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Biochar, hydrochar and uncarbonized feedstock application to permanent grassland—Effects on greenhouse gas emissions and plant growth

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ABSTRACT

Both reductions of greenhouse gas emissions and carbon sequestration have the potential to reduce global climate warming and avoid dangerous climate change. We assessed the sequestration potential as well as possible risks and benefits of carbon amendments (16 ± 4% of soil organic C) from *Miscanthus* × *giganteus* in different carbonization stages of a temperate grassland soil together with pig slurry: (1) untreated dried biomass (feedstock), (2) hydrothermally carbonized biomass (hydrochar) and (3) pyrolyzed biomass (biochar) in comparison to a control (only pig slurry application).

The field study was complemented by a laboratory incubation study, followed by a growth experiment with *Lolium perenne*. In the field, greenhouse gas emissions (CO_2, N_2O, and CH_4) were monitored weekly over 1.5 years and over three months in the lab. Initial nitrogen losses via ammonia emissions after substrate–slurry application were assessed in an additional greenhouse study.

We found that biochar reduced soil and ecosystem respiration in incubation and in the field, respectively. Additionally, biochar improved methane oxidation, though restricted by emissions outbursts due to slurry amendment. It also reduced N_2O emissions significantly in the lab study but not in the field. Hydrochar and feedstock proved to be easily degradable in incubation, but had no effect on ecosystem respiration in the field. Feedstock amendment significantly increased N_2O emissions in incubation and one year after application likewise in the field. In a growth experiment subsequent to the incubation, only biochar amendment increased *L. perenne* biomass (+29%) significantly, likely due to N retention. In the field, biochar caused a significant shift in the plant species composition from grasses to forbs, whereas hydrochar significantly reduced yields within two growth periods (2011 and 2012). Ammonia emissions were significantly higher with feedstock and biochar compared to the control or acidic hydrochar. The overall results indicate that biochar is better suited for C sequestration and GHG mitigation in grasslands than hydrochar or the uncarbonized feedstock. However, NH_3 emission reductions may only occur when the biochar is neutral or slightly acidic.

1. Introduction

Biochar, an organic carbon soil amendment, has great potential to alleviate the CO_2 accumulated in the atmosphere by sequestration of recalcitrant carbon into the soil (Lehmann, 2007; Glaser et al., 2009). Such a biological sequestration of CO_2 would be cost-effective (Blair et al., 2006) and serve as a fast action strategy for climate change mitigation (Molina et al., 2009). Positive effects of biochar amendments on crop yields (Jeffery et al., 2011; Biederman and Harpole, 2013) would provide an additional incentive for its agricultural use. However, before using biochar as a carbon sink and environmental management tool, it must be proven that it remains stable after soil application and that such application does not create adverse effects, e.g. increased greenhouse gas emissions (GHG). Greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), increase the radiative forcing of

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the Earthsí atmosphere (Houghton et al., 1997) by contributing to ozone depletion (N_2O) (Ravishankara et al., 2009) and by interaction with aerosols (CH_4) (Shindell et al., 2009). Possible positive feedback effects of biochar or biochar–slurry mixtures on GHG emissions would be detrimental for the field use of biochar as a carbon sequestration tool. To date, the effects of biochar on GHG emissions are rather diverse. They depend on the biochar production process parameters, the feedstock used, the ecosystem and soil properties to which biochar is applied, and the strategy of application and (agricultural) management.

Biochar could be beneficial as a soil conditioner in degraded or naturally poor soils by improving nutrient availability and mycorrhiza abundance (Chan et al., 2008; Alvum-Toll et al., 2011). Although it might not be needed as a soil conditioner in fertile temperate soils, an increment of the grassland carbon stocks by carbon amendment may act as carbon sink due to long C turnover times (Scurlock and Hall, 1998). Biochar use in grasslands may even be based on ancient soil types in temperate climates, i.e. chernozems, of which some are assumed to have developed under grassland (steppe) vegetation (Eckmeier et al., 2007). For anthropogenically used grasslands, which are typically used for livestock breeding with considerable amounts of manure and urine accumulation, positive biochar–slurry interactions may offer new ways for reducing GHG emissions (Winsley, 2007). Indeed, Bruun et al. (2011) showed in an incubation study that the addition of 3% fast pyrolysis biochar on a mass basis reduced CO_2 and N_2O emissions from a slurry amended soil significantly. Biochar and slurry can also reduce the wind erosion of biochar during application and alleviate the odor of the slurry (Blackwell et al., 2009). However, the promising idea of charging biochar with the nutrients contained in the slurry still has to be proven effective. Experiments with biochar and slurry showed that biochar can bind ammonia by surface interactions (Spokas et al., 2012). Furthermore, biochar reduced NO_3 and total N leaching from manure-amended soil significantly (Laird et al., 2010; Ventura et al., 2013), with subsequent positive effects on plant-available nitrogen and thus plant growth. Concerning the N-efficiency of ecosystems, ammonia and denitrificatory N losses (including N_2O emissions) are very important factors, as well as losses of NO_3—N by leaching, the main pathways for losses of N from an ecosystem. NH_3 losses from grasslands can account for up to 28% (grazed pasture) or 27% (grassland fertilized with pig slurry) of the annual N input (Ball and Keeney, 1981; Pain et al., 1989), depending on farm management practices. N_2O emissions can add up to 2–2.2% total N loss of added fertilizer of a grassland ecosystem (Velthof et al., 1996; Clayton et al., 1997).

However, results of biochar effects on ecosystems in temperate climates are still scarce, and the interactions of different biochar–slurry mixtures in the field still have to be elucidated. Consequently, the background of this study was to assess possible risks and chances of carbon amendment co-applied with slurry to a temperate grassland site with a focus on GHG- and ammonia emissions. We hypothesized that, first, the materials would degrade in the sequence of their carbonization grade: feedstock > hydrochar > biochar and that degradation would be measurable in the ecosystem respiration. To assess possible priming effects of biochar on hydrochar or vice versa, we introduced a mixed treatment in the incubation study. Second, we hypothesized that biomass growth will be negatively impacted by hydrochar application, as reported by others who found negative effects on plant germination and growth with hydrochar use in soils (Bargmann et al., 2012; Gajić and Koch, 2012). Third, that biochar will reduce N_2O and CO_2 emissions (Augustenborg et al., 2012; Case et al., 2012; Dempster et al., 2012), improve CH_4 oxidation (Karhu et al., 2011; Liu et al., 2011), and that hydrochar will have rather adverse effects on the GHG balance (Kammann et al., 2012), as shown by incubation studies so far.

2. Material and methods

2.1. Laboratory incubation

A laboratory study was carried out with the same parameters as the field experiment but under controlled conditions. Soil for incubation was taken from the top 15 cm of the experimental field site prior to initiation of the field experiment. The grassland site in Linden, near Giessen, Germany (50°32′N und 8°41.3′E) has been managed extensively for decades as grassland with two cuts per year (Jäger et al., 2003). The soil, a haplic stagnosol (WRB, 2006), has a soil texture of 25% sand, 28% clay, 47% silt and a pH of 5.8–6.0. For the incubation study, 500 g of the field-fresh soil (or 373 g of dry soil) with 3.6% total organic carbon (TOC, see Table 1) was mixed with carbon substrates. All carbon amendments originated from *Miscanthus* × *giganteus* and were applied non-carbonized (feedstock), hydrothermally carbonized in a steam atmosphere (hydrochar) or pyrolyzed (biochar). *Miscanthus* straw had been harvested in winter 2009, when all aboveground plant material had receded. The hydrothermal carbonization was produced by keeping the feedstock in a water vapor atmosphere for 2 h at a temperature of 200 ± 3 °C under a pressure of 1.6 MPa (Revatec, Geeste, Germany, at that time Hydrocarb GmbH, Ohmes, Germany).

Biochar was produced using a pyrolysis unit with a continuous flow reactor at 550–600 °C (Pyreg GmbH, Bingen). Soil and substrate characterization parameters are given in Table 1.

All materials were ground to <10 mm before admixture with the soil (SM 300, Retsch GmbH, Haan, Germany). The amount of the substrates applied to the incubation jars and the field was equivalent to an increase of the soil organic carbon (SOC) content (3.5%) of 16 ± 4%, with total amounts of 16 t ha^{-1} feedstock application, 14.5 t ha^{-1} hydrochar application and 9.3 t ha^{-1} biochar application, respectively.

In the incubation, we introduced a new treatment where biochar was mixed with hydrochar in equal shares, depending on the C content from each source. The soil–substrate mixtures (n = 4 per treatment) were placed in 1100 ml incubation jars (WECK GmbH u. Co. KG, Wehr, Germany) and incubated in the lab at 21 ± 1 °C for 125 days. Soil moisture was controlled gravimetrically by adjusting it weekly to the initial field-fresh soil conditions at the start (WHC 31–37%); soil moisture raised to WHC 38–46% with slurry addition, depending on the treatment. WHC_{max} was determined following the DIN ISO 11274 guideline with slight modifications due to the increased soil sorptive capacity after biochar application. In brief, field fresh soil was mixed with the

Table 1
Key characteristics of the soil and C-substrates used.

	pH (H_2O)	C [%]	N [%]	Ash content [%]	C/N ratio	O/C ratio	H/C ratio	BET surface area [m^2 g^{-1}]	P-content [mg kg^{-1}]	Liming equivalence [%$CaCO_3$]
Soil	5.8	3.5 ± 0.01	0.33 ± 0.01	n.d.	10.6	n.d.	n.d.	n.d.	n.d.	n.d.
Feedstock	6.8	47.94 ± 0.41	0.12 ± 0.02	2.04 ± 0.69	399.5	0.71	1.56	1.1	n.d.	−1.02
Hydrochar	5.1	50.47 ± 1.04	0.19 ± 0.02	3.13 ± 0.63	265.6	0.55	1.28	3.5	0.44	−2.77
Biochar	10.1	60.8 ± 14.54	0.4 ± 0.09	34.93 ± 15.17	152.0	0.07	0.11	864.2	2.98	0.21

Numbers behind plus minus signs represent the standard deviation (n = 3 for feedstock and hydrochar, n = 30 for biochar).