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Research Article

Biochar with N-Fertilizer Effects on Soil CO_2 Emissions and Soil Physical Properties

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Biochar has gained attention as a soil amendment due to its potential to mitigate climate change by improving soil properties and reducing greenhouse gas emissions. This study investigates the effects of biochar application and reapplication, in combination with different nitrogen (N) fertilization levels, on soil CO_2 emissions and soil physical properties. The field experiment was conducted in a temperate climate zone over a five-year period, with biochar applied at doses of 0, 10, and 20 $t.ha^{-1}$, and N-fertilizer applied at 0, 108, and 162 $kg.N.ha^{-1}$. Soil temperature, soil water content (SWC), and CO_2 fluxes were monitored biweekly during the 2019 growing season (April–October). Results showed that biochar reapplication significantly reduced cumulative CO_2 emissions, particularly at higher application rates and in fertilized treatments. In contrast, a single biochar application led to increased CO_2 emissions in some cases. A strong correlation was found between CO_2 emissions and soil temperature ($p < 0.001$), while the relationship between CO_2 emissions and SWC was not significant ($p > 0.05$) except in one fertilized treatment. These findings suggest that biochar application, particularly when reapplied, can play a role in reducing soil CO_2 emissions while influencing soil physical properties. However, further research is needed to assess its long-term effects across various soil types and climatic conditions.

Keywords: biochar, N-fertilization, soil CO_2 emissions, soil water content

1 Introduction

The increase in man-made greenhouse gas (GHG) emissions from human activities is a serious global challenge (Rothenberg, 2023). GHGs contribute significantly to global warming by trapping heat in the atmosphere (Jeffry et al., 2021). This concern is reflected in the 2015 Paris Agreement and Conference of the Parties (COP) meetings, which demonstrate global efforts to reduce emissions and mitigate climate change. In 2019, approximately 60 billion tons of CO_2-equivalent emissions were produced across all sectors (Rothenberg, 2023). Without strict climate policies, the continued rise in emissions threatens the global goal of limiting temperature increases to below 2 °C relative to pre-industrial levels. Despite efforts to reduce CO_2 emissions over the past two decades, emissions grew more rapidly in the 2000s than in the 1990s, reaching around 50 Gt CO_2-equivalent per year by 2010 (Peters et al., 2013; Edenhofer, 2015). Among the key sources of CO_2 emissions, agriculture plays a major role, accounting for about 20% of global emissions (FAO, 2020). Following the energy (35%) and industrial (21%) sectors, agriculture is the third-largest contributor to climate change (FAO, 2016). Since this trend will worsen environmental issues worldwide, reducing agricultural emissions is crucial for sustainable development (Gokmenoglu & Taspinar, 2018; Ridzuan et al., 2020). Global mean CO_2 concentrations in the atmosphere hit record highs of 423 parts per million in 2024, making a 19% increase from 1990 levels (Li et al., 2025). One promising solution for reducing agricultural emissions is biochar – a carbon-rich byproduct of biomass pyrolysis. Biochar has been recognized as one of the most cost-effective negative emission technologies (NETs) for large-scale carbon dioxide removal (CDR) in the future

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(Tisserant & Cherubini, 2019). Produced by heating biomass at 300–1,000 °C under low-oxygen conditions, biochar possesses unique structural and chemical properties depending on its feedstock and processing conditions (European Commission, 2010). Biochar has been used for thousands of years to enhance soil fertility (Weber & Quicker, 2018). More recently, it has gained attention for its ability to sequester carbon, reduce soil nutrient leaching, improve soil structure, and lower GHG emissions (Wang & Wang, 2019; Ippolito et al., 2012; Zhang et al., 2019). Soil respiration commonly refers to the CO_2 efflux from the soil surface to the atmosphere and plays a crucial role in global carbon cycling, as it accounts for 50–80% of total ecosystem respiration (Bond-Lamberty & Thomson, 2010; Shafawi et al., 2021). Globally, soil respiration emits nearly ten times more CO_2 per year than fossil fuel combustion (Bond-Lamberty & Thomson, 2010). Since soils store twice as much carbon as the atmosphere (Post et al., 1982; IPCC, 2014; Scharlemann et al., 2014), understanding soil respiration dynamics is crucial for predicting future atmospheric CO_2 concentrations (Cox et al., 2000; Heimann & Reichstein, 2008). Soil respiration consists of heterotrophic respiration, root respiration, soil fauna respiration, and non-biological CO_2 production (Xu & Shang, 2016). The breakdown of dead soil organic matter (SOM) by soil bacteria is known as heterotrophic respiration. Both aerobic and anaerobic organic matter degradation are carried out by the two primary species of these decomposers, which are bacteria and fungi (Romaní et al., 2006). Carbon is metabolized by a variety of metabolic processes, the end result of which is the emission of CO_2 (Xu & Shang, 2016). Root respiration is major source of soil CO_2 production, as plant roots consume oxygen and release CO_2 (Raich & Tufekciogul, 2000). The CO_2 that soil animals produce through metabolic activities is referred to as "soil fauna respiration," and it typically makes up less than 5% of all soil respiration (Petersen & Luxton, 1982). Non-biological CO_2 production occurs through physical and chemical processes, such as geothermal activity, volcanic degassing, and soil compression during rainfall (Tang et al., 2003; Xu et al., 2004; Werner & Brantley, 2003). Soil CO_2 efflux is significantly influenced by temperature and moisture variability, affecting annual CO_2 fluxes into the atmosphere (Vargas et al., 2010). Soil temperature and moisture are among the most important factors regulating soil respiration, along with carbon inputs from plant and microbial activity. Biochar application has shown promising results in suppressing CO_2 emissions (He et al., 2016) while also altering soil temperature (Zhang et al., 2013) and moisture content (Karhu et al., 2011). We hypothesized that biochar application to soil influences the sensitivity of soil respiration to temperature and moisture, particularly over a long-term period in 2019. We investigated the potential effects of a 5-year-old field application of biochar and a 1-year-old biochar reapplication, combined with different levels of N-fertilization, on soil respiration, with a sampling frequency of every 2 weeks. Our objectives were therefore to determine (H1) How biochar application or reapplication is more effective in decreasing soil CO_2 emissions and (H2) How the sensitivity of soil respiration varies with soil temperature and soil moisture content. The findings from this study may contribute to climate change mitigation in agriculture, but further research is needed on different soil types and biochar produced from various feedstocks to enhance its effectiveness.

2 Material and Methods

2.1 Field Site

The field experiment was launched in 2014 by the Slovak University of Agriculture at the experimental site in Dolná Malanta, located near Nitra, Slovakia (48° 19´ N, 18° 09´ W). The site is located in a temperate climate zone, with a mean annual temperature of 9.8 °C and an average

Table 1 Average air temperature and precipitation during the 2019 growing season compared to the climatic normal (CN) 1951 to 2000

Treatments	Average air temperature			Precipitation		
	average temperature for each studied month (°C)	deviation from climatic norm (°C)	description	total (mm)	% of normal	description
April	9.7	-0.7	normal	12.3	29.6	very dry
May	9.3	-5.9	extremely cold	114.7	204.8	extremely wet
June	18.7	0.4	normal	32.6	49.2	very dry
July	21.9	1.9	warm	21.0	35.4	very dry
August	22.3	2.6	very warm	83.7	154.4	very wet
September	16.2	0.7	normal	60.3	139.9	wet
October	12.0	1.8	warm	15.0	36.6	very dry

annual precipitation of 539 mm (based on the 30-year climate normal, 1961–1990). Table 1 shows the monthly average air temperature and precipitation during the 2019 growing season, compared to the long-term climatic normal (1951–2000). In 2019, the mean annual air temperature was 10.9 °C and a total annual precipitation of 560.8 mm. Before the experiment, the agricultural field was conventionally managed for several decades. The soil is classified as Haplic Luvisol and categorized as silt loam according to the USDA classification. Its key properties are summarized in Table 2.

Table 2 Soil properties

sand	15.2%
silt	59.9%
clay	24.9%
$\mathrm{pH}_{(KCl)}$	5.71
SOC	9.13 $g.kg^{-1}$

Source: Kotuš et al., 2022

2.2 *Experimental Design*

This experiment used a randomized block design with two main experimental factors: biochar application and mineral nitrogen fertilization. In 2014, biochar was applied at doses of 0, 10, and 20 $t.ha^{-1}$ (B0, B10, B20), and in 2018, the original plots were split into two sections, with biochar reapplied at the same doses (reapB10, reapB20). The second factor involved nitrogen fertilizer at three levels: N0 (without N-fertilizer), N1 (based on crop requirements), and N2 (50% more than N1). In 2019, N-fertilizer was applied at varying rates: 0, 108, and 162 kg $N.ha^{-1}$. The crop studied in 2019 was corn (*Zea mays* L.). The experiment included a total of 45 plots, consisting of 27 original plots and 18 reapplication subplots (Fig. 1). Plots without biochar or nitrogen fertilizer served as controls.

2.3 *Biochar Production and Properties*

The biochar used in this study was produced by pyrolyzing a mixture of paper fibre sludge and grain husks (1 : 1 ratio, Sonnenerde, Austria) at 550 °C for 30 minutes in a Pyreg reactor (Pyreg GmbH, Dörth, Germany). The properties of the biochar are as follows: pH 8.8, bulk density 0.21 $g.cm^{-3}$, surface area 21.7 $m^2.g^{-1}$, ash content 38.3%, total nitrogen (TN) content 14.0 $g.kg^{-1}$, and total carbon (TC) content 53.1 $g.kg^{-1}$.

2.4 *Soil Sampling and Analysis*

Soil samples were collected at two-week intervals from April to October at a depth of 0–0.1 m from random

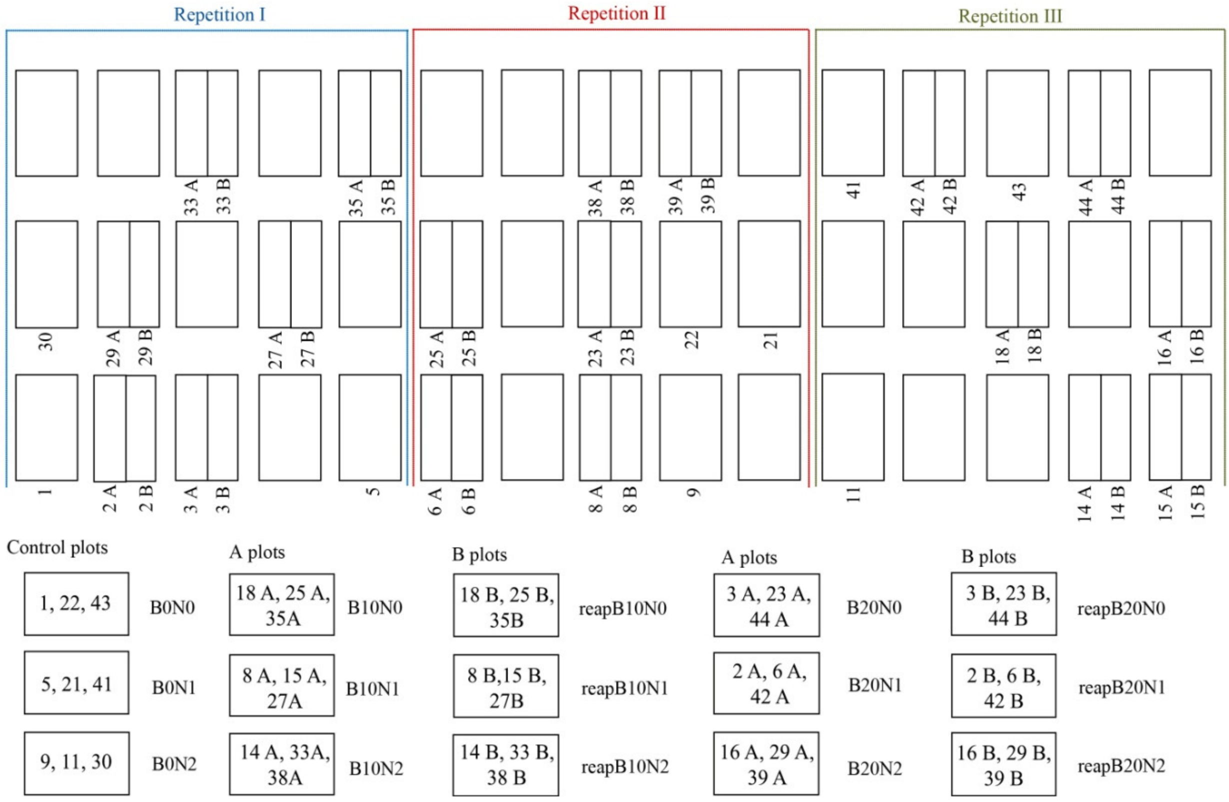

Figure 1 Design arrangement of the experimental field with 27 highlighted plots, which were used in this experiment
A – subplots with the biochar applied only in 2014; B – subplots with the biochar reapplication in 2018; and control plots without biochar but with different rates of the mineral N-fertilizer

locations within each plot. Additionally, disturbed soil samples were taken during each gas sampling event to measure soil temperature at a depth of 0.05 m using a Volcraft DET3R thermometer and to determine soil water content (SWC) using the gravimetric method.

2.5 Air Sampling and CO_2 Analysis

Air samples were collected from April to October 2019 using the closed chamber method (Elder & Lal, 2008). Metal collars were installed 0.1 m deep in the soil at each sampling location. During sampling events, PVC chambers (0.25 m high, 0.3 m in diameter) were sealed onto these collars, and gas samples were collected biweekly at 0, 30, and 60 minutes after chamber deployment. The samples were analysed for CO_2 concentration (in ppm) using a gas chromatograph (GC-2010 Plus Shimadzu) equipped with a thermal conductivity detector (TCD). Before analysing CO_2 emissions, three standard gas mixtures with different concentrations of N_2O, CO_2, and N_2 were used to calibrate the gas chromatograph in the laboratory. Daily average CO_2 emissions are expressed in kg.ha^{-1}.day^{-1}. Emissions between each sampling day were interpolated to calculate the cumulative CO_2 fluxes (April through October), which are expressed in t.ha^{-1}.

2.6 Statistical Analysis

Statistical analyses were performed using Statgraphics Centurion XV.I software. One-way analysis of variance (ANOVA) and the least significant difference (LSD) test ($p < 0.05$) were used to compare mean values between the corresponding controls and treatments within each fertilization level. Regression analysis was conducted to examine the relationship between CO_2 emissions and specific soil properties (temperature and SWC).

3 Results and Discussion

Table 3 contains the results of soil physical properties (soil temperature, soil water content – SWC), which varied according to the dose of added biochar and different levels of N-fertilization. Soil temperature in treatments without N-fertilizer increased from 0.59% to 2.26% compared to the control (B0N0). In the first level of N-fertilization, the temperature decreased from 0.75% to 1.71% compared to the control (B0N1). In the second level of N-fertilization, temperature increased from 1.52% to 3.32% compared to the control (B0N2). In general, soil temperature increased in all treatments with or without N-fertilization compared to the relevant control variants (B0N0, B0N1 and B0N2). Xiong et al. (2020) observed a decrease in soil temperature, which they attributed to the influence of soil moisture content, soil depth and biochar application rates. In contrast, Feng et al. (2021) reported that biochar application increased the average soil temperature by 2 °C. Additionally, biochar altered the soil colour, which subsequently influenced soil temperature. Applying 30–60 t.ha^{-1} of biochar can reduce

Table 3 Effect of different biochar and N-fertilizer treatments on soil physical properties

Treatments	**Soil temperature (°C)**	**SWC (%)**
N0 level – unfertilized treatments		
B0N0	18.60 ±0.4 a	14.63 ±0.8 a
B10N0	18.87 ±0.3 a	14.04 ±0.7 a
B20N0	18.71 ±0.3 a	15.23 ±0.9 a
reapB10N0	19.02 ±0.3 a	14.23 ±0.6 a
reapB20N0	18.97 ±0.3 a	15.20 ±1.0 a
N1 level – fertilized treatments		
B0N1	18.74 ±0.3 a	12.85 ±0.7 a
B10N1	18.60 ±0.5 a	14.53 ±1.0 a
B20N1	18.42 ±0.3 a	14.65 ±0.9 a
reapB10N1	18.57 ±0.4 a	14.09 ±0.7 a
reapB20N1	18.51 ±0.3 a	15.07 ±1.1 a
N2 level – fertilized treatments		
B0N2	18.38 ±0.3 a	14.15 ±1.3 a
B10N2	18.84 ±0.4 a	13.99 ±1.3 a
B20N2	18.66 ±0.2 a	14.77 ±0.8 a
reapB10N2	18.81 ±0.4 a	14.37 ±1.0 a
reapB20N2	18.99 ±0.3 a	15.44 ±0.9 a

soil albedo by up to 80% (Crutzen, 2006). Soil moisture content directly affects the soil's ability to absorb light and heat (Krull et al., 2004; Jin et al., 2016). Shackley et al. (2016) also highlighted the positive effect of biochar on soil temperature, attributing it to its strong heat conductivity and dark colour.

Soil water content (SWC) varied in treatments without N-fertilization but there was observed increase from 3.90% to 4.10% in B20N0, reapB20N0 treatments compared to the control (B0N0) variant. Generally, the application of biochar in treatments with the first and second levels of N-fertilization increased SWC compared to the relevant control variants (B0N1, B0N2), respectively. In the first level of N-fertilization, SWC increased from 9.65% to 17.28% compared to the control (B0N1). In the second level of N-fertilization, SWC increased from 1.55% to 9.12% compared to the control (B0N2). A similar increase in SWC was reported by Huang et al. (2024), where biochar application resulted in a 20.7% to 132.3% increase, depending on the feedstock used for biochar production. Similarly, Razzaghi et al. (2020) observed an increase of 21–45% across different soil types. Different mechanisms have been proposed to explain how biochar enhances soil water retention. According to Shackley et al. (2016), biochar increases SWC due to its swelling capacity and the ability of water to enter and be strongly retained within its micropores. According to Feng et al. (2021), biochar increases SWC by altering soil structure. The low density of biochar reduces soil bulk density, leading to increased soil porosity. Since pores serve as storage for capillary water, higher porosity enhances the soil's capillary water content, thereby improving its water retention capacity.

Daily soil CO_2 flux (Figure 2) generally increased with start of the onset of summer due to rising temperatures and gradually declined as autumn approached and temperatures dropped. Variations in daily CO_2 flux were observed at each level of nitrogen fertilization, depending on the biochar application rate, when compared to the corresponding control treatments (B0N0, B0N1, B0N2). An irregular decrease in daily CO_2 flux was observed in mid-July. As temperatures increased, CO_2 concentrations also began to rise, possibly due to the increase in soil temperature. The addition of biochar lowers soil surface

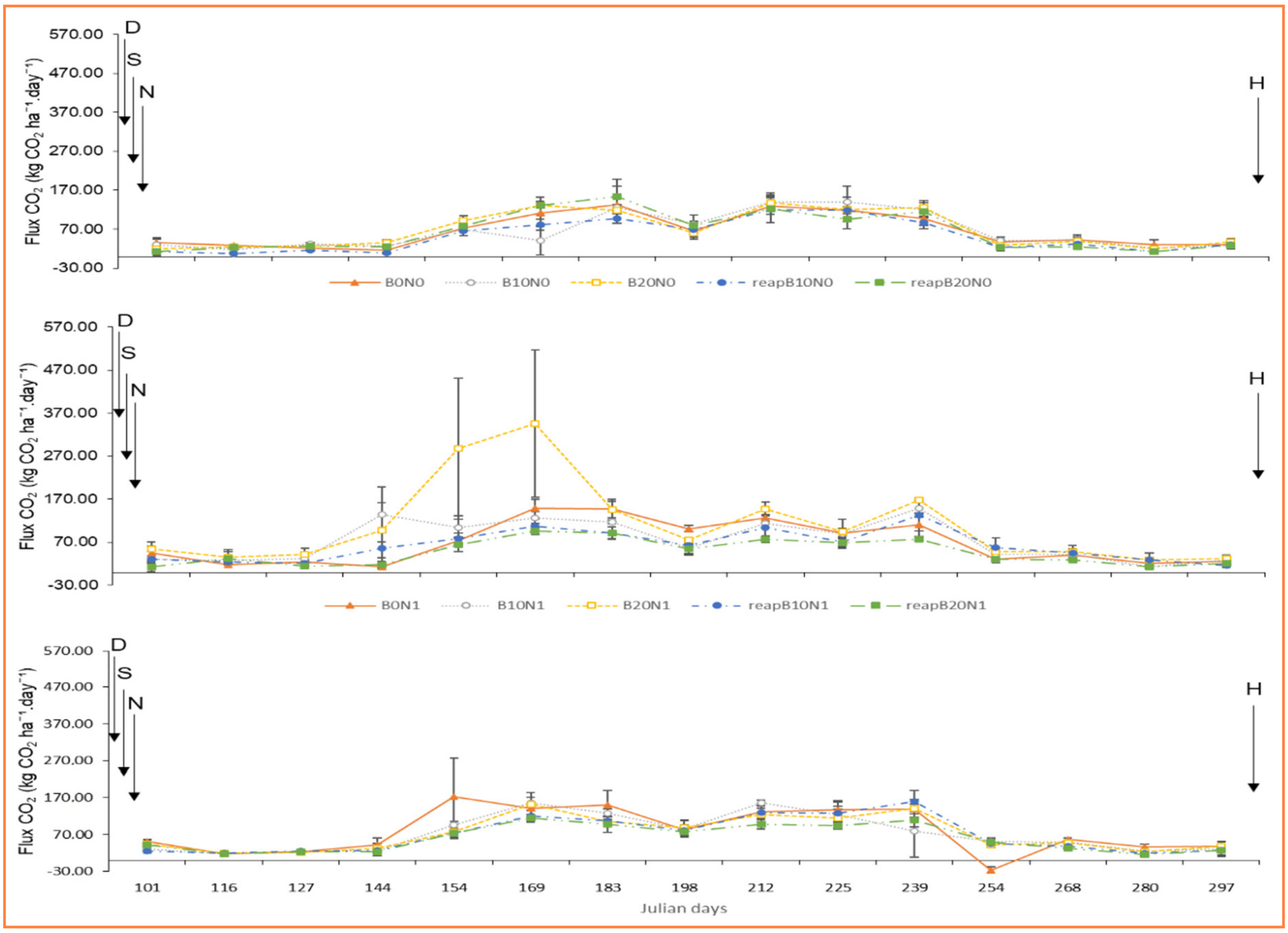

Figure 2 Flux CO_2 emissions (kg.ha^{-1}.day^{-1})
Error bars indicate standard errors of the means (*n* = 3) D – disking (2. 4. 2019), S – sowing (3. 4. 2019); N – application of nitrogen 0, 108 and 162 kg.ha^{-1} (5. 4. 2019); H – harvesting (28. 10. 2019)

albedo, which can significantly stimulate microbial activity, as discussed by Zhu et al. (2020). Figure 2 shows that biochar reapplication (reapB10N0) without N-fertilization resulted in lower CO_2 concentrations for most of the season, particularly at the beginning of summer when temperatures rose sharply compared to the spring months, relative to the control (B0N0). With the addition of N-fertilizer, a strong CO_2-reducing effect of biochar was observed, especially in treatments with biochar reapplication (reapB10N1, reapB20N1) at the first level of N-fertilization, compared to the control (B0N1). At the second level of N-fertilization, nearly all biochar treatments exhibited lower CO_2 concentrations than the control (B0N2), except in early September, when the control (B0N2) showed the lowest CO_2 concentration. Previous studies have also reported similar findings. Yoo and Kang (2012) found that biochar with higher available nitrogen reduced CO_2 emissions in nitrogen-limited soils. Mukherjee et al. (2014) observed a 43% reduction in CO_2 emissions following biochar application. Bovsun et al. (2021) suggested that biochar reduces soil CO_2 emissions by trapping CO_2 on the surface of its pores.

Table 4 presents the average daily CO_2 emissions throughout the growing season (April–October) and cumulative emissions for entire period. In general, treatments with biochar reapplication at each level of N-fertilization showed the most effective reduction in daily CO_2 flux. Among treatments without N-fertilization, all except B20N0 exhibited slightly lower daily CO_2 emissions, ranging from 1.19% to 18.94% compared to the control (B0N0), though the differences were not statistically significant ($p > 0.05$). At the first level of N-fertilization, a statistically significant difference ($p < 0.05$) was observed between B20N1 and all other treatments, including the control (B0N1). However, in this case, CO_2 flux increased significantly ($p < 0.05$) by 61.87%. At the second level of N-fertilization, CO_2 flux decreased across all treatments as the biochar application rate increased. The reductions followed the same pattern as the increasing biochar dosage: B0N2 (control) >B10N2 >B20N2 >reapB10N2 >reapB20N2, with respective decreases of 9.37% >10.32% >13.98% >25.03%. Overall, these findings suggest that increasing the biochar application rate, including biochar reapplication, leads to a more pronounced reduction in daily CO_2 flux. He et al. (2017) found that biochar application significantly increased soil CO_2 fluxes by 43.3% in unfertilized soil. However, in N-fertilized soil they observed a decrease of 8.6%.

Figure 3 shows the cumulative CO_2 emissions during growing season in 2019 (April–October). Treatments without N-fertilization showed varying increases (0.08–5.77%) and decreases (0.38–24.25%) in cumulative CO_2 emissions compared to the control (B0N0), with

Table 4 Average daily flux of CO_2 emissions and cumulative emissions of CO_2 throughout the growing season (means ±standard error; *n* = 3)

Treatments	Average daily CO_2 flux ($kg.ha^{-1}.day^{-1}$)	Cumulative CO_2 emission ($t.ha^{-1}$)
N0 level – unfertilized treatments (0 $kg.N.ha^{-1}$)		
B0N0	64.64 ±14.38 a	12.99 ±1.35 a
B10N0	63.87 ±14.29 a	12.94 ±1.40 a
B20N0	67.98 ±9.97 a	13.74 ±0.90 a
reapB10N0	52.40 ±11.11 a	9.84 ±0.99 a
reapB20N0	63.71 ±13.36 a	13.00 ±1.41 a
N1 level – fertilized treatments (108 $kg.N.ha^{-1}$)		
B0N1	68.09 ±11.05 a	13.72 ±1.03 a
B10N1	74.00 ±17.67 a	15.04 ±1.94 ab
B20N1	110.22 ±35.33 b	22.09 ±4.49 b
reapB10N1	62.07 ±14.84 a	12.63 ±1.37 a
reapB20N1	46.87 ±8.64 a	9.52 ±0.94 a
N2 level – fertilized treatments (162 $kg.N.ha^{-1}$)		
B0N2	79.47 ±19.17 a	16.87 ±2.05 a
B10N2	72.02 ±14.34 a	14.53 ±1.18 a
B20N2	71.27 ±13.93 a	14.31 ±1.35 a
reapB10N2	68.36 ±12.84 a	13.89 ±1.11 a
reapB20N2	59.58 ±8.70 a	11.96 ±0.85 a

no significant difference (*p* >0.05). In the first level of N-fertilization, a statistically significant increase (*p* <0.05) was observed between the control (B0N1) and the B20N1 treatment (Table 4). Specifically, in treatments with single biochar application, cumulative CO_2 emissions increased by 9.62% and 61.01%, respectively, compared to the control (B0N1). However, in treatments with biochar reapplication, cumulative CO_2 emissions decreased by 7.94% and 30.61%, respectively, compared to the control (B0N1). At the second level of N-fertilization, there was a gradual decrease in cumulative CO_2 emissions as the biochar dosage increased, in the following order: B0N2 (control) >B10N2 >B20N2 >reapB10N2 >reapB20N2, with reductions of 13.87%, 15.17%, 17.66%, and 29.10%, respectively. Generally, treatments with biochar reapplication led to a decrease in cumulative CO_2 emissions across all levels of N-fertilization. Similarly, Bovsun et al. (2021) observed a decrease in cumulative soil CO_2 emissions over a two-year experiment, with reductions of 28.2% and 57.7%, depending on the biochar application rate.

Soil temperature and moisture are the primary climatic factors influencing the decomposition of organic carbon and the subsequent release of greenhouse gases (Tang et al., 2016; Zhou et al., 2014; Zhang et al., 2015). Table 5 presents the relationship between soil CO_2 emissions, soil temperature, and soil water content (SWC). This study highlights the significant impact of temperature on soil CO_2 emissions. A statistically significant correlation (*p* <0.001) was observed between CO_2 emissions and soil temperature across all treatments and N-fertilization levels (0, 108, and 162 $kg.N.ha^{-1}$). In treatments without N-fertilization, a strong correlation was found (*p* <0.001; *R* = 0.87–0.91) in every treatment except B10N0, where the correlation was slightly weaker but still significant (*p* <0.01; *R* = 0.75). At the first level of N-fertilization, statistical significance varied (*p* <0.01, *p* <0.001), with the strongest correlation observed in the reapB20N1

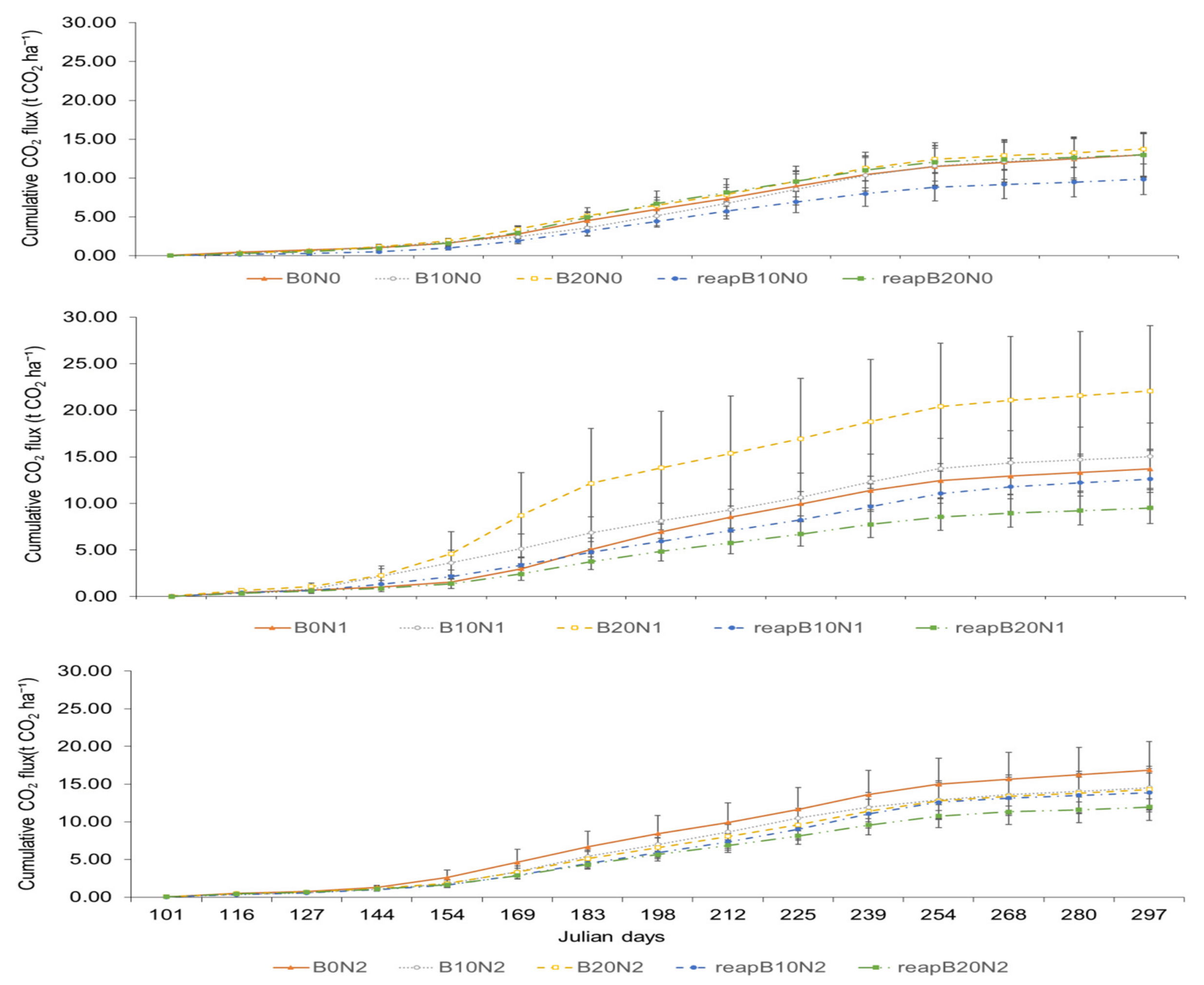

Figure 3 Cumulative CO_2 emissions ($t.ha^{-1}$)
Error bars indicate standard errors of the means (*n* = 3)

Table 5 Pearson correlation coefficient between soil CO_2 emissions and soil temperature and soil water content

Treatments	Soil temperature (°C)	SWC (% mass)
N0 level – unfertilized treatments (0 kg.N.ha^{-1})		
B0N0	0.90***	0.40
B10N0	0.75**	0.35
B20N0	0.90***	0.22
reapB10N0	0.87***	0.28
reapB20N0	0.91***	0.37
N1 level – fertilized treatments (108 kg.N.ha^{-1})		
B0N1	0.89***	0.53*
B10N1	0.76***	0.08
B20N1	0.73**	0.09
reapB10N1	0.83***	0.08
reapB20N1	0.95***	0.41
N2 level – fertilized treatments (162 kg.N.ha^{-1})		
B0N2	0.85***	0.34
B10N2	0.89***	0.38
B20N2	0.86***	0.28
reapB10N2	0.85***	0.32
reapB20N2	0.90***	0.39

* p <0.05; **p <0.01; ***p <0.001

treatment ($p < 0.001$; $R = 0.95$). In the second level of N-fertilization, all treatments showed a significant correlation between soil CO_2 emissions and temperature ($p < 0.001$; $R = 0.85–0.90$).

One possible explanation for the strong influence of temperature on CO_2 emissions is that large amounts of both easily and less-easily decomposable organic matter in the soil are rapidly broken down as temperatures rise, leading to increased CO_2 fluxes and cumulative emissions (Davidson & Janssens, 2006, Fang et al., 2005, Fierer et al., 2006, Knorr et al., 2005).

In contrast, the correlation between soil CO_2 emissions and SWC was generally not significant ($p > 0.05$), except for treatment B0N1 in the first level of N-fertilization, which showed a statistically significant correlation ($p < 0.05$; $R = 0.53$). A possible explanation for these differing effects of soil moisture is that while rhizosphere soil moisture (or water potential) may fluctuate significantly throughout the day – directly influencing CO_2 production and gas diffusion – depth-integrated soil moisture remains more stable and does not exert the same level of control on CO_2 emissions (Zhang et al., 2015).

4 Conclusions

This study demonstrates that biochar application and reapplication, in combination with N-fertilization, influence soil CO_2 emissions and soil physical properties. Biochar reapplication was particularly effective in reducing cumulative CO_2 emissions, while a single biochar application, especially at higher doses, led to mixed results. A significant correlation was observed between CO_2 emissions and soil temperature across all treatments, confirming temperature as a key driver of soil respiration. In contrast, SWC showed a generally weak correlation with CO_2 emissions, suggesting that its influence may depend on site-specific conditions. Our findings highlight the potential of biochar as a tool for climate change mitigation in agricultural systems. However, the effects of biochar on soil microbial activity, carbon stability, and nutrient dynamics require further investigation. Future studies should focus on long-term field experiments across diverse soil types and climatic conditions to better understand the broader implications of biochar application for soil health and carbon sequestration.

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