Greenhouse Gas Emissions from Dryland Farmland Under Different Biochar Input Levels (Postprint)

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Abstract

In the arid and semi-arid region of the central Loess Plateau, a field plot experiment was conducted to continuously observe the emission fluxes of greenhouse gases (CO2, N2O and CH4) from spring wheat farmland soil throughout the entire growth period under different biochar input levels, and to analyze their influencing factors. The results showed that: under six biochar input level treatments [0 t · hm 2 (CK), 10 t · hm 2, 20 t · hm 2, 30 t · hm 2, 40 t · hm 2, 50 t · hm 2], dryland farmland soil acted as a weak CH4 source, and N2O and CO2 sources during the entire growth period of spring wheat. The average emission fluxes of CH4 during the entire growth period for each treatment were: 0.005 7 mg · m 2 · h 1, 0.004 7 mg · m 2 · h 1, 0.003 6 mg · m 2 · h 1, 0.003 3 mg · m 2 · h 1, 0.002 7 mg · m 2 · h 1 and 0.000 4 mg · m 2 · h 1; the average emission fluxes of N2O were: 0.230 5 mg · m 2 · h 1, 0.144 1 mg · m 2 · h 1, 0.135 3 mg · m 2 · h 1, 0.098 9 mg · m 2 · h 1, 0.125 0 mg · m 2 · h 1 and 0.151 3 mg · m 2 · h 1; and the average emission fluxes of CO2 were: 0.449 2 mol · m 2 · s 1, 0.447 0 mol · m 2 · s 1, 0.430 3 mol · m 2 · s 1, 0.391 4 mol · m 2 · s 1, 0.408 0 mol · m 2 · s 1 and 0.416 4 mol · m 2 · s 1. Soil CH4 emission flux decreased with increasing biochar input amount; when biochar input amount was less than 30 t · hm 2, soil N2O and CO2 emission fluxes decreased significantly with increasing input amount, but when the input amount exceeded 30 t · hm 2, N2O and CO2 emission fluxes showed a significant increasing trend. Significant differences existed in average soil temperature in the 5-15 cm soil layer among treatments ($P<0.05$), and significant differences in average soil water content in the 5-10 cm soil layer ($P<0.05$); soil temperature and water content were significantly affected by biochar; and the CK treatment showed the greatest fluctuations in soil temperature and water content in different soil layers, biochar input could reduce the amplitude of hydrothermal changes in different soil layers to a certain extent; N2O and CO2 emission fluxes showed significant negative correlation with soil temperature in the 10–15 cm soil layer, and significant positive correlation with soil temperature in the 20–25 cm soil layer; CH4 average emission flux showed significant negative correlation with soil temperature in the 5–10 cm soil layer, and significant positive correlation with its water content; N2O average emission flux showed significant positive correlation with soil temperature in the 15–20 cm soil layer; CH4, N2O and CO2 average emission fluxes showed significant negative correlation with soil moisture in the 0–5 cm soil layer. Biochar input can reduce greenhouse gas emissions, and the effect varies with its input amount, therefore appropriate application of biochar is beneficial for increasing carbon sinks and reducing emissions during the growth period of dryland farmland.

Full Text

Preamble

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Abstract

Biochar is a carbon-rich solid product resulting from biomass heated in the absence of oxygen. Biochar application is deemed to have potential for greenhouse gas mitigation. Dryland farming areas in Northwest China contribute tremendously to greenhouse gas emissions; however, few studies have been conducted in the region involving biochar application to improve carbon sequestration and reduce emissions, and the optimal biochar application rate remains uncertain.

The aim of this study was to determine the effects of biochar on methane (CH), nitrous oxide (N O), and carbon dioxide (CO) emissions in semi-arid regions. Observations were conducted throughout the entire growth period of spring wheat. The treatments consisted of six different biochar application rates—CK (0 t · hm ^{2}), T1 (10 t · hm ^{2}), T2 (20 t · hm ^{2}), T3 (30 t · hm ^{2}), T4 (40 t · hm ^{2}), and T5 (50 t · hm ^{2})—based on a randomized complete block design with three replications. A carbon dioxide analyzer and static chamber-gas chromatographic techniques were used to continuously measure and analyze greenhouse gas fluxes. Soil moisture and temperature were measured simultaneously with gas sampling.

The results showed that dry spring wheat fields under different biochar treatments acted as sources of CH , N O, and CO throughout the entire growth period. The average emission fluxes of CH across all treatments were 0.0057, 0.0047, 0.0036, 0.0033, 0.0027, and 0.0004 mg · m ^{2} · h ^{1}, respectively. For N O, the average fluxes were 0.2305, 0.1441, 0.1353, 0.0989, 0.1250, and 0.1513 mg · m ^{2} · h ^{1}, respectively. The average CO fluxes were 0.4492, 0.4470, 0.4303, 0.3914, 0.4080, and 0.4164 mol · m ^{2} · s ^{1}, respectively. Soil CH emission flux decreased with increasing biochar application rate. When biochar input was less than 30 t · hm ^{2}, soil N O and CO emission fluxes decreased significantly with increasing input; however, when input exceeded 30 t · hm ^{2}, N O and CO fluxes showed a significant increasing trend. Soil temperature and moisture were significantly affected by biochar application, with significant differences observed in average soil temperature at 5-15 cm depth ($P<0.05$) and average soil moisture at 5-10 cm depth ($P<0.05$) among treatments. The CK treatment showed the greatest fluctuations in soil temperature and moisture across different layers, indicating that biochar input can reduce the amplitude of hydrothermal variation in soil profiles. N O and CO fluxes were significantly negatively correlated with soil temperature at 10-15 cm depth but significantly positively correlated with temperature at 20-25 cm depth. CH flux was significantly negatively correlated with soil temperature at 5-10 cm depth and significantly positively correlated with moisture at the same depth. N O flux was significantly positively correlated with soil temperature at 15-20 cm depth. Average fluxes of CH , N O, and CO were all significantly negatively correlated with soil moisture at 0-5 cm depth. The study concludes that biochar application can reduce greenhouse gas emissions, with effects varying by application rate, and that appropriate biochar application is beneficial for enhancing carbon sequestration and reducing emissions during the crop growth period in dryland farmland.

Keywords: Dry farmland; Biochar; Emission flux; CH ; N O; CO ; Soil temperature; Soil moisture

Introduction

The increase in greenhouse gases such as CH , N O, and CO is an undisputed major cause of global climate warming [1]. Agricultural sources contribute approximately 20% of atmospheric CO , while agricultural N O and CH emissions account for about 60% and 50% of anthropogenic emissions, respectively [2]. As farmland soil represents an important source of greenhouse gas emissions [3], improving soil properties, enhancing farmland carbon sinks, and reducing agricultural greenhouse gas emissions are critically important for mitigating global climate change.

Biochar is a porous, carbon-rich, highly aromatic, and recalcitrant solid substance produced through pyrolysis of biomass at high temperatures (350-600°C) under anaerobic or oxygen-limited conditions, characterized by high stability, large specific surface area, and strong adsorption capacity [4]. When applied to soil, biochar can convert organic carbon fixed through photosynthesis into recalcitrant carbon, thereby increasing soil organic carbon, improving soil structure, enhancing nutrient use efficiency, expanding stable carbon pool reserves [5], and slowing microbial mineralization of organic carbon to achieve carbon sequestration and emission reduction [6]. Consequently, biochar application in agriculture has attracted increasing attention. Although numerous studies have demonstrated the significance of biochar for carbon sequestration and emission reduction [7-9], most domestic research has focused on paddy fields, while studies on biochar' s effects in Northwest China' s dryland farming regions—a major source of greenhouse gas emissions—remain scarce [10]. Therefore, investigating the application mechanisms of biochar in dryland farming areas, enriching biochar application theory, and achieving scientific biochar application to reduce greenhouse gas emissions in arid regions are essential research priorities.

This study examined continuous greenhouse gas emission characteristics throughout the entire growth period of spring wheat under different biochar input levels in the Loess Plateau semi-arid region, and analyzed the influence of related environmental factors on CH , N O, and CO fluxes. The objective was to provide a scientific basis for rational biochar application to reduce farmland greenhouse gas emissions and mitigate global climate warming in dryland agricultural regions.

Materials and Methods

Study Site

The experiment was conducted at the Dryland Agriculture Experimental Station of Gansu Agricultural University in Li Jiabao Town, Anding District, Dingxi City, Gansu Province. The site is located in the semi-arid hilly and gully region of the central Loess Plateau in southern Gansu, representing a typical rain-fed dryland farming area. The region has an average elevation of approximately 2,000 m, annual sunshine duration of 2,300 h, average annual solar radiation of 594.9 kJ • cm ^{2}, mean annual temperature of 6.5°C, frost-free period of 149 days, mean annual precipitation of 390.99 mm, and annual evaporation of 1,531 mm. Precipitation at 80% assurance rate is 365 mm with a variation coefficient of 24.3% and aridity index of 2.53. The soil is typical loessial soil (Huangmian soil), characterized by soft texture, deep profile, uniform structure, and good water storage capacity. Soil pH is 8.36, average bulk density is 1.17 g • cm ^{3}, organic matter content is 12.01 g • kg ^{1}, total nitrogen is 0.76 g • kg ^{1}, total phosphorus (P O) is 1.77 g • kg ^{1}, wilting moisture content is 7.3%, and saturated moisture content is 21.9%.

The year 2015 was a strong El Niño year. Figure 1 [Figure 1: see original paper] shows the variation curves of precipitation and maximum/minimum temperatures during the greenhouse gas measurement period.

Experimental Design and Methods

The experiment included six biochar application treatments: CK (0 t · hm^{2}), T1 (10 t · hm^{2}), T2 (20 t · hm^{2}), T3 (30 t · hm^{2}), T4 (40 t · hm^{2}), and T5 (50 t · hm^{2}), with three replications arranged in a randomized complete block design. Each plot measured 2.8 m × 6 m. Before sowing, biochar was applied uniformly to the soil surface according to treatment design and incorporated into the plow layer (approximately 15 cm depth) as a one-time application with no subsequent additions.

The spring wheat cultivar 'Dingxi 35' was sown in late March 2015 and harvested at the end of July. The seeding rate was 187.5 kg · hm^{2} with row spacing of 20 cm and sowing depth of 7 cm. Fertilizer was applied once at sowing with no topdressing. All treatments received the same nitrogen and phosphorus fertilizer levels: pure N at 105 kg · hm^{2} (as urea, 46% N) and pure P O at 105 kg · hm^{2} (as superphosphate, 14% P O).

Gas Sampling and Analysis

Gas Sample Collection. CH and N O fluxes were measured using the static opaque chamber method [11]. Sampling was conducted from March to August 2015 at 7-day intervals, with all gas collections completed between 8:30 and 11:30 AM.

The sampling chamber consisted of a cylindrical base and top, constructed from 1 mm thick 304 K stainless steel plate. The top chamber had a diameter of 38 cm and height of 35 cm. The base had an inner diameter of 36.5 cm and height of 16 cm, with a sealing groove at the upper end. Bases were installed in the center of each plot after sowing and remained in place throughout the sampling period. The exterior of the top chamber was covered with aluminum foil reflective insulation film, with a rubber-stoppered temperature measurement port at the top for inserting a thermometer to record chamber temperature during sampling. A fan inside the chamber ensured gas mixing, and a three-way valve sampling port on the side allowed syringe sampling. During sampling, the top chamber was inserted into the base groove, sealed with water, a thermometer was inserted, and the fan was powered on. Gas samples were immediately collected at 0, 10, and 20 minutes using syringes and injected into 150 mL aluminum-plastic composite gas bags for laboratory analysis.

CO flux was measured using an EGM-4 portable CO analyzer (PP Systems, UK) simultaneously with N O and CH sampling.

Gas Sample Analysis. Gas concentrations were analyzed using an Agilent 7890A gas chromatograph. The chromatographic column was a ParkQ 15 m × 0.53 mm × 25 m. CH was detected using a front FID detector (detector temperature 200°C, column temperature 55°C) with high-purity N as carrier gas. N O was detected using a rear ( )ECD detector (detector temperature 300°C, column temperature 45°C) with high-purity N as carrier gas. The gas emission flux was calculated using the formula:

$$F = (C \times V \times M \times 273) / (A \times (T + T) \times t)$$

where: F is gas emission flux (mg · m ^{2} · h ^{1}), A is chamber base area (m^{2}), V is chamber volume (m^{3}), M is gas molecular weight, C and C are greenhouse gas volume concentrations (mol · mol ^{1}) at chamber closure and before opening, respectively, T and T are chamber temperatures (K) at closure and before opening, and t and t are start and end times of measurement (h).

Concurrent Measurements. Soil temperature was measured simultaneously with gas sampling using geothermometers at depths of 5, 10, 15, 20, and 25 cm. Soil moisture content was determined by collecting soil samples from 0–5, 5–10, and 10–30 cm layers using an auger during gas sampling, with moisture content measured by the oven-drying method at 105±2°C.

Data Processing and Analysis

Raw experimental data were processed using Microsoft Office Excel 2010. Multi-factor analysis of variance and LSD significance tests for differences among treatments were performed using SPSS 17.0 software.

Results

CH Flux Under Different Biochar Application Levels

Figure 2 [Figure 2: see original paper] shows the dynamic variation curves of CH flux in spring wheat fields under different biochar application rates throughout the growth period. Across all six treatments, flux variation was greatest from flowering stage (around June 26) to harvest (around August 10), followed by the tillering stage (around April 27) to booting stage (around June 10), and smallest from sowing (around March 27) to seedling emergence (around April 12). The fluctuation range of CH uptake flux was -0.0174 to -0.0001 mg · m ^{2} · h ^{1}, while emission flux ranged from 0.0002 to 0.0197 mg · m ^{2} · h ^{1}. CH emission flux was significantly greater than uptake flux throughout the growth period. The CH flux varied distinctly with growth stage, with all treatments showing similar trends and generally acting as weak CH emission sources.

The occurrence and magnitude of CH emission peaks were related to wheat growth stage and biochar input level. Except for April 12–27 when differences among treatments were minor, CH emission flux under CK treatment was significantly higher than other treatments from sowing to before flowering (June 26). Emission peaks occurred during tillering stage (around May 11) and grain filling stage (around July 10), while an uptake peak occurred after harvest (around August 10). Except for the initial sowing period (around March 24) and before flowering (June 26), T5 treatment showed lower emission flux than other treatments at the same time. As growth stage and environmental factors changed, the first emission peak appeared between tillering and jointing stages (around

May 11), coinciding with temperature and precipitation changes. From the three-leaf stage, air temperature gradually increased, enhancing soil respiration rates. Around May 27, during the transition from tillering to jointing, wheat plants grew vigorously, and both root and microbial respiration in soil were active. During this period, CH emissions showed a negative correlation with biochar input level ($y = -1796.3x + 29.683$, $r = -0.889$, $P<0.05$). This may be because biochar input, with its large specific surface area and high porosity, increased soil aeration [9], improved soil ventilation, increased oxygen availability, and reduced the anaerobic conditions required for CH production. Additionally, biochar can increase soil available potassium content [9], and its inherent high potassium content can raise soil redox potential [12], thereby reducing methanogen activity and decreasing CH emissions [13]. The second emission peak occurred during grain filling, the period with most frequent temperature and moisture changes. Compared with CK, all biochar treatments except T4 showed higher CH emissions, possibly because frequent rainfall and high temperatures in July provided suitable hydrothermal conditions for methanogens, facilitated by biochar. After harvest (around August 10), with no vegetation cover and reduced precipitation, CH uptake peaks appeared in CK, T1, and T2 treatments.

Although CH flux in spring wheat fields alternated between uptake and emission across growth stages under different biochar levels, the fields acted as weak emission sources throughout the entire growth period, with emission flux decreasing as biochar input level increased. The ranking of average CH emission flux across treatments was: CK > T1 > T2 > T3 > T4 > T5.

N O Flux Under Different Biochar Application Levels

Figure 3 [Figure 3: see original paper] shows the dynamic variation curves of N O flux under different biochar treatments throughout the growth period. N O flux varied distinctly with growth stage, showing consistent trends across treatments and generally following a double-peak pattern of increase-decrease-increase-decrease.

Before tillering stage (before April 27), N O emissions were low with flat peaks. During this period, wheat growth depended on seed energy reserves, and external factors had limited influence, resulting in minor differences among treatments. From tillering to harvest (July 27), two emission peaks occurred. The first peak appeared during the transition from tillering to jointing (around May 27), with CK showing the highest peak and T3 the lowest. The second peak occurred during the transition from grain filling to maturity (around July 27), with T5 showing the highest peak, followed by CK, and T4 the lowest. N O emission fluctuated from 0.0023 to 0.4393 mg·m^{2}·h^{1}, while uptake ranged from -0.1129 to -0.0213 mg·m^{2}·h^{1}. Emission flux exceeded uptake flux throughout the growth period, making spring wheat fields a net N O source.

Analysis of N O data across growth stages showed that although fluxes alternated between emission and uptake, spring wheat fields were net N O sources throughout the growth period. The ranking of average N O emission flux was: CK > T5 > T1 > T2 > T4 > T3. CK treatment had the highest average emission flux at 0.2305 mg · m ^{2} · h ^{1}, while T3 had the lowest at 0.0989 mg · m ^{2} · h ^{1}.

CO Flux Under Different Biochar Application Levels

Figure 4 [Figure 4: see original paper] shows the dynamic variation curves of CO emission flux under different biochar application rates throughout the growth period. CO emission trends were consistent across treatments, showing distinct growth stage characteristics and generally following a single-peak curve.

After sowing (March 25), soil disturbance accelerated organic matter decomposition, resulting in higher CO emissions than post-harvest levels. However, low soil temperatures limited microbial activity, causing minor differences among treatments until seedling emergence (around April 12). As the growth period progressed and temperatures rose, CO emission flux increased gradually, peaking during jointing stage (around May 27) with the ranking T1 > T2 > CK > T3 > T4 > T5. This period represented vigorous wheat growth with enhanced photosynthesis and soil respiration, leading to increased CO emissions. Subsequently, emissions decreased slowly to maturity (around July 27) and continued declining after harvest due to reduced CO emissions from the soil-plant system. The ranking of average CO emission flux across the six biochar treatments was: CK > T1 > T2 > T5 > T4 > T3.

Effects of Biochar Levels on Average CH , N O, and CO Fluxes

Table 1 presents the average fluxes of the three greenhouse gases throughout the growth period. Since flux variations during different growth stages only reflect conditions at specific times and special weather events may cause deviations, we conducted ANOVA and multiple comparisons on average CH , N O, and CO fluxes across treatments (Table 2) to estimate treatment effects.

Results showed that CK treatment had significantly higher average CH flux than T2, T3, T4, and T5 treatments, exceeding them by 59.52%, 70.39%, 111.80%, and 1237.91%, respectively. CK was significantly different from T2 and T3, highly significantly different from T4 and T5, but not significantly different from T1. No significant differences existed among T1, T2, T3, and T4, while T5 was highly significantly different from all other treatments. This indicates that CH emission flux without biochar application was significantly higher than under high input levels, while low biochar input levels had minor effects on CH flux. CH emission flux decreased with increasing biochar input, consistent with previous findings [6,14]. This study further demonstrates that higher biochar application rates have more pronounced CH reduction effects, aligning with Gao et al. [14].

N O emission flux showed clear patterns across the six treatments. Table 1 shows that CK and T3 treatments were significantly different from other treatments. Compared with CK, N O emissions in T1, T2, T3, T4, and T5 decreased by 37.50%, 41.33%, 57.10%, 45.77%, and 34.39%, respectively. This demonstrates that biochar application in dryland farmland can reduce N O emissions through nitrogen retention, though the reduction was not strictly proportional to biochar input rate. When biochar exceeded a certain amount, N O emission flux increased instead. Studies by Gao et al. and Zhang et al. [14-15] showed that biochar application at 40 t · hm ^{2} achieved substantial N O reduction, similar to our findings.

Similar to CH and N O, CO emission flux showed patterns related to biochar input level. Table 1 shows that CK was not significantly different from T1, significantly different from T2, and highly significantly different from other treatments. T3 was significantly different from T4 and highly significantly different from other treatments. T4 was highly significantly different from CK, T1, and T2, but not significantly different from T5. Compared with CK, CO emissions in T1, T2, T3, T4, and T5 decreased by 5.30%, 10.48%, 23.59%, 21.36%, and 19.12%, respectively. This indicates that appropriate biochar application in dryland farmland benefits CO sequestration and emission reduction, with the best reduction effect at 30 t · hm ^{2} input level. Excessive biochar input was not conducive to CO reduction, possibly because biochar addition reduced respiration in loessial soil with low initial organic matter content, decreasing CO emissions. However, excessive biochar may have saturated the soil organic carbon pool [16], leading to increased CO emissions.

Soil Hydrothermal Conditions and Their Effects on Greenhouse Gas Emissions

Soil Temperature Figure 5a [Figure 5: see original paper] shows that average soil temperature was highest in the surface 0-5 cm layer across different biochar input levels, likely because the surface receives more solar radiation and warms more obviously. Significant differences in average soil temperature were observed at 5-15 cm depth among treatments ($P<0.05$). CK treatment showed the greatest temperature fluctuations across all five soil layers, possibly because biochar input reduced soil temperature variation amplitude through moisture adsorption [17]. However, in dryland farmland with low soil moisture, biochar' s moisture control capacity is limited. When soil moisture is fully controlled, biochar' s warming effect [18] becomes apparent, causing differences among treatments.

Regression and correlation analyses between greenhouse gas fluxes and soil temperature at different depths (Table 2) showed that average CH flux was significantly negatively correlated with soil temperature at 5-10 cm depth ($P<0.05$), following a linear function, with no other significant correlations. Average N O flux was significantly negatively correlated with temperature at 10-15 cm depth ($P<0.05$) but significantly positively correlated with temperature at 15-20 cm and 20-25 cm depths ($P<0.05$), following linear functions. Average CO flux was significantly negatively correlated with temperature at 0–5 cm and 10–15 cm depths ($P<0.05$) but significantly positively correlated with temperature at 20–25 cm depth ($P<0.05$), following a linear function.

Soil Moisture Content In addition to temperature, soil moisture significantly affected average fluxes of CH , N O, and CO in dryland spring wheat fields, with effects varying by moisture level. Figure 5b shows significant differences in average soil moisture at 5–10 cm depth among treatments ($P<0.05$). Except for T3 treatment where moisture changes in the 10–30 cm layer were not significant, other treatments showed consistent trends. Soil moisture was highest in the 5–10 cm layer, moderate in 10–30 cm, and lowest in 0–5 cm. This pattern occurs because the 5–10 cm layer, covered by surface soil, experiences less evaporation and contains dense wheat roots that absorb and store surface water. The 0–5 cm layer has the lowest moisture due to surface evaporation, while the 10–30 cm layer maintains relatively stable moisture. CK treatment showed the greatest moisture fluctuations, with significantly higher moisture in the 5–10 cm layer than in surface and deeper layers, and significantly higher than other treatments at this depth. This may be because biochar input increased soil porosity, enhancing field water capacity while promoting surface soil water evaporation.

Table 3 shows that average CH flux was significantly negatively correlated with moisture at 0–5 cm depth and highly significantly positively correlated with moisture at 5–10 cm depth. N O flux was significantly negatively correlated with moisture at 0–5 cm depth, with no significant correlations at other depths. CO flux was significantly negatively correlated with moisture at 0–5 cm depth, showing a negative but non-significant correlation with moisture.

Discussion and Conclusions

Although some studies have examined biochar’ s effects on carbon sequestration and emission reduction in farmland soils, systematic understanding remains limited and results are inconsistent [9,14,19]. This study found that spring wheat fields were weak CH emission sources throughout the growth period, with emission flux decreasing as biochar input increased. The reason may be that during the strong El Niño year, the soft-textured, water-retentive loessial soil, combined with frequent precipitation and high temperatures during the observation period, created certain anaerobic conditions that enhanced methanogen activity and increased CH emissions compared to normal years. However, biochar input increased field water capacity and promoted soil aggregate formation [20], improving soil porosity, aeration, and oxygen supply [9], thereby reducing CH emissions through microbial regulation of CH production and oxidation [21]. Biochar may also reduce CH emissions by inhibiting methanogen activity and increasing methanotroph activity and diversity [8,21]. However, some studies have reported increased CH emissions after biochar application [7,22], possibly because easily decomposable organic carbon in biochar provided substrates for methanogens [23] and affected methanotroph activity, reducing CH oxidation [22], or because biochar contained substances toxic to methanotrophs [23].

Numerous studies have shown that biochar addition positively affects N O sequestration and emission reduction [8,15,21]. This study found that spring wheat fields were N O emission sources, with flux decreasing initially then increasing with biochar input. This pattern may occur because biochar addition improved soil aeration [8], increased cation exchange capacity, and adsorbed NH [24], reducing denitrification substrates, inhibiting nitrification, and decreasing N O production. Increased soil O may also have reduced N O production during the second stage of nitrification and denitrification processes [9]. However, N O reductase (Nos) is much more sensitive to O than other enzymes in the denitrification process. When biochar input was excessive, increased O supply may have halted denitrification at N O, causing increased N O emissions [25], which may explain why T4 and T5 showed reduced mitigation effectiveness compared to T3.

Biochar addition can either increase or suppress CO emissions from dryland soils, with effects varying by biochar source, production process, and soil type [26-28]. This study found that appropriate biochar application in spring wheat dryland fields benefited CO sequestration and emission reduction, consistent with Liu et al. [8,29]. Biochar addition can fix carbon in soil due to its high stability, reducing CO emissions in the carbon cycle. Additionally, biochar' s large surface area and strong adsorption capacity can adsorb soil organic matter onto its surface or into pores, reducing organic matter availability and isolating microorganisms from organic matter through encapsulation, thereby inhibiting organic matter degradation and reducing CO emissions [26]. However, some studies have reported increased CO emissions after biochar application [14,27], possibly due to differences in biochar input levels and types. Hua et al. [30] found that CO emissions increased with biochar application rates of 1-5%, but decreased when application exceeded 5%. Soil CO is produced through heterotrophic and autotrophic respiration, and biochar addition directly affects crop growth [15], influencing root autotrophic respiration. Therefore, biochar' s effects on soil CO emissions occur through both direct and indirect mechanisms.

Greenhouse gas emissions are closely related to environmental factors, with soil moisture and temperature being the primary factors affecting emissions. Numerous studies have shown that biochar addition significantly improves soil water retention [31], with saturated water content, field capacity, and available water content increasing with biochar input level [32]. Biochar also significantly affects soil temperature at 0 and 10 cm depths [18]. Therefore, biochar' s effects on soil hydrothermal conditions inevitably cause variations in greenhouse gas emissions. This study found that greenhouse gas fluxes were significantly negatively correlated with soil moisture at 0-5 cm depth, negatively correlated with temperature at 0-15 cm depth, and positively correlated with temperature at 15-25 cm depth, with different gases showing different correlations with temperature at various depths. For CH , under strong surface solar radiation and intense tillage layer temperature effects, biochar treatments had significantly lower soil moisture than CK at 5-10 cm depth, where methane oxidation is strongest [33], providing sufficient oxygen and suitable conditions for methanotrophs and reducing CH emissions. For N O emissions from dryland soils, our findings align with most studies: frequent rainfall and high temperatures during tillering-jointing and grain filling-maturity stages enhanced nitrification and denitrification with increasing temperature, while soil gases were expelled with increasing evaporation, causing N O emissions to increase with temperature and decrease with moisture [34-35]. Compared with CK, biochar treatments had higher soil moisture due to improved water retention, thus reducing N O emissions. For CO , this study found significant negative correlations between flux and shallow soil temperature and moisture, possibly because increased soil moisture under biochar masked temperature effects, dissolving CO in soil water and reducing emissions. CO flux was significantly positively correlated with deep soil temperature and negatively correlated with moisture, consistent with most studies.

However, differences in biochar and soil types may affect greenhouse gases differently, and post-application soil hydrothermal combinations may vary with climate. Mechanistic research on biochar input levels and greenhouse gas emissions remains in its early stages without unified conclusions, requiring future systematic and in-depth studies.

Conclusions

Under all six biochar input levels, spring wheat field soils acted as emission sources for CH , N O, and CO throughout the growth period. CH emission flux decreased with increasing biochar input level, while N O and CO fluxes decreased initially then increased. T5 treatment showed significantly lower average CH emissions than all other treatments. T3 treatment showed significantly lower average N O and CO fluxes than other treatments. Compared with no biochar application, a biochar input rate of 30 t · hm ^{2} had the most significant effect on reducing soil greenhouse gas emissions.

As the growth period progressed, changes in environmental factors such as hydrothermal conditions in the plant-soil system resulted in lower CH , N O, and CO fluxes during sowing, seedling, and post-harvest periods compared to other stages. Emission peaks occurred around tillering-jointing stage for all gases and around grain filling-maturity stage for CH and N O. Significant differences in emissions of the three greenhouse gases among different biochar treatments suggest that biochar' s effects on soil structure and hydrothermal conditions may be the primary cause of emission variations, requiring further investigation.

Average CH flux was negatively correlated with moisture at 0-5 cm depth, significantly negatively correlated with temperature at 5-10 cm depth, and highly significantly positively correlated with moisture at the same depth. N O flux was significantly negatively correlated with moisture at 0-5 cm depth, significantly negatively correlated with temperature at 10-15 cm depth, and significantly positively correlated with temperature at 15-20 cm and 20-25 cm depths. Average CO flux was significantly negatively correlated with moisture and temperature at 0-5 cm depth, significantly negatively correlated with temperature at 10-15 cm depth, and significantly positively correlated with temperature at 20-25 cm depth.

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Note: Figure translations are in progress. See original paper for figures.