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Mitigation of Greenhouse Gas Emissions with Biochar Application in Compacted and Uncompacted Soil

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Abstract: Biochar may offer a substantial potential as a climate change mitigation and soil improvement agent; however, little is known about its effects in fertile soils subjected to standard agricultural practices. The aim of this short-term (60 days) lab experiment, under controlled temperature and soil moisture regimes, was to investigate the interaction between soil compaction and fertiliser and biochar addition in relatively fertile Luvisol. Three different biochar types and two soil compaction levels were investigated to describe their interactive effect on soil greenhouse gas emission (GHG). A very strong effect of soil compaction on N_2O emission (+280%) and an interaction with biochar were found. The cumulative N_2O emissions from the compacted soil were higher (from +70 to +371%, depending on the biochar type) than the uncompacted soil. Soil compaction resulted in a faster onset and a faster decrease of N_2O production. Biochar did not affect the temporal dynamics of N_2O evolution from either soil. The addition of digestate/crop biomass biochar has resulted in a significant increase in CO_2 evolution both in compacted and uncompacted soils, compared to softwood from spruce (mixture of branches and wood chips) and wood pallets from softwood (spruce without bark) biochar. In the compacted soil, NH_4^+ availability was positively related to N_2O efflux, and CO_2 emission was positively correlated to both NH_4^+ and SOC content. An increase in GHGs as a result of an increase in NH_4^+ availability was seen both in compacted and uncompacted soils, while the rates of N_2O emission were modified by biochar type. Our results show a strong interaction between biochar and soil conditions and a strong effect of biochar type on GHG emissions from agricultural soils.

Keywords: N_2O emissions; CO_2 emissions; biochar; soil compaction

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1. Introduction

Agricultural soils are one of the most important anthropogenic sources of GHG emissions to the atmosphere [1]. According to the IPCC [2], agriculture generates 11% of global GHG emissions due to soil and nutrient management and livestock farming. Modern agriculture is characterised by its reliance on mechanised agronomic operations and intensive soil management practices. Heavy vehicular traffic accompanying these operations increases the risk of soil compaction in arable soils [3–5], with a consequent change in GHG emissions [6]. At the same time, soil compaction is among the most significant drivers of soil degradation [3,5,7]. Soil compaction strongly affects soil properties; soil particles are pushed together at the expense of pores. Thus, compaction decreases total porosity [8], lowers macroporosity and connectivity between pores [9], and limits plant root growth [10], and soil microbial activity [11]. The degree of soil compaction in a specific soil is affected by its texture [3,7], humic substances content [12], and the presence of soil water [13,14].

Soil compaction is a global environmental problem; its negative impact on the food production capacity of the world's soils is especially prominent in arable soils [3,7] and in countries with mechanised agriculture [15]. In addition, several non-productive soil functions are also affected by its compaction. Modifying soil physical properties alters element mobility and changes nitrogen and carbon cycles, interfering with GHG emissions from soils, especially under wet conditions [3]. Hartmann et al. [16] reported that soil CO_2 efflux was reduced by soil compaction due to the reduction of carbon mineralisation in anaerobic conditions. On the other hand, limited soil aeration as a result of soil compaction decreases methanotrophic activity and enhances methanogenic activities [17].

Many strategies have been proposed and tested to avoid or alleviate soil compaction in agricultural fields [7]. An innovative solution that may concurrently reduce GHG emissions is the application of biochar. This could be especially effective in intensively managed soils with severe loss of organic carbon and where the mechanical working of the soil compromised soil structure. Biochar has various distinctive properties which potentially contribute to making it an effective, economic, and sustainable approach for soil carbon sequestration [18]. Biochar has already been identified as a potential agronomic tool for improving soil fertility [19–24], and at the same time it can reduce GHGs [25]. Biochar is often proposed as a useful GHG sequestration tool due to its recalcitrance [26]. Raw biochar has a proven ability to store carbon in the soil [27]. Enriched biochar [28] or biochar substrates [29,30] have been shown to increase it further. The application of biochar and enriched biochar reduced net nitrification by 81% and 94%, ammonification by 48% and 74%, and carbon dioxide by 50% and 92%, respectively, compared to control. Šimanský et al. [29] reported that in sandy soil, the biochar substrates at rate of 20 t ha^{-1} increased the sum of basic cations (by +112%) and CEC (by +93%) compared to the control.

Biochar is an organic material with a lower specific weight than soil, its application is thus likely to reduce the bulk density of the soil [22,31–33]. Several studies have shown a positive effect of biochar application on soil structure. Biochar is a porous material; its application increases the overall porosity of the soil [31]. This is likely to benefit crop growth [34,35]. Tying these observations together, biochar application to a compacted soil should increase its aeration and thus enhance aerobic microbial respiration. The balance of GHG emitted from the soil may thus shift as a result of biochar application, away from the products of anaerobic respiration and towards CO_2. Little information is available about this process, there is an indication that the biochar application rate, length, and time of residence in the soil may affect the outcome [36]; in combination with mineral fertilisers [37] or its activation during the production process [38].

This study aimed to evaluate the effects of two factors on GHG emissions from agricultural soil: biochar addition and soil compaction. Current literature indicates that biochar could counteract some of the negative effects of soil compaction. Specifically, we hypothesise that (H1) soil compaction lowers overall GHG emission (N_2O, CO_2) as a result of limiting gas flux through soil pores, (H2) biochar addition lowers GHG emissions by stabilising soil C and N compounds, and (H3) different types of biochar vary in their GHG mitigation potential.

2. Materials and Methods

2.1. Materials and Mesocosm Setup

The soil used in this laboratory experiment was collected in November 2020 from the plow layer of an agricultural field in Kostelec nad Ohří (50°23′ N and 14°05′ E), Czech Republic. The soil was collected from the 0–20 cm layer from a single location, it contained 20.5% of sand, 52.5% of silt, and 27% of clay and was classified as loamy Luvisol [39]. The soil had 12.1 g kg^{-1} of SOC on average, its pH (KCl) was 6.0, and the bulk density (BD) was 1.49 g cm^{-3}. The soil was homogenised, air-dried at 22 °C for 7 days, and finally sieved through a 10 mm sieve to remove larger debris and coarse materials to prepare the soil substrate for the experiment.

This study used three different biochars, pyrolyzed from different feedstocks by varying methodologies (Table 1). A mesocosm experiment was set up in a complete factorial design with 5 replicates per treatment for GHGs measurements and another set of 6 replicates per treatment for soil properties measurements. All treatments featured the addition of the equivalent of 70 kg N ha^{-1} to mimic typical arable farm soil management. Mesocosms were established by filling 1000 cm^3 polypropylene buckets (surface area: 70.9 cm^2, height: 14.3 cm) with 0.7 kg of dry soil. They were pre–incubated for 7 days until the initial flush of CO_2 flux decreased to the background level. After that, four soil treatments were established, one with N addition only (NPK 15:15:15) and three with the addition of N and a specific type of biochar (B1, B2, and B3) at the rate corresponding to 30 t ha^{-1}.

Table 1. Biochar feedstock, pyrolysis temperature, pyrolysis duration, and physicochemical properties of three biochars used in this study.

Biochar Types	B1	B2	B3
Feedstock	Softwood from spruce (mixture of branches and wood chips) made in kon-tiki kiln	Separate from the digestate (corn) 35%, cereal straw 35%, greenery 30%	Wood pallets from softwood (spruce without bark)
Pyrolysis temperature (°C)	600	460	500 and 750
Pyrolysis duration (min)	15	25	180–360
pH (H_2O)	9.7	9.8	11.4
C (%)	80	45	86.8
N (%)	0.3	1	0.58
P (g kg^{-1})	0.6	16	0.72
K (g kg^{-1})	2.4	17	3.59
Ca (g kg^{-1})	20.4	56.3	12.94
Mg (g kg^{-1})	1.3	6.6	2.43
specific surface area (SSA) (m^2 g^{-1})	301	120	444

Each set of treatments (set for GHGs measurements and set for soil properties measurements) was established twice to test compacted and uncompacted soil. In loamy soils such as those used here, optimal bulk density (BD) values range from 1.1 to 1.3 t m^{-3}. The critical BD value indicating soil compaction in loamy soils is 1.45 t m^{-3} [40]. At this BD, the physical condition deteriorates to such an extent that the growth of plant roots is limited, resulting in a reduction in crop yield. Correspondingly, the first series of mesocosms was set up to represent compacted soil as sampled in the field, with an average BD of 1.49 g $cm^{-3.}$ Adequate mass of soil was weighed into each mesocosm and then manually compacted to the required volume. The second series of mesocosms featured uncompacted soil at 1.02 g cm^{-3}, simulating uncompacted conditions after the tillage of the soil. Soil water content of 18% by weight was established to represent the mean water content in field conditions at the agricultural field in Kostelec nad Ohří during the vegetation period. Soil water content was adjusted gravimetrically after each air sampling event throughout the experiment.

2.2. Incubation Experiment and Soil Analysis

The 60-day incubation experiment was carried out at a constant room temperature of 22 °C, and all mesocosms were left open throughout the experiment and kept in the dark to prevent potential autotrophic C fixation. Half of the mesocosms were randomly allocated to the gas flux observations, while the other half were assigned to soil sampling. For the GHG emission mesocosms, the headspace of each bucket was hermetically closed during the time of observation by a polypropylene lid equipped with a rubber septum. Direct fluxes of N_2O and CO_2 from the soils were then measured by a variation of the closed chamber technique [41]. Air samples were taken four times during the first week, then two to three times a week for three weeks, and then once a week for four weeks. In total, there were 16 measurement episodes during the experiment. Mesocosm lids were closed for 30 min, and air samples from each mesocosm were collected using an air-tight syringe (Hamilton, Bellefonte, PA, USA) through the rubber septa. Air samples were immediately transferred to hermetically close pre-evacuated 10 mL glass vials (Labco Exetainer, Lampeter, UK). A gas chromatograph (Shimadzu GC-2010 Plus, Kyoto, Japan) was used, fitted with an electron capture detector (ECD) for N_2O and a thermal conductivity detector (TCD) for CO_2 analysis. The chromatograph was calibrated using three certified standard gas mixtures (N_2O, CO_2, and N_2) in the expected concentration range. Daily and cumulative N_2O and CO_2 fluxes were then calculated [42].

Samples were collected from the soil sampling mesocosms on the first day and then every 10–14 days throughout the experiment: 6 times throughout the experiment, each mesocosm was destructively sampled only once. We used a 2 cm diameter corer to take three subsample cores, these were mixed together to create a single composite sample per mesocosm. Samples were then analysed for soil mineral N (NO_3^-, NH_4^+) content, soil pH (KCl), and soil organic carbon (SOC). Inorganic forms of N (NH_4^+ and NO_3^-) was isolated in 1% K_2SO_4 as described by Yuen and Pollard [43] and determined using the calorimetric spectrometer method (WTW SPECTROFLEX 6100, Weilheim, Germany). The SOC was estimated by the Tyurin wet oxidation method using a mixture of 0.07 mol dm^{-3} of H_2SO_4 and $K_2Cr_2O_7$ with titration using 0.01 mol dm^{-3} of Mohr's salt [44]. Soil pH was measured potentiometrically in 1 mol dm^{-3} KCl (1 g soil to 2.5 mL KCl) using a pH meter (HI 2211, HANNA Instruments, Smithfield, RI, USA).

2.3. Statistical Analyses

A mesocosm was the unit of replication in this study; all observations carried out within a mesocosm were averaged to this level. GHG emission data were examined by fitting a series of models to the timeline of gas measurements and then choosing the best-fitting model (second-order polynomial, apart from cumulative N_2O data where exponential plateau was fitted). The cumulative totals of CO_2 and N_2O emissions were used to compare the treatments. A two-way ANOVA was performed where biochar type was nested within soil compaction. All data were tested for ANOVA assumptions (Levene and Shapiro–Wilk test), no correction was necessary. Where an overall significant effect of biochar or compaction was detected, a post-hoc pairwise comparison with Bonferroni correction was performed. Statistical significance of effects is reported at $p < 0.05$. Simple and multiple linear regression models were used to assess the contribution of selected soil parameters to GHG emissions. Mean values per treatment were used for each data point for gas and soil variables ($n = 24$), not allowing for comparison of biochar type.

3. Results

3.1. Effects of Soil Compaction and Biochar on N_2O Emission

We found a very strong positive effect of soil compaction on N_2O emission, as well as interaction with biochar. The cumulative N_2O emissions were about three times higher in the compacted soil than in the uncompacted soil ($p < 0.001$, Figure 1). Biochar addition did not have an overall effect on N_2O emission ($p = 0.317$). We saw a significant difference in the production of N_2O as a result of biochar type only in compacted soils ($p = 0.047$). Looking at the pairwise comparisons, we did not find any difference between the effects of biochar type on N_2O emissions.

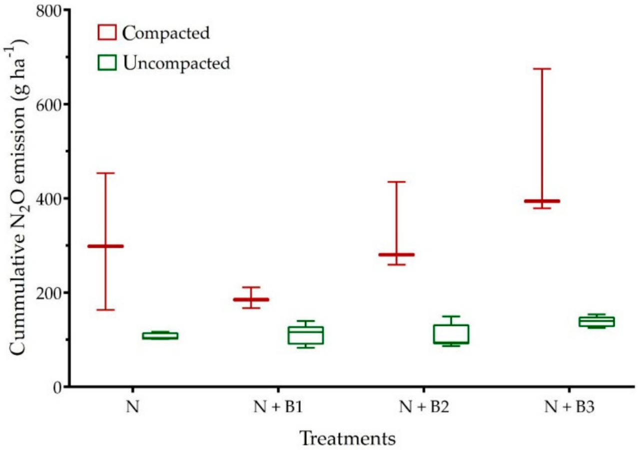

Figure 1. Cumulative N_2O emissions, box plots show median, percentiles, error bars confidence intervals. Soil addition treatments: N—nitrogen fertilisation, B1—softwood from spruce (mixture of branches and wood chips) biochar, B2—digestate biochar, and B3—wood pallets from softwood (spruce without bark) biochar.

Figure 2 shows the temporal dynamics of cumulative N_2O emissions over the observed period. As well as higher totals, the compacted soil is characterised by a faster onset and faster decrease of N_2O production. The evolution of N_2O reached 90% of its final value on day 16 of the experiment, whereas on average, it took 36 days to reach this threshold in the uncompacted soil. Interestingly, biochar did not affect the temporal dynamics of N_2O production from either soil compaction type.

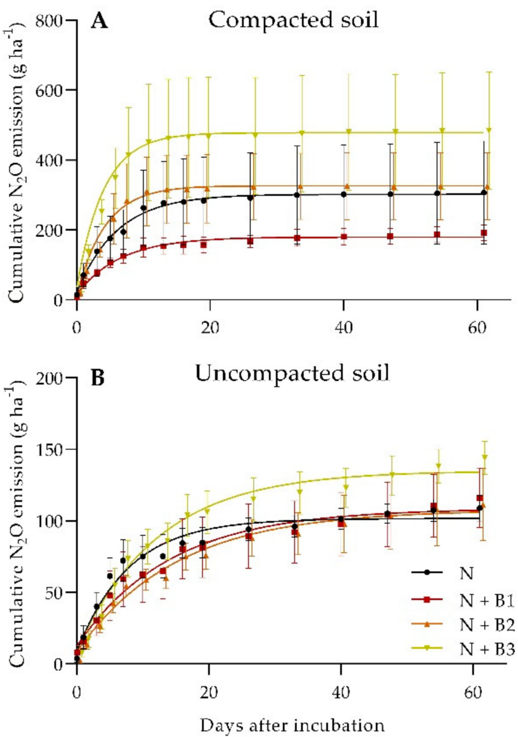

Figure 2. Timeline of cumulative N_2O emissions from compacted (**A**) and uncompacted (**B**) Luvisol. Soil addition treatments: N—nitrogen fertilisation, B1—softwood from spruce (mixture of branches and wood chips) biochar, B2—digestate biochar, and B3—wood pallets from softwood (spruce without bark) biochar.

3.2. Effects of Soil Compaction and Biochar on CO_2 Emission

In contrast to N_2O, we found a very strong effect of biochar type on CO_2 production. Adding N + B1 and N + B3 did not affect cumulative CO_2 production when compared to the no biochar treatment (N) in either compacted or uncompacted soil. Mixing N + B2 into the soil, however, has resulted in a significant increase of CO_2 evolution both in compacted ($p < 0.001$) and uncompacted ($p = 0.005$) soils (Figure 3). In compacted and uncompacted soil under N + B2 treatments, the overall cumulative increase in CO_2 was 233% and 40% higher than the N-only treatment. We also observed a significant effect of soil compaction ($p < 0.001$), in the uncompacted soil. All except the N + B2 treatment acted as a CO_2 sink very shortly after the start of the experiment. Interestingly, as can be seen in Figure 4, all treatments consumed CO_2 by the end of the experiment.

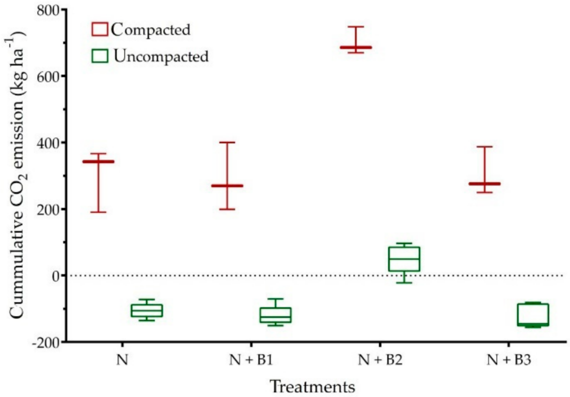

Figure 3. Cumulative CO_2 emissions, box plots show median, percentiles, error bars confidence intervals, from compacted and uncompacted Luvisol. Soil addition treatments: N—nitrogen fertilisation, B1—softwood from spruce (mixture of branches and wood chips) biochar, B2—digestate biochar, and B3—wood pallets from softwood (spruce without bark) biochar.

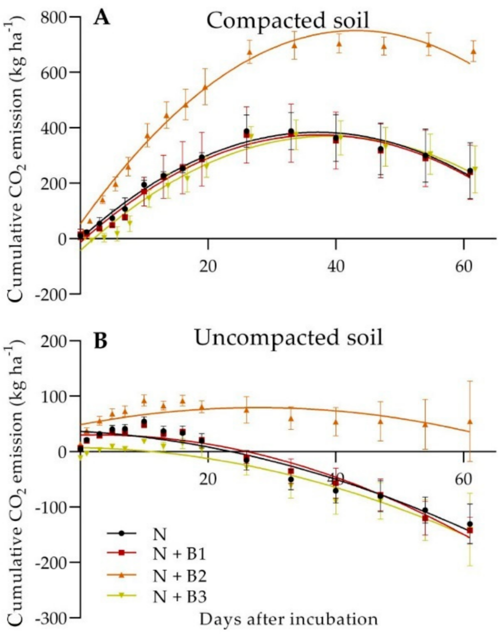

Figure 4. Timeline of cumulative CO_2 emissions from compacted (**A**) and uncompacted (**B**) Luvisol. Soil addition treatments: N—nitrogen fertilisation, B1—softwood from spruce (mixture of branches and wood chips) biochar, B2—digestate biochar, and B3—wood pallets from softwood (spruce without bark) biochar.

3.3. Relationships between Greenhouse Emissions and Soil Properties

We investigated the relationships between key soil parameters (pH, NH_4^+, NO_3^-, and SOC) and the emission of GHGs. Multiple regression models did not indicate any capacity of these four soil parameters to predict either N_2O or CO_2 emission from uncompacted soil (Tables 2 and 3). In compacted soil, on the other hand, we found that NH_4^+ availability had a positive relationship with N_2O efflux ($p < 0.05$). In addition, CO_2 emission from compacted soils was positively affected by both NH_4^+ and SOC ($p < 0.05$).

Table 2. Multiple regression models between key soil parameters and N_2O emissions in compacted and uncompacted Luvisol ($n = 24$).

	Regression Summary for Dependent Variable: N_2O											
	R = 0.067142835 R^2 = 0.45081603 Adjusted R^2 = 0.33519836 F (4.19) = 3.8992 $p < 0.01779$ Standard Error of Estimate: 5.8556						R = 0.55106459 R^2 = 0.30367218 Adjusted R^2 = 0.15707685 F (4.19) = 2.0715 $p < 0.12477$ Standard Error of Estimate: 20.492					
	Compacted						**Uncompacted**					
	b *	**Standard Error of b ***	**b**	**Standard Error of b**	**t (19)**	***p*-Value**	**b ***	**Standard Error of b ***	**b**	**Standard Error of b**	**t (19)**	***p*-Value**
Intercept			67.924	97.782	0.695	0.496			526.164	310.221	1.696	0.106
NH_4^+	**0.500**	**0.188**	**0.233**	**0.088**	2.662	0.015	0.247	0.217	0.275	0.240	1.142	0.268
NO_3^-	−0.055	0.196	−0.028	0.100	−0.278	0.784	−0.020	0.228	−0.079	0.878	−0.090	0.930
pH	−0.195	0.258	−11.072	14.702	−0.753	0.461	−0.431	0.275	−76.277	48.555	−1.571	0.133
SOC	0.486	0.258	0.269	0.143	1.881	0.075	0.009	0.263	0.012	0.340	0.034	0.973

NH_4^+—ammonium, NO_3^-—nitrate, pH—soil pH, SOC—soil organic carbon, **bold**—coefficient is statistically significant $p < 0.05$, *—regression through origin (assuming that intercept = 0).

Table 3. Multiple regression models between key soil parameters and CO_2 emissions in compacted and uncompacted Luvisol ($n = 24$).

	Regression Summary for Dependent Variable: CO_2											
	R = 0.71504881 R^2 = 0.51129480 Adjusted R^2 = 0.40840949 F (4.19) = 4.9696 $p < 0.00651$ Standard Error of Estimate: 8.2868						R = 0.41932597 R^2 = 0.17583427 Adjusted R^2 = 0.00232569 F (4.19) = 1.0134 $p < 0.42532$ Standard Error of Estimate: 28.129					
	Compacted						**Uncompacted**					
	b *	**Standard Error of b ***	**b**	**Standard Error of b**	**t (19)**	***p*-Value**	**b ***	**Standard Error of b***	**b**	**Standard Error of b**	**t (19)**	***p*-Value**
Intercept			117.905	138.380	0.852	0.405			64.161	425.829	0.151	0.882
NH_4^+	**0.452**	**0.177**	**0.316**	**0.124**	2.553	0.019	0.361	0.236	0.505	0.330	1.530	0.143
NO_3^-	−0.160	0.185	0.316	0.142	−0.864	0.399	−0.084	0.248	−0.408	1.205	−0.339	0.738
pH	−0.217	0.244	−0.123	20.806	−0.890	0.385	−0.040	0.299	−8.879	66.650	−0.133	0.895
SOC	**0.532**	**0.244**	**−18.518**	**0.203**	2.183	0.042	0.051	0.286	0.083	0.467	0.177	0.862

NH_4^+—ammonium, NO_3^-—nitrate, pH—soil pH, SOC—soil organic carbon, **bold**—coefficient is statistically significant $p < 0.05$, *—regression through origin (assuming that intercept = 0).

Simple linear relationships between CO_2, N_2O, and soil parameters were also constructed (Tables 4 and 5). The model fits between N_2O and soil properties were more accurate than in the case of CO_2. N_2O emissions were reduced by increasing soil pH. The intensity of the relationship was influenced by the type of biochar itself but also by soil compaction (Table 4). In all biochar treatments in compacted or uncompacted soils, N_2O emissions increased linearly as a result of increasing NH_4^+ in the soil. In uncompacted soil and in N + B1, N + B2, and N + B3 treatments, N_2O emission increased for each 1 g kg^{-1} NH_4^+ by 6.09, 3.05, and 3.71 mg kg^{-1} soil, respectively. In compacted soil, the same trend was observed, however, the rates of increase were significantly lower. CO_2 emissions increased due to increasing NH_4^+ content in both compacted and uncompacted soil (except

N + B3 in uncompacted soil) (Table 5). Interestingly, greater SOC as a result of biochar application did not affect either N_2O (except N + B2) or CO_2 emissions.

Table 4. Linear regression models between key soil parameters and N_2O emissions in compacted and uncompacted Luvisol.

Treatments	Linear Model	Trend	Probability	Linear Model	Trend	Probability
	Compacted			Uncompacted		
N	$N_2O = -0.00005$ soil pH + 6.59	n.d.	n.s.	$N_2O = -0.0156$ soil pH + 6.62	decrease	0.595 **
	$N_2O = 0.0316\ NO_3^- + 47.01$	n.d.	n.s.	$N_2O = 0.3011\ NO_3^- + 54.03$	n.d.	n.s.
	$N_2O = 0.0141\ NH_4^+ + 15.87$	n.d.	n.s.	$N_2O = 4.5145\ NH_4^+ + 17.76$	increase	0.644 **
	$N_2O = 0.006$ SOC + 14.44	n.d.	n.s.	$N_2O = -0.363$ SOC + 14.38	n.d.	n.s.
N + B1	$N_2O = -0.0077$ soil pH + 6.86	decrease	0.559 *	$N_2O = -0.0132$ soil pH + 6.88	decrease	0.664 **
	$N_2O = -0.726\ NO_3^- + 37.13$	n.d.	n.s.	$N_2O = -0.9659\ NO_3^- + 60.74$	decrease	0.575 **
	$N_2O = 2.3578\ NH_4^+ + 9.47$	increase	0.680 **	$N_2O = 6.0922\ NH_4^+ + 10.62$	increase	0.802 ***
	$N_2O = 0.3697$ SOC + 25.09	n.d.	n.s.	$N_2O = -0.5007$ SOC + 27.27	n.d.	n.s.
N + B2	$N_2O = -0.001$ soil pH + 6.84	n.d.	n.s.	$N_2O = -0.0057$ soil pH + 6.84	n.d.	n.s.
	$N_2O = -0.355\ NO_3^- + 56.66$	decrease	0.468 *	$N_2O = -0.3472\ NO_3^- + 56.72$	n.d.	n.s.
	$N_2O = 0.739\ NH_4^+ + 12.58$	increase	0.666 **	$N_2O = 3.0485\ NH_4^+ + 21.57$	increase	0.532 *
	$N_2O = -0.009$ SOC + 35.03	n.d.	n.s.	$N_2O = -3.6418$ SOC + 46.07	decrease	0.732 ***
N + B3	$N_2O = -0.0032$ soil pH + 6.89	decrease	0.723 ***	$N_2O = -0.0105$ soil pH + 6.90	decrease	0.495 *
	$N_2O = 0.1923\ NO_3^- + 22.84$	n.d.	n.s.	$N_2O = -1.2616\ NO_3^- + 57.92$	decrease	0.631 **
	$N_2O = 0.6088\ NH_4^+ + 8.77$	increase	0.672 **	$N_2O = 3.7047\ NH_4^+ + 17.68$	increase	0.630 **
	$N_2O = -0.1178$ SOC + 48.70	n.d.	n.s.	$N_2O = 0.4076$ SOC + 51.80	n.d.	n.s.

n.d.—non-detecated, n.s.—nonsignificant, * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; Soil addition treatments: N—nitrogen fertilisation, B1—softwood from spruce (mixture of branches and wood chips) biochar, B2—digestate biochar, and B3—wood pallets from softwood (spruce without bark) biochar.

Table 5. Simple regression models between key soil parameters and CO_2 emissions.

Treatments	Linear Model	Trend	Probability	Linear Model	Trend	Probability
	Compacted			Uncompacted		
N	$CO_2 = -0.0015$ soil pH + 6.59	decrease	0.558 *	$CO_2 = -0.0007$ soil pH + 6.59	n.d.	n.s.
	$CO_2 = -0.103\ NO_3^- + 47.45$	n.d.	n.s.	$CO_2 = 0.1209\ NO_3^- + 54.71$	n.d.	n.s.
	$CO_2 = 0.2429\ NH_4^+ + 17.26$	n.d.	n.s.	$CO_2 = 2.1865\ NH_4^+ + 28.23$	increase	0.684 **
	$CO_2 = -0.0033$ SOC + 14.59	n.d.	n.s.	$CO_2 = -0.0893$ SOC + 13.60	n.d.	n.s.
N + B1	$CO_2 = -0.0003$ soil pH + 6.84	n.d.	n.s.	$CO_2 = -0.0033$ soil pH + 6.85	n.d.	n.s.
	$CO_2 = -0.2583\ NO_3^- + 33.81$	decrease	0.699 **	$CO_2 = 0.0522\ NO_3^- + 58.18$	n.d.	n.s.
	$CO_2 = 0.2756\ NH_4^+ + 17.91$	increase	0.531 *	$CO_2 = 1.7288\ NH_4^+ + 26.58$	increase	0.550 *
	$CO_2 = -0.0028$ SOC + 26.22	n.d.	n.s.	$CO_2 = -0.0606$ SOC + 25.95	n.d.	n.s.
N + B2	$CO_2 = -0.0004$ soil pH + 6.83	n.d.	n.s.	$CO_2 = 0.0006$ soil pH + 6.83	n.d.	n.s.
	$CO_2 = -0.1026\ NO_3^- + 54.27$	n.d.	n.s.	$CO_2 = -0.2835\ NO_3^- + 57.37$	decrease	0.470 *
	$CO_2 = 0.2464\ NH_4^+ + 17.42$	increase	0.510 *	$CO_2 = 0.6126\ NH_4^+ + 23.76$	increase	0.494 *
	$CO_2 = 0.0563$ SOC + 34.75	n.d.	n.s.	$CO_2 = -0.129$ SOC + 40.92	n.d.	n.s.
N + B3	$CO_2 = 0.0003$ soil pH + 6.86	n.d.	n.s.	$CO_2 = 0.0044$ soil pH + 6.87	n.d.	n.s.
	$CO_2 = -0.0953\ NO_3^- + 24.66$	n.d.	n.s.	$CO_2 = 0.2228\ NO_3^- + 54.41$	n.d.	n.s.
	$CO_2 = 0.1356\ NH_4^+ + 16.71$	n.d.	n.s.	$CO_2 = -2.2031\ NH_4^+ + 20.93$	n.d.	0.808 ***
	$CO_2 = 0.045$ SOC + 47.52	n.d.	n.s.	$CO_2 = -0.6719$ SOC + 50.20	n.d.	n.s.

n.d.—non-detecated, n.s.—nonsignificant, * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; Soil addition treatments: N—nitrogen fertilisation, B1—softwood from spruce (mixture of branches and wood chips) biochar, B2—digestate biochar, and B3—wood pallets from softwood (spruce without bark) biochar.

4. Discussion

4.1. Soil Compaction, Biochar Addition, and GHG Emission

Soil compaction alters soil structure and hydrology, chiefly by changing the physical arrangement of soil aggregates. In turn, alteration of soil physics in arable soil influences root and shoot growth and consequently crop production [7]. If soil properties change as a result of the compaction, the flux of GHGs is likely to change; the suggestion is confirmed by our results (Figures 1 and 3). Changes in GHG production and efflux are linked to changes in soil structure and physical properties [45]. Clearly a negative factor, soil compaction can be reduced mechanically or through the addition of manures and various organic additives such as biochar. Organic material particles typically are less dense than compacted mineral soil, and their application to the soil reduces the bulk density of the soil [31–33,46]. Organic material also supports the formation of the soil structure and increase of the porosity [34,47]. Tullberg et al. [48] reported that soil compaction affects GHG emissions, N_2O production in compacted soil was increased by 30–50% compared to uncompacted soil. In our case, the average cumulative production of N_2O was increased by 70–371% as a result of compaction (Figures 1 and 2). Our results also show that the application of different types of biochar affects the production of GHGs to a varying degree. The onset and the subsequent dynamics of GHG emission depend on the availability of more easily degradable organic substances in the soil–biochar complex [49,50]. The porosity of biochar itself and its ability to form soil aggregates and pores [33,34] can support aeration, which reduces N_2O production through nitrification [51]. Biochar can reduce the emission of N_2O from the soil into the atmosphere via adsorption of NH_3 [26] and decrease the inorganic N pool by enhancing the activity of nitrifiers [52]. On the other hand, if the soil is saturated with water, the soil pores and the pores of biochar itself (biochar is not part of soil aggregates), are filled with water, and an anaerobic environment is created. Such conditions typically lead to increased denitrification and subsequent N_2O emissions [48]. Biochar properties affect its interaction with the soil and affect the GHG balance of the system [53]. For example, higher pyrolysis temperatures contribute to incorporating C and N into aromatic and heterocyclic rings and reducing mineralisation, and thus their availability once applied to the soil [54]. Conversely, a final product of pyrolisation conducted at a lower temperature is characterised by higher mineralisation in the soil [55].

In the case of CO_2 emissions, soil quality seems to be one of the most fundamental factors: more fertile and healthier soils seem better at C sequestration than their less productive counterparts [56]. Healthier, more productive soil is typically richer in stable SOM, which is less prone to oxidation and contributes to the chemical bonding capacity of the soil. This observation is likely is confirmed by our findings in uncompacted soil (Figure 4). We used Luvisol, which usually denotes a highly fertile but very intensively used soil, subjected to extensive cultivation, fertilization, or liming [57]. As suggested by our results, an important factor influencing GHG emission could be the interaction between compaction and the type of biochar. Biochar surface contains functional groups which favour the adsorption of simple dissolved organic compounds and NH_4^+ ions, thus providing a suitable microbial habitat [58]. The CO_2 flux showed a decreasing trend in all soils, but especially so in uncompacted soil (Figure 4). This is usually attributed to decreasing substrate accessibility to microorganisms [59,60]. Here, biochar may stimulate microbial activity by providing a steady supply of organic compounds and nutrients. For example, biochar B2 was produced from 35% corn digestate residues, 35% cereal straw, and 30% green compost at lower temperatures compared to B1 and B3. B2 was also characterised by the highest macronutrients content, the narrowest C:N ratio, and the lowest specific surface area. The stimulating effect of B2 addition on microbe respiration and subsequent CO_2 emission was very clear in our study. Faster mineralisation of biochar was observed when it was produced at lower pyrolysis temperatures from grass biomass [55], whereas biochar produced at higher temperatures from wood materials had lower mineralisation rate [61]. Finally, we observed negative CO_2 emissions in our mesocosms. The growth of soil algae can sequester CO_2 from the atmosphere, we did not observe algal growth in our mesocosms, however this process cannot be entirely ruled out. The other likely process driving CO_2 sequestration in the soil in our mesocosms is the dissolution of CO_2 in deionised soil water used to maintain stable soil moisture [60].

4.2. Relationships between Greenhouse Emissions and Soil Properties

It is evident from our observations that finding a uniform mechanism affecting GHGs in soils at different levels of compaction and after the application of different types of biochar is not straightforward. Multiple regression models did not indicate any capacity of soil pH, NO_3^-, NH_4^+, and SOC to predict N_2O or CO_2 emission from uncompacted soil. On the other hand, in compacted soil, NH_4^+ had a positive relationship with N_2O, while CO_2 emission was positively affected by both NH_4^+ and SOC. An increase in CO_2 emissions as a result of increasing NH_4^+ in the soil was confirmed by our linear model in both compacted and uncompacted soil, while the rates of N_2O emissions efflux depend on biochar type. Observations published by Balashov [62] suggest that a very strong factor influencing GHG emissions is the filling of soil pores with water forcing a switch between anaerobic and aerobic conditions in soils. Horák et al. [63] stated that the soil pH, but also the NH_4^+ content, have a major effect on increasing N_2O emissions in particular since soil pH exerts control over the N_2O:N_2 ratio during denitrification [64] which was partially confirmed in a few treatments (Tables 2 and 3).

5. Conclusions

Our results suggest that some biochar types offer the promise of mitigating GHG emissions from agricultural soils, however, the effects can be different in compacted and uncompacted soils. None of the biochar types tested in this experiment affected N_2O emissions in either compacted or uncompacted soils. Soil compaction significantly enhanced both N_2O and CO_2 emission from Luvisol used in this experiment. In addition, biochar produced from a combination of digestate and crop biomass strongly increased CO_2 production in both compacted and uncompacted soils. Clearly, more research into the interactive effects of biochar and soil properties on GHG emissions must be conducted before the GHG benefits of large-scale application of biochar to arable soils can be recommended.

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