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# The effect of biochar addition on $N_2O$ and $CO_2$ emissions from a sandy loam soil – The role of soil aeration

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ABSTRACT

Biochar application to soil has significant potential as a climate change mitigation strategy, due to its recalcitrant C content and observed effect to suppress soil greenhouse gas emissions such as nitrous oxide ($N_2O$). Increased soil aeration following biochar amendment may contribute to this suppression.

Soil cores from a *Miscanthus X. giganteus* plantation were amended with hardwood biochar at a rate of 2% dry soil weight (22 t $ha^{-1}$). The cores were incubated at three different temperatures (4, 10 and 16 °C) for 126 days, maintained field moist and half subjected to periodic wetting events. Cumulative $N_2O$ production was consistently suppressed by at least 49% with biochar amendment within 48 h of wetting at 10 and 16 °C. We concluded that hardwood biochar suppressed soil $N_2O$ emissions following wetting at a range of field-relevant temperatures over four months. We hypothesised that this was due to biochar increasing soil aeration at relatively high moisture contents by increasing the water holding capacity (WHC) of the soil; however, this hypothesis was rejected.

We found that 5% and 10% biochar amendment increased soil WHC. Also, 10% biochar amendment decreased bulk density of the soil. Sealed incubations were performed with biochar added at 0–10 % of dry soil weight and wetted to a uniform 87% WHC (78% WFPS). Cumulative $N_2O$ production within 60 h of wetting was 19, 19, 73 and 98% lower than the biochar-free control in the 1, 2, 5 and 10% biochar treatments respectively. We conclude that high levels of biochar amendment may change soil physical properties, but that the enhancement of soil aeration by biochar incorporation makes only a minimal contribution to the suppression of $N_2O$ emissions from a sandy loam soil. We suggest that microbial or physical immobilisation of $NO_3^-$ in soil following biochar addition may significantly contribute to the suppression of soil $N_2O$ emissions.



## 1. Introduction

### 1.1. Greenhouse gas emissions from soils

Nitrous oxide ($N_2O$) is a greenhouse gas of high importance, with emissions accounting for approximately 6% of total anthropogenic radiative forcing (Davidson, 2009). Agriculture accounts for 58% of anthropogenic emissions of $N_2O$ (Solomon et al., 2007). A large proportion of $N_2O$ from agriculture comes from the inefficient use of N-based fertiliser, particularly from incomplete denitrification in wet or saturated soils (Davidson, 2009).

$N_2O$ is produced in soils primarily via microbial activity through nitrification (Khalil et al., 2004), nitrifier denitrification (Wrage et al., 2005) and denitrification (Gillam et al., 2008). At high moisture contents, $N_2O$ production from denitrification is thought to be the dominant source (Bateman and Baggs, 2005). Denitrification is known to be strongly affected by soil temperature, nitrate ($NO_3^-$) content, organic matter availability and lability, redox potential and pH (Hofstra and Bouwman, 2005).

Both nitrification and denitrification are highly moisture sensitive, as increased moisture content reduces oxygen availability to soil microorganisms (Barnard et al., 2005; Gillam et al., 2008). Across soil types, nitrifier activity peaks at around 60% of water holding capacity (WHC) and decreases above this when oxygen becomes more limiting. Denitrifier activity increases above 70% WHC (Linn and Doran, 1984). Considering instead a measure of soil aeration – water filled pore space (WFPS) – nitrifier activity has been found to peak at 60% WFPS and denitrifier activity increases above 70% WFPS (Bateman and Baggs, 2005). In soils approaching fully waterlogged conditions (and thus fully anoxic conditions) complete denitrification to $N_2$ may occur resulting in decreased

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$N_2O$ emissions (Firestone and Davidson, 1989; Clough and Condron, 2010). $N_2O$ production from soils can also be highly sensitive to intermittent wetting; $N_2O$ emissions are generally enhanced for several days following wetting in both laboratory and field conditions (Skiba et al., 1996; Dobbie and Smith, 2001; Khalil and Baggs, 2005; Sänger et al., 2010).

### 1.2. Biochar

Biochar is created by heating biomass (generally between 350 and 600 °C) in an oxygen-limited environment, a process called pyrolysis (Sohi et al., 2010). Its physical and chemical properties are similar to charcoal, typified by its relatively high C content, low nutrient content, high surface area and cation exchange capacity compared to unheated biomass (Singh et al., 2010a). Previous studies have focused on the range of effects that biochar can have on soil condition (Novak et al., 2009), crop yield (Laird et al., 2010), uptake of nutrients or contaminants (Cao et al., 2009; Steiner et al., 2010) and soil greenhouse gas emissions (Spokas and Reicosky, 2009).

Suppression of $N_2O$ emissions following the wetting of biochar amended soil has been observed both under laboratory conditions (Yanai et al., 2007; Spokas and Reicosky, 2009; Singh et al., 2010b) and in the field (Zhang et al., 2010; Wang et al., 2011). $N_2O$ emissions have also been suppressed following the addition of urine to biochar amended soils (van Zwieten et al., 2010; Taghizadeh-Toosi et al., 2011). However, there are studies where biochar did not significantly affect soil $N_2O$ emissions in the field (Scheer et al., 2011) and following urine addition in the lab (Clough et al., 2010).

Soil $N_2O$ emissions increase with temperature (Bouwman et al., 2002). Previously, laboratory experiments investigating $N_2O$ emissions from biochar amended soils have incubated soils kept at a single temperature (~20 °C, Yanai et al., 2007; Singh et al., 2010b; van Zwieten et al., 2010). In this paper we investigate the effect of biochar on soil $N_2O$ emissions at several temperatures relevant to field conditions.

Enhanced soil aeration (Yanai et al., 2007; van Zwieten et al., 2010), sorption of $NH_4^+$ or $NO_3^-$ by biochar (Singh et al., 2010b; van Zwieten et al., 2010) and the presence of inhibitory compounds such as ethylene (Spokas et al., 2010) have all been suggested as mechanisms to explain the suppression of $N_2O$ emissions with biochar addition. In this paper we focus on soil aeration.

Biochar has been observed to affect soil physical properties. With biochar amendment, a field study observed an increase in saturated hydraulic conductivity (Asai et al., 2009); while a pot study observed reduced tensile strength and increased field capacity (Chan et al., 2007). By changing physical properties of the soil, biochar may suppress $N_2O$ production from denitrification by increasing the air content of the soil (van Zwieten et al., 2010) or by absorbing water from the soil, thus improving aeration of the soil (Yanai et al., 2007). We aimed to investigate the little-understood interaction between biochar amendment to soil, changes in soil physical properties (WHC, bulk density and related WFPS) that are linked to increased soil aeration and soil $N_2O$ emissions. To do so we conducted two laboratory studies with the following aims.

### 1.3. Aims

The aim of experiment 1 was to elucidate any differences in $N_2O$ production from an agricultural soil, with and without biochar amendment, under a range of field-relevant temperatures and subjected to wetting/drying cycles. We hypothesised that biochar amendment would suppress soil $N_2O$ production following wetting at all temperatures. We also hypothesised that this effect would not be seen under field moist conditions, as $N_2O$ production would be too low to observe significant differences between control and biochar amended soil.

The aim of experiment 2 was to investigate the mechanism(s) behind observed differences in $N_2O$ production with and without biochar. We hypothesised that previously observed suppression of $N_2O$ production was due to biochar increasing soil aeration. By maintaining uniform WHC across several biochar amendment levels (0–10 %), we would cancel out the effect of increasing soil aeration with biochar addition. Therefore, $N_2O$ production would remain constant with increasing biochar content.

## 2. Materials and methods

### 2.1. Soil and biochar

Bare soil was collected from a Miscanthus (*Miscanthus X giganteus*, a species of elephant grass) field close to Lincoln, Lincolnshire, UK (planted in 2007). The soil is a dense, compacted sandy loam with 53% sand, 32% silt and 15% clay, a bulk density of $1.68 \pm 0.03$ g cm$^{-3}$ ($n = 3$), a low total C ($14.7 \pm 0.2$ g kg$^{-1}$, $n = 105$) and total N content ($2.70 \pm 0.10$ g kg$^{-1}$, $n = 105$), and low extractable inorganic-N content ($NH_4^+$–N: $0.6 \pm 0.10$ mg kg$^{-1}$, $n = 18$, $NO_3^-$–N: $1.8 \pm 0.35$ mg kg$^{-1}$, $n = 18$). The crop received an application of 500 kg ha$^{-1}$ PK fertiliser in March 2010 (Fibrophos, UK).

The biochar was produced from thinnings of hardwood trees (oak, cherry and ash greater than 50 mm in diameter, Bodfari Charcoal, UK). The feedstock was heated in a ring kiln, first to 180 °C to allow the release of volatile gases, and then to approximately 400 °C for 24 h. After sieving and homogenisation, the fresh biochar had a particle size of <2 mm, a gravimetric moisture content (GMC) of <5%, a bulk density of 0.24 g cm$^{-3}$ ($n = 1$), a total C content of 723 g kg$^{-1}$ ± 15.1 ($n = 3$), a total N content of 7.12 g kg$^{-1}$ ± 0.10 ($n = 3$), an extractable $NH_4^+$ and $NO_3^-$ content below detectable limits (<1 mg kg$^{-1}$ $NH_4^+$–N and $NO_3^-$–N < 1.3 mg kg$^{-1}$, $n = 3$), a pH of $9.25 \pm 0.04$ ($n = 4$, see Section 2.2.1 for description of methods) and a cation exchange capacity (CEC, analysed by ICP-OES) of 145 cmol$^+$ kg$^{-1}$ ($n = 1$). Further biochar properties such as exchangeable cations, heavy metal content, polyaromatic hydrocarbon (PAH) content and Benzene, Ethylbenzene, Toluene and Xylene (BETX) content are available in Supplementary information. Metal contents (As, Cd, Ni, Pb, Zn, Hg, Cr) were analysed using ICP-OES. BETX were analysed by HS–GC–MS and PAHs (USEPA 16) were analysed by GC–MS.

### 2.2. Experiment 1: soil cores undergoing wetting/drying cycles

We assessed the effect of biochar addition on soil $N_2O$ emissions with a fully-factorial experiment ($n = 4$) at three incubation temperatures (4, 10 and 16 °C) and two moisture conditions (field moist, 23% GMC and wetted, 28% GMC). Environmental conditions were selected based on monthly temperature and moisture sampling at the field site taken over one year from 2008 to 2009 (data not shown).

Soil cores were collected in March 2010. PVC pipes (W 102 mm, H 215 mm) were inserted to a depth between 150 and 180 mm (~2 kg dry soil wt.). Soil cores were stored at 4 °C for four weeks prior to biochar addition. Biochar (<2 mm) was added to half of the cores, mixed into the top 7 cm of soil at a rate of 2% dry soil weight (~22 t ha$^{-1}$). Control cores without biochar were also mixed in a similar fashion. Mixed soil bulk density was determined ($1.00 \pm 0.01$ g cm$^{-3}$, $n = 42$) following Emmett et al. (2008). The WFPS in the field moist and wetted treatments ($37 \pm 1\%$, $n = 24$ and $45 \pm 1\%$, $n = 19$ respectively, assuming uniform distribution of applied water throughout soil core) was calculated assuming