Effects of Biochar Application and Straw Return on CO2 and N2O Emissions from Cropland in North China (Postprint)

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Abstract

Using soils from a winter wheat-summer maize rotation system in North China farmland that had received continuous biochar application and straw return for 6 consecutive years as the study object, CO2 and N2O fluxes were continuously measured throughout the entire rotation period from October 2013 to September 2014 using the static dark chamber-gas chromatography method to investigate the effects of biochar application and straw return on their emission fluxes. The experiment included four treatments: CK (control), C1 (low biochar rate 4.5 t hm ^{2} a ^{1}), C2 (high biochar rate 9.0 t hm ^{2} a ^{1}), and SR (straw return). The results demonstrated that during the entire rotation period, the temporal variation trends of CO2 and N2O fluxes were basically consistent across all treatments. As biochar application rate increased, CO2 emission flux increased by 0.3%-90.3% (C1), 1.0%-334.2% (C2), and 0.4%-156.3% (SR). The C2 treatment exerted the greatest influence on cumulative CO2 emissions, with an increase of 42.9%. Regarding N2O, the C2 treatment significantly decreased cumulative N2O emissions, but enhanced the combined global warming potential of CO2 and N2O emissions, whereas C1 and SR treatments had no significant effects on either cumulative N2O emissions or combined global warming potential. Correlation analysis revealed that soil temperature and soil water content were the primary factors influencing CO2 flux, showing a highly significant positive correlation between them; N2O flux exhibited highly significant positive correlations with soil temperature, soil water content, NO -N, and NH -N, but a highly significant negative correlation with soil pH. These findings indicate that biochar amendment holds substantial potential for mitigating gaseous nitrogen loss.

Full Text

Preamble

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Effects of Biochar and Straw Return on CO and N O Emissions from Farmland in the North China Plain

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Abstract

A six-year biochar and straw return experiment was conducted using a winter wheat-summer maize rotation system in the North China Plain to investigate the effects of biochar and straw return on CO and N O fluxes using the static chamber/gas chromatography method. The experiment consisted of four treatments with three replicates: CK (control), C1 (biochar 4.5 t hm ^{2}), C2 (biochar 9.0 t hm ^{2}), and SR (straw return). Results showed that CO and N O flux trends were generally consistent throughout the entire rotation period. After biochar application, CO fluxes increased by 0.3%-90.3% (C1), 1.0%-334.2% (C2), and 0.4%-156.3% (SR). The C2 treatment had the greatest effect on cumulative CO emissions, with an increase of 42.9%. The N O flux results showed that the C2 treatment significantly ($P < 0.05$) reduced cumulative N O emissions but increased the comprehensive warming potential of CO and N O emissions. In contrast, the C1 and SR treatments had no significant effect on cumulative N O emissions and the comprehensive warming potential. Correlation analysis showed that CO flux was significantly positively correlated with soil temperature and soil water content ($P < 0.01$), while N O flux was significantly positively correlated with soil temperature, soil water content, NO -N, and NH -N, but significantly negatively correlated with soil pH ($P < 0.01$). In summary, the addition of biochar has the potential to significantly reduce nitrogen gas loss.

Keywords: biochar; straw return; CO ; N O; global warming potential (GWP); North China Plain

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1. Introduction

As important greenhouse gases, increasing emissions of CO and N O are major contributors to global climate warming, with agricultural soils representing a significant emission source that cannot be ignored. According to relevant statistics, agricultural activities account for a substantial portion of total anthropogenic emissions. Consequently, reducing greenhouse gas emissions from farmland has become an urgent challenge. Biochar refers to a class of refractory, carbonized solid materials produced through high-temperature pyrolysis of biomass under complete or partial anoxic conditions. Applying biochar to soil can alter soil physicochemical properties, significantly affecting mineral nitrogen content, pH values, and water-holding capacity. These properties influence the community structure, abundance, and diversity of ammonia-oxidizing archaea and bacteria, thereby affecting nitrification processes and inhibiting soil greenhouse gas emissions. However, due to differences in biochar feedstock, pyrolysis temperature, and regional climate conditions, consensus has not been reached regarding the positive or negative effects of biochar on greenhouse gas emissions.

Straw return represents an important utilization method for crop residues that can reduce inorganic nitrogen content in surface soil, enhance water and nutrient retention capacity, and alter microbial activity. While many studies indicate that straw return can significantly reduce N O emissions, other research suggests it may increase emissions. The long-term effects of biochar and straw return on CO and N O emissions remain poorly understood. Based on a multi-year biochar application experiment in North China farmland, this study investigated the effects of different biochar application rates and straw return on CO and N O emissions, changes in soil NO -N and NH -N content, and soil pH values to provide scientific guidance for enhancing carbon sequestration, reducing nitrogen loss, and achieving agricultural greenhouse gas mitigation.

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2. Experimental Site Overview

The experiment was conducted at the Ecology and Sustainable Development Experimental Station in Huantai County, Shandong Province (117°58 E, 36°57 N). The region has an elevation of 17.0 m, mean annual temperature of 12.4°C, and mean annual precipitation of 600 mm, concentrated during June-September (accounting for approximately 70% of annual rainfall). The climate is characterized as temperate continental monsoon. The cropping system follows a winter wheat-summer maize rotation, and the soil type is lime concretion black soil (Shajiang soil). Basic soil physicochemical properties before the experiment are shown in .

Basic properties of the topsoil before experimentation

Property	Value
pH (1:2.5)	8.1±0.05
Organic C (g/kg)	10.8±0.1
Total N (g/kg)	0.7±0.02
Available N (mg/kg)	48.0±2.0
Available P (mg/kg)	11.5±1.0

Property	Value
Available K (mg/kg)	210.1±9.0

3. Experimental Materials

The biochar used in this study was produced from maize straw through incomplete combustion, purchased as black powder from Liaoning Jinhe Fuyuan Agricultural Development Co., Ltd. The biochar had a pH of 8.2±0.05, bulk density of (0.297±0.05) g/cm^3, total carbon content of (65.7±1.2)%, total nitrogen of (0.9±0.02)%, total phosphorus of (1.6±0.1)%, total potassium of (0.08±0.003)%, and effective phosphorus content of (0.9±0.02)%. The wheat variety was Jimai 22 and the maize variety was Zhengdan 958.

4. Experimental Design

The long-term positioning experiment began in October 2008. The experiment followed a randomized complete block design with four treatments and three replicates, with each plot measuring 6 m × 6 m (36 m^2). The treatments were: CK (control), C1 (low biochar rate of 4.5 t hm ^{2}), C2 (high biochar rate of 9.0 t hm ^{2}), and SR (full straw return). All treatments received nitrogen, phosphorus, and potassium fertilizers at average rates of N 200 kg hm ^{2}, P O 52.5 kg hm ^{2}, and K O 37.5 kg hm ^{2}. Nitrogen fertilizer (urea) was applied half as basal fertilizer and half as topdressing, while phosphorus (calcium superphosphate) and potassium (potassium sulfate) fertilizers were applied as basal fertilizers once. Biochar and fertilizers were evenly spread after harvest of the previous crop and incorporated into the soil during plowing. The biochar application amount was equally divided between winter wheat and summer maize seasons. Straw return was performed by mechanical crushing of the previous crop’ s residues to 3–7 cm pieces and full incorporation into the soil. For wheat, straw return occurred on October 8, 2013, and October 10, 2014; for maize, on June 12, 2014, and June 15, 2015. Topdressing and irrigation were applied on April 15, 2014, and April 18, 2015, for wheat, and on July 20, 2014, and July 23, 2015, for maize.

5. Measurement Indicators and Methods

5.1 Greenhouse Gas Flux Measurement

Greenhouse gas fluxes were measured using the static opaque chamber method. Sampling chambers were made of polycarbonate plates with specifications of

43 cm × 43 cm × 50 cm and 43 cm × 43 cm × 100 cm, with height adjusted according to crop growth. Chambers were installed in the center of each plot after sowing, with bases inserted 15 cm into soil. Dense holes were drilled in the inserted portion to ensure exchange of water and fertilizer between inside and outside the base. Before sampling, the base groove was filled with water to prevent gas leakage. To prevent rapid temperature increase, chambers were wrapped with aluminum foil. Sampling was conducted weekly from 2013 to 2015, with increased frequency after fertilization and irrigation. Gas samples were collected between 9:00–11:00 AM, with four samples taken at 0, 10, 20, and 30 minutes after chamber closure. Previous studies showed that fluxes during this period approximated daily average emissions. Chamber temperature was recorded simultaneously. Gas samples (100 mL) were injected into gas bags and analyzed using an Agilent 7890A gas chromatograph equipped with a flame ionization detector for CO and an electron capture detector for N O.

The gas flux calculation formula was:

$$F = \rho \times V/A \times \Delta c/\Delta t \times 273/(273 + T)$$

where F is the gas emission rate (mg m ^{2} h ^{1} for CO ; g m ^{2} h ^{1} for N O), ρ is the gas density under standard conditions (g/L), V is the chamber volume (L), A is the soil surface area inside the base (m^{2}), $\Delta c/\Delta t$ is the rate of gas concentration change, and T is the average temperature inside the chamber during sampling (°C).

Cumulative emissions were calculated using linear interpolation between sampling dates. The global warming potential (GWP) was calculated for a 100-year time horizon as:

$$\mathrm{GWP} = \mathrm{CO_2} + \mathrm{N_2O} \times 298$$

where GWP is expressed in CO -equivalent kg/hm^{2}.

5.2 Soil Sampling and Analysis

After gas collection, soil samples were collected from 0–10 cm depth within the chamber base using a soil auger. Soil temperature was measured using a portable thermometer (JM624, Beijing Jinren Instrument Co., Ltd.). Soil water content was determined by the oven-drying method. Fresh soil samples were passed through a 2 mm sieve. For mineral nitrogen analysis, 25 g of fresh soil was extracted with 100 mL of 0.01 mol/L CaCl solution, shaken for 5 minutes, filtered, and the filtrate was frozen. NO -N and NH -N concentrations were determined using a continuous flow analyzer (AA3, Bran and Lübbe, Norderstedt, Germany). Soil pH was measured using a pH meter (PHS-2F, Shanghai Yidian Scientific Instrument Co., Ltd.) on air-dried soil samples.

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6. Data Analysis

One-way ANOVA was performed using SPSS 20.0 to compare differences in soil parameters and gas fluxes among treatments, with significance level set at $P < 0.05$. Pearson correlation analysis was used to examine relationships between gas fluxes and influencing factors. Data processing and graphing were performed using Microsoft Office Excel 2010 and Matlab 7.0.

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7. Results

7.1 Soil Temperature, Water Content, and Inorganic Nitrogen Dynamics

Throughout the rotation cycle, soil temperature and water content showed consistent trends across treatments, with wheat season values lower than maize season values. No significant differences were observed among treatments for soil temperature. However, soil water content in biochar and straw return treatments was significantly higher than in the control ($P < 0.05$), with increases of 3.2%-13.4% in C1, 5.2%-33.3% in C2, and 3.2%-13.4% in SR. The dynamic trends of soil NO -N and NH -N content were also consistent across treatments. After fertilization and irrigation, soil NO -N content increased significantly in biochar treatments compared to the control ($P < 0.05$). During the wheat overwintering period, NH -N content in C1 and C2 treatments was significantly higher than in CK ($P < 0.05$), with increases of 32.1% and 83.6%, respectively. In the maize season, NH -N content in C1 and C2 treatments was 41.3% and 95.6% higher than CK, respectively ($P < 0.05$). [Figure 1: see original paper] and [Figure 2: see original paper] illustrate the variations in soil temperature, water content, and pH across different treatments.

7.2 Effects of Biochar and Straw Return on CO Flux

CO emission fluxes were highest after sowing and topdressing irrigation. During the wheat season, peak emissions occurred on November 11, 2013, and November 13, 2014, reaching 1029.8, 1026.5, 1123.6, and 1031.3 mg m ^{2} h ^{1} for CK, C1, C2, and SR, respectively, with no significant differences among treatments. After November 25, fluxes gradually declined until wheat harvest. During the maize season, CO fluxes showed multi-peak fluctuation patterns, with the highest peak on August 23, 2014, reaching 1553.8 mg m ^{2} h ^{1} in C2, significantly higher than CK (938.5 mg m ^{2} h ^{1}), C1 (1521.5 mg m ^{2} h ^{1}), and SR (1479.2 mg m ^{2} h ^{1}) ($P < 0.05$). Throughout the entire rotation period, CO flux increased significantly with biochar application rate. The C2 treatment increased CO flux by 1.0%-334.2% compared to CK ($P < 0.05$), while C1 and SR increased fluxes by 0.3%-90.3% and 0.4%-156.3%, respectively. [Figure 3: see original paper] shows the dynamic changes in soil NO -N and NH -N under different treatments, while [Figure 4: see original paper] illustrates CO flux variations.

7.3 Effects of Biochar and Straw Return on N O Flux

N O emission fluxes peaked after sowing and fertilization irrigation in both wheat and maize seasons. During the wheat season, peak fluxes occurred on November 11, 2013, reaching 186.6 g m^{2} h^{1} in CK, which was significantly higher than C2 (105.2 g m^{2} h^{1}) and SR (275.6 g m^{2} h^{1}) ($P < 0.05$). During the maize season, peak fluxes on August 23, 2014, reached 288.3 g m^{2} h^{1} in CK, significantly higher than C2 ($P < 0.05$). Throughout the rotation period, N O fluxes were lower in the wheat season than in the maize season. The C2 treatment significantly reduced N O flux compared to CK ($P < 0.05$), while C1 and SR showed no significant differences from CK. [Figure 5: see original paper] presents the N O flux variations across treatments.

7.4 Cumulative Emissions and Global Warming Potential

Cumulative CO emissions were significantly increased by high biochar application (C2) and straw return (SR) ($P < 0.05$), with C2 increasing emissions by 42.9% compared to CK. Low biochar application (C1) had no significant effect on cumulative CO emissions. High biochar application (C2) significantly reduced cumulative N O emissions by 18.3% ($P < 0.05$), while C1 and SR had no significant effect. The comprehensive GWP showed that C2 significantly increased total GWP ($P < 0.05$), whereas C1 and SR had no significant impact. summarizes the cumulative emissions and GWP values across treatments.

7.5 Relationships Between Gas Fluxes and Environmental Factors

Correlation analysis revealed that CO flux was extremely significantly positively correlated with soil temperature and water content in both wheat and maize seasons ($P < 0.01$), but not significantly correlated with soil pH or mineral nitrogen content ($P > 0.05$). N O flux was extremely significantly positively correlated with soil temperature, water content, NO -N, and NH -N ($P < 0.01$), but extremely significantly negatively correlated with soil pH ($P < 0.01$). and detail these correlation coefficients.

8. Discussion

The results demonstrate that biochar application significantly increased CO emissions, primarily due to enhanced microbial activity, enzyme activity, and the "positive priming effect" that accelerates decomposition of native soil organic carbon. The increase in CO flux with higher biochar application rates suggests that labile carbon fractions in biochar stimulate microbial degradation, increasing soil respiration. These findings align with previous research showing that biochar improves soil aeration and increases microbial biomass, thereby promoting CO release. Straw return also significantly increased CO emissions, likely because straw incorporation improves soil physicochemical properties, provides substrates for microbial activity, and creates favorable conditions for enhanced microbial respiration.

Soil temperature and water content were identified as the primary factors influencing CO emissions, with higher temperatures and moisture levels during the maize season corresponding to greater CO fluxes compared to the wheat season. The extremely significant positive correlation between CO flux and both temperature and moisture confirms that these environmental factors directly affect microbial respiration and organic matter decomposition.

Regarding N O emissions, biochar application significantly reduced fluxes, particularly at the high application rate (C2). This reduction may be attributed to biochar’ s adsorption capacity and its influence on nitrogen transformation processes. Biochar’ s high C/N ratio and ability to improve soil aeration may limit nitrification and denitrification processes under anaerobic conditions, thereby reducing N O production. The significant negative correlation between N O flux and soil pH suggests that biochar-induced pH changes affect the microbial processes governing N O emissions.

Straw return showed variable effects on N O emissions, with some increases observed. This may be due to straw decomposition consuming soil oxygen, creating anaerobic conditions that favor denitrification, particularly during the moist maize season. The peak N O fluxes observed after fertilization and irrigation support this mechanism, as these events provide both nitrogen substrate and anaerobic conditions necessary for denitrification.

The GWP analysis revealed that while high biochar application reduced N O emissions, the substantial increase in CO emissions resulted in a net increase in comprehensive GWP. This suggests that in the high biochar treatment, the carbon input to the atmosphere exceeded the carbon sequestered. In contrast, low biochar application and straw return did not significantly affect the overall GWP, indicating these practices may be more environmentally favorable in terms of net greenhouse gas balance.

9. Conclusion

Throughout the entire winter wheat-summer maize rotation cycle, biochar and straw return significantly increased CO emission fluxes, with fluxes increasing as biochar application rate increased. High biochar application (C2) significantly reduced N O cumulative emissions but increased the comprehensive GWP, while low biochar application (C1) and straw return had no significant effect on N O emissions or GWP. CO flux was extremely significantly positively correlated with soil temperature and water content, while N O flux was extremely significantly positively correlated with soil temperature, water content, and mineral nitrogen, but extremely significantly negatively correlated with soil pH. These results indicate that biochar addition has potential for reducing nitrogen gas loss, though the overall greenhouse gas balance depends on application rate and trade-offs between CO and N O emissions.

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