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Impact of pine chip biochar on trace greenhouse gas emissions and soil nutrient dynamics in an annual ryegrass system in California

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ABSTRACT

Manure generated by dairy cattle is a useful soil amendment but contributes to greenhouse gas (GHG) emissions and water pollution from nutrient leaching. In order to assess the impact of pine chip biochar produced at a peak temperature of 550 °C when added to a dairy grassland system, a one-year field study was conducted on a sandy loam soil under annual ryegrass (*Lolium multiflorum Lam.*) grown for silage in Petaluma, California. Manure was applied to all plots at a rate of ca. 150 m^3 ha^{-1} (410 kg N ha^{-1}). Control plots received no biochar, high application biochar plots (HB) received biochar (with a 17% ash content) at a rate of 18.8 t ha^{-1}, and low application biochar plots (LB) received the same biochar at 5.7 t ha^{-1}. Although the HB plots demonstrated the lowest cumulative nitrous oxide (N_2O) and methane (CH_4) emissions, there was no significant difference between treatments ($p = 0.152$ and $p = 0.496$, respectively). Soil pH results from samples collected throughout the year indicated a significant treatment effect ($p = 0.046$), though Tukey test results indicated that there was no difference between mean values. Soil total carbon was significantly higher in HB plots at the end of the experiment ($p = 0.025$) and nitrate (NO_3^-) intensity throughout the year (which expresses potential exposure of NO_3^- to the soil microbial community) was significantly lower in HB plots compared to the control ($p = 0.001$). Annual cumulative potassium (K^+) loss from HB plots was significantly higher than from the other treatments ($p = 0.018$). HB plots also demonstrated a short-term increase in phosphorus (P) and ammonium (NH_4^+) in leachate during the first rainfall event following manure and biochar application ($p < 0.0001$ and $p = 0.0002$, respectively) as well as a short-term decrease of NO_3^- in leachate during a heavy rainfall event following a long dry spell ($p = 0.036$), though differences between treatments for cumulative nutrient losses were not significant ($p = 0.210$, $p = 0.061$, and $p = 0.295$, respectively for P, NH_4^+, and NO_3^-). These data indicate that biochar produced from pine wood chips at 550 °C having high ash content (17%) is not likely to impact GHG emissions in systems with high manure application rates. Further research should be conducted in order to investigate the impact of biochar amendment on the dynamics and mobility of nutrients applied in subsequent repeated applications of dairy manure.

1. Introduction

Large scale livestock production is considered an important contributor to global greenhouse gas (GHG) emissions and water pollution from nutrient leaching and runoff (Food and Agriculture Organization, 2006). Global livestock production has rapidly increased in recent decades due to global population growth and changes in human diet, leading to a large increase in manure production (Food and Agriculture Organization, 2006; Oenema et al., 2007). Land application of manure is a waste management practice in dairy systems that can also return nutrients back to subsequent crops. Due to the high water content and low density of nutrient value in manure, cost of transport more than a short distance exceeds the nutrient value of the manure. Thus, the land area to which manure can reasonably be added is limited to

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a short radius from the point of production (DEFRA, 2004), which frequently includes fields in which grasses are grown for silage or grazing.

The addition of nutrients to soil in excess of what crops use can result in nutrient leaching, which is an important source of water pollution (Stout et al., 2000). High levels of nitrogen may damage ecological systems through increased soil nutrient loss, acidification of soils and surface water, accelerated loss of biological diversity (Vitousek et al., 1997), and contamination of groundwater (Spalding and Exner, 1993). If manure is applied at a rate sufficient for crop N requirements, rapid accumulation of soil phosphorus (P) is inevitable, which is likely to result in P leaching and runoff (Olson et al., 2010). Freshwater systems are highly sensitive to pollution by P (Carpenter and Bennett, 2011), which is a limiting nutrient for algal growth and eutrophication (Schindler et al., 2008).

Management of manure is also important for GHG emission control (Oenema et al., 2007). It has been estimated that 2.0% of manure N has been emitted to the atmosphere as nitrous oxide (N_2O) since 1860 (Davidson, 2009), and N_2O fluxes from manure-amended soil can be greater in magnitude and extend over a longer period of time than N_2O fluxes from mineral fertilizer (Senbayram et al., 2009). Intensive manure application can also result in substantial amounts of methane (CH_4) emissions (Chadwick et al., 2000).

In recent years, biochar has been evaluated as a tool for GHG suppression and carbon sequestration in soils (Lehmann, 2007). Biochar has shown the potential to suppress N_2O emissions in a wide variety of incubation studies (Bruun et al., 2011; Spokas and Reicosky, 2009; Yanai et al., 2007) and in field studies using commercial fertilizers on soils used to grow rice (Liu et al., 2012) or maize (Zhang et al., 2012). Biochar has also demonstrated the suppression of N_2O from pasture soil amended with bovine urine (Taghizadeh-Toosi et al., 2011). Effect of biochar on N_2O emissions in the above mentioned publications has largely been attributed to changes in soil aeration or moisture dynamics, an increase in pH, direct adsorption of N to biochar surfaces, microbial immobilization due to an increased C to N ratio, or microbial toxicity due to organic substances present in biochar. However, other field studies reported no significant impact of biochar on N_2O emissions from soils amended with green manure on an organically managed 5-year crop rotation (Karhu et al., 2011) or pasture amended with chemical fertilizers (Scheer et al., 2011). In some of the above mentioned field experiments, biochar has also been demonstrated to decrease CH_4 emissions from soil potentially due to inhibition of methanogenic activity or lack of substrate availability (Liu et al., 2011), or to increase the potential of the soil as a CH_4 sink due to increased methanotrophy (Karhu et al., 2011; Zhang et al., 2012). However, there was no demonstrated effect of biochar on CH_4 fluxes measured by Scheer et al. (2011).

In addition to impacts on GHG emissions, biochar has demonstrated the potential to improve soil nutrient retention. Aged biochar may decrease ammonium (NH_4^+) leaching through increased cation exchange capacity (CEC) (Singh et al., 2010). Fresh biochar has demonstrated the potential to decrease nitrate (NO_3^-) loss from soils amended with biosolids, possibly due to suppressed mineralization (Knowles et al., 2011), increased N use efficiency (Chan et al., 2007), and/or immobilization of N (Nelissen et al., 2013). Biochar has also demonstrated the ability to retain phosphate (PO_4^{3-}) (Lehmann, 2007) and reduce P in leachate (Laird et al., 2010). However, the presence of biochar has also contributed to an increase in total soil P and K^+ due to surface runoff (Schnell et al., 2012), and P and K^+ in leachate (Lehmann et al., 2003). All of the above nutrient-retention experiments were pot trials, soil-column experiments, or were described as lab- or greenhouse-based, with the exception of Knowles et al. (2011). The latter study utilized undisturbed soil lysimeters that were removed from the field, but received natural rainfall outside an experimental station. None of the nutrient-related experiments listed above were field-based.

Hence, the purpose of the present study was to: examine the impact of pine chip biochar produced at 550 °C on N_2O and CH_4 emissions and on nutrient leaching (NO_3^-, NH_4^+, PO_4^{3-}, and K^+) from soil under ryegrass in the field, after co-application with dairy manure.

2. Materials and methods

2.1. Site description and study design

The field study was conducted on a dairy farm in Petaluma, Sonoma County, California (Lat. 38°16′ N; Long. 122°48′ W) between May 2011 and May 2012 with biochar application occurring in July 2011. This area has a mild Mediterranean climate where most of the precipitation falls as rain between October and April. Over the course of the experiment, there was ca. 692 mm of rainfall and average daily maximum and minimum air temperatures of 21.7 °C and 6.4 °C, respectively (Fig. 1). The site is located on a USDA NRCS classification Blucher series fine sandy loam soil (thermic Fluvaquentic Haploxerolls) in a field used to grow annual ryegrass (*Lolium multiflorum Lam.*) with a topsoil bulk density (to 15 cm) of 0.8 g cm^{-3}, and a pH of 7.3 (Table 1). Manure application occurred once during the course of the experiment at a rate of ca. 150 m^3 ha^{-1} (410 kg N ha^{-1}) in late July 2011. Manure was applied to all treatment plots at the same rate and at the same time. Manure contained 7.6% dry matter, 11 g C L^{-1}, 2.7 g N L^{-1}, 0.03 g PO_4^{3-}-P L^{-1}, and 2.6 g K^+ L^{-1} (Table 1). Soil and manure characterization methods are described in Section 2.3. Harvesting of grasses occurred once in early June, once in early July, and once in late August (supplementary data Table S1). In order to facilitate biochar incorporation with minimal soil disturbance, an aerator with 7.6 cm coring tines (BlueBird, Charlotte, NC, USA) was used over the experimental area immediately following the second harvest and prior to biochar application. Disking occurred once in November, prior to the broadcasting of seeds. Due to heavy rainfall in March 2012, the site was temporarily flooded for a two-week period. Gas sampling began in May 2011 (ca. three weeks prior to the first harvest of 2011) and was concluded in May 2012 (one day prior to the first harvest of 2012). Soil sampling occurred between June 2011 and May 2012. Resins were used between July 2011 and May 2012.

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The field site included three treatments (n = 4): the control which received only manure (as described above), the low application biochar (LB) plots which received manure and 5.7 t ha^{-1} biochar (thoroughly mixed into the manure as it was applied to the field) in late July, and the high application biochar (HB) plots which received manure and 18.8 t ha^{-1} biochar in early July, immediately following second harvest and field aeration and 17 days prior to manure application. The LB application rate was determined in order to apply manure and biochar at a 2:1 ratio based on dry weight. The HB application rate was determined on the basis of achieving a 2% mass concentration in the top 7.6 cm of the soil profile, the depth to which the soil was penetrated by coring tines during aeration. The treatments were organized in a randomized complete block design (RCBD). Each plot was 5 m × 5 m and contained one collar for attaching a gas sampling chamber and one resin lysimeter (see below).

Biochar was obtained from New Earth Renewable Energy, Inc. (Seattle, WA, USA) and applied directly to the soil or manure in a mixed particle size range. The majority (64.1%) was 250–1000 μm in size, 35.1% was 1000–2000 μm, 0.5% was 53–250 μm, 0.2% was