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Greenhouse gas emissions from a wastewater sludge-amended soil cultivated with wheat (*Triticum* spp. L.) as affected by different application rates of charcoal

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ABSTRACT

Applying biochar to soil is an easy way to sequester carbon in soil, while it might reduce greenhouse gas (GHG) emissions and stimulate plant growth. The effect of charcoal application (0, 1.5, 3.0 and 4.5%) on GHG emission was studied in a wastewater sludge-amended arable soil (Typic Fragiudepts) cultivated with wheat (*Triticum* spp. L.) in a greenhouse. The application of charcoal at ≥1.5% reduced the CO_2 emission rate significantly ≥37% compared to unamended soil (135.3 g CO_2 ha^{-1} day^{-1}) in the first two weeks, while the N_2O emission rate decreased 44% when 4.5% charcoal was added (0.72 g N_2O ha^{-1} day^{-1}). The cumulative GHG emission over 45 days was 2% lower when 1.5% charcoal, 34% lower when 3.0% charcoal and 39% lower when 4.5% charcoal was applied to the sludge-amended soil cultivated with wheat. Wheat growth was inhibited in the charcoal-amended soil compared to the unamended soil, but not yields after 135 days. It was found that charcoal addition reduced the emissions of N_2O and CO_2, and the cumulative GHG emissions over 45 days, without altering wheat yield.

1. Introduction

It has been reported that application of biochar to a soil can raise pH, water holding capacity and the availability of P, Ca and Mg, and sometimes decreases N mineralization (Schiemenz and Eichler-Loebermann, 2010; Major et al., 2010; Streubel et al., 2011). Consequently, biochar can improve plant development (Solaiman et al., 2010). For instance, Kammann et al. (2011) showed that biochar increased growth, drought tolerance, leaf-N and water use efficiency of the pseudo-cereal *Chenopodium quinoa* Willd despite a larger plant leaf area. Biochar is resistant to microbial degradation so C is sequestered in soil (Sohi et al., 2010).

Nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) are important greenhouse gases (GHG) (IPCC, 2007) and agricultural activities are an important source of anthropogenic GHG, contributing up to 20% of the annual emissions (Lemke et al., 2007). Wastewater sludge is often applied to soil as it is rich in nutrients and organic material. Application of organic residues to soil is known to increase crop growth and improves soil structure (Jouquet et al., 2011). However, application of sludge to soil is known to increase emissions of GHG (Paramasivam et al., 2008). The organic material in the sludge is mineralized so the emission of CO_2 increases from a sludge-amended soil (Sheppard et al., 2005). The ammonium (NH_4^+) added to the soil and liberated through the mineralization of the organic material is oxidized to nitrite (NO_2^-) and then to nitrate (NO_3^-). During this oxidation process, i.e. nitrification, N_2O is formed. The produced NO_3^- is then reduced to N_2O under anaerobic conditions, i.e. denitrification, further contributing to GHG emissions. Application of wastewater sludge to soil can also increase emissions of CH_4 (Sheppard et al., 2005).

It has been shown that biochar affects emissions of greenhouse gases (GHG). Emissions of CH_4 and N_2O are often reduced in a biochar-amended soil (Zhang et al., 2010; Rogovska et al., 2011), but the effect on emissions of CO_2 is not unequivocal (Zimmerman et al., 2011). Spokas and Reicosky (2009) used 16 different types of biochars and found increases, decreases or no effect at all on the emission of CO_2. As such, biochar and soil characteristics and their interaction will affect the emissions of GHG. Application of biochar might induce a priming effect, but that will depend again on the type of biochar applied and the easily decomposable soil organic matter fraction (Keith et al., 2011). If the biochar still contains easily decomposable organic material, then a priming effect might occur (Luo et al., 2011; Zavalloni et al., 2011; Zimmerman et al., 2011).

As such, charcoal could be applied to soil to sequester C, improve soil characteristics, stimulate crop growth and reduce GHG emissions (Atkinson et al., 2010). Soil was amended with 0, 1.5, 3.0 and

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4.5% charcoal and cultivated with wheat (*Triticum* spp. L.) fertilized with wastewater sludge. The emissions of CO_2, CH_4 and N_2O were monitored for 45 days, while plant characteristics (roots, shoot and yields) were determined at harvest. The objective of this study was to investigate how different application rates of charcoal to a wastewater sludge-amended soil cultivated with wheat (*Triticum* spp. L.) affected emissions of GHG and plant growth. It was hypothesized that the application of charcoal would reduce emissions of GHG and stimulate plant growth.

2. Materials and methods

2.1. Area description and soil sampling

The sampling site is located in Otumba in the State of México (19° 42′ N 98° 49′ W) and the soil was classified as Typic Fragiudepts. The soil is mainly cultivated with maize for >20 years, receiving a minimum amount of mineral fertilizer (mainly urea), i.e. < 50 kg N ha^{-1}, without being irrigated. Soil was sampled 30 times randomly by augering the 0–15 cm top-layer of five plots of approximately 0.5 ha spatially separated. A total of five soil samples were thus obtained. The soil from each plot ($n = 5$) was pooled and characterized. The sandy loam soil with pH 8.9 and electrolytic conductivity (EC) 1.23 dS m^{-1}, had a total C content of 29.1 g C kg^{-1} soil and a total N content of 2.41 g N kg^{-1} and water holding capacity (WHC) of 567 g kg^{-1} dry soil. Details of techniques used to characterize the soil can be found in Franco-Hernández et al. (2003). The field-based replication was maintained in the incubation study.

2.2. Charcoal

Charcoal is still used commonly as fuel in rural communities of central Mexico. Details of the production process and characteristics are described in Gómez-Luna et al. (2009). Briefly, charcoal was made by burning wood in a kiln creating internal suppressed combustion with the least possible flame. Wood of netleaf oak (*Quercus rugosa* Neé) was piled up in the centre of the kiln site, covered with the litter, lit and then covered with soil. Some airing points at a high of 1.5 m are left uncovered and the incomplete combustion with a minimum of flame production is maintained for 12–14 days. The temperature of the covering soil varies between 200 °C and 300 °C.

2.3. Wastewater sludge characteristics

Wastewater sludge was obtained from Reciclagua (*Sistema Ecológico de Regeneración de Aguas Residuales* Ind., S. A. de C. V.) in Lerma, State of México (México). The wastewater was digested aerobically in a reactor and the biosolids obtained after the addition of a flocculant were passed through a belt filter and sampled. Details of the production of the wastewater sludge, sampling and characterization can be found in Franco-Hernández et al. (2003). Briefly, the pH of the sludge was 8.7, the water content 820 g kg^{-1}, the organic C content in the fresh sludge was 81.2 g kg^{-1} and total N 5.41 g kg^{-1}, while the concentration of NH_4^+ was 556.5 mg N kg^{-1}, NO_2^- 2.2 mg N kg^{-1} and NO_3^- 8.4 mg N kg^{-1}.

2.4. Cultivation of wheat in the greenhouse

The experimental design was a completely randomized 1 × 4 factorial with five replications (maintained from the field site replications). The factors were one soil and four treatments all of them cultivated with wheat. The four treatments were: 1) soil mixed with wastewater sludge so that plants were fertilized with 150 kg N ha^{-1}, using the soil surface area of the PVC tubes as the reference, considering the mineral N in the sludge and assuming that 40% of the organic N in the sludge was mineralized within the experimental period (considered the CONTROL treatment), and 2) soil mixed with the same amount of wastewater sludge and charcoal at 1.5%, 3) charcoal at 3.0% and 4) charcoal at 4.5%. The amount of charcoal mixed with the soil was on a dry matter base. Twenty sub-samples of 3.25 kg soil, i.e. five soil samples × four treatments, were added to PVC tubes (length 50 cm and diameter 16 cm) filled at the bottom with 7 cm of gravel topped up with 3 cm sand.

Seeds of wheat cultivar 'Temporalera M87' were provided by the '*Research Center for Agricultural and Forestry of the State of Mexico, Campo Experimental Valle de Mexico*' (INIFAP) (Texcoco, Mexico). Six wheat seeds were planted in each of the PVC tubes. Seeds were placed at 3 cm depth. The PVC tubes were placed at random in the greenhouse until grain maturity. During the experiment, 500 ml water was added to each column every seven days. The amount of water applied to the plants was such that no leaching occurred and no nitrate got lost. The temperature, relative humidity and light intensity in the greenhouse were monitored during the experiment.

At the end of the experiment, the entire soil column was removed from the PVC tube. The roots were separated from the shoots. The fresh weight of the roots, ears and shoots was determined and the root and shoot length measured. The dry weight of grains and number of grains per plant were determined. The grains, ears, roots and shoots were dried at 45 °C in an oven for a week and weighed.

2.5. Emissions of CO_2 and N_2O

From the onset of the experiment until day 45, a cylindrical PVC chamber (length 50 cm and diameter 16 cm) fitted with two sampling ports was inserted into the PVC tube with the soil column. The two PVC tubes, i.e. the soil column and PVC tube for gas sampling, were joined and airtight sealed with Teflon tape. Two or three times a week, just after joining both PVC tubes and sealing them airtight, 15 cm^3 air was injected into the PVC chamber headspace, while the gas was mixed by flushing at least 3 times with the air inside the chamber followed by gas collection for analysis. This process of flushing and sampling the headspace was repeated after 15 and 30 min. The 15 cm^3 air sample was injected into 15-ml evacuated vials closed with a butyl rubber stopper and sealed with an aluminium cap pending analysis.

The headspace of the vials was analysed on an Agilent Technology 4890D gas chromatograph (GC) fitted with an electron capture detector (ECD) for the determination of CO_2 and N_2O and a flame ionization detector (FID) for CH_4. Details of the settings of the GC can be found in Serrano-Silva et al. (2011). Concentrations of CO_2, N_2O and CH_4 were calculated by comparing peak areas against a standard curve prepared from known concentrations, i.e. 1 and 10 ppm N_2O in N_2, 5 ppm CH_4 in N_2 and 2500, 20,000 and 40,000 ppm CO_2 in N_2, every time samples were analysed.

2.6. Calculations and statistical analysis

Emission of CO_2, CH_4 and N_2O was regressed on elapsed time, i.e. after 0, 15 and 30 min, using a linear model forced to pass through the origin, but allowing different slopes (production rates). The sample at time 0 accounted for the atmospheric CO_2, CH_4 and N_2O and was subtracted from the measured values.

Significant differences among plant characteristics as a result of the different treatments were determined by analyses of variance (ANOVA) and based on the least significant difference using the general linear model procedure (PROC GLM, SAS Institute, 1989).