fertilizer regime (CO under CF) practiced by the local producers (Fig. 3a).

5. Conclusions

The fertilizer regime practiced by the local farmers in the studied area is unbalanced with high N and low P. The current study demonstrated that maize production could be greatly improved by balancing nutrient inputs. This also contributed to a significant reduction in N₂O emissions including the direct emission from field and the avoided emissions during N fertilizer production. Balanced fertilization practices could be extended in this region. In addition to soil carbon sequestration, biochar has the potential to improve soil fertility and maize yield and mitigate greenhouse gases emissions. Further studies are needed to investigate the long-term benefit of balanced fertilization and biochar amendment.

Acknowledgments

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