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Increased retention of soil nitrogen over winter by biochar application: Implications of biochar pyrolysis temperature for plant nitrogen availability

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ABSTRACT

While soil freeze-thaw cycles can decrease soil nutrient retention over winter by increasing leaching losses and greenhouse gas emissions, biochar as a soil amendment could mitigate these effects. Nevertheless, there is often variation in the effectiveness of different biochar formulations with respect to soil nutrient retention. We added ^{15}N tracer to soil mesocosms to examine the effects of biochar produced under a series of pyrolysis temperatures (250–600 °C) on soil nitrogen retention in response to variation in soil freeze-thaw cycle intensity (−10 °C vs. 0 °C following spring melt). We also examined the subsequent effects on plant nitrogen uptake, soil nitrous oxide (N_2O) emissions and nitrogen leaching losses. As we predicted, increased soil freezing increased inorganic nitrogen losses through leaching and decreased the biomass of the test crop Arugula (*Eruca sativa*) the following growing season. Biochar amendment increased both soil ^{15}N retention over winter and the subsequent plant ^{15}N uptake, with the biochar generated at the highest temperature exhibiting the strongest effects on plant ^{15}N uptake. Biochar addition also significantly mitigated the negative soil freezing effect on subsequent plant biomass. Nevertheless, biochar addition combined with freezing increased N_2O emissions. Overall, our results confirm that biochar application can mitigate soil nitrogen losses over winter, although it may also interact with soil freezing to increase emissions of the greenhouse gas N_2O.

1. Introduction

In northern temperate regions, climate warming in recent decades has increased the ratio of rain to snow (Huntington et al., 2004; Feng and Hu, 2007). Reduced snow cover over winter can increase soil exposure to cold air (Hardy et al., 2001; Vankoughnett and Henry, 2014a), increasing the intensity of soil freezing and/or the frequency of freeze thaw cycles (Groffman et al., 2001; Henry, 2008). Increased soil freezing can subsequently increase soil nutrient losses through leaching (Joseph and Henry, 2008; Matzner and Borken, 2008; Campbell et al., 2014) and increase soil trace gas (e.g. nitrous oxide (N_2O)) emissions (Teepe et al., 2001; Matzner and Borken, 2008; Risk et al., 2013).

A possible solution to mitigate such N_2O losses and enhance soil nitrogen (N) retention, thereby minimizing N pollution and increasing crop productivity, is biochar amendment. Biochar, a by-product of the pyrolysis process from bio-energy production, can have beneficial environmental properties. In agricultural soil, biochar can reduce greenhouse gas (GHG) emissions (Lehmann et al., 2011; Fernandez et al., 2014; Hua et al., 2014; Sun et al., 2014), and decrease N_2O emissions in particular (Singh et al., 2010; Taghizadeh-Toosi et al., 2011; Zhang et al., 2012; Cayuela et al., 2014); it can also reduce N losses from leaching and surface run-off (Lehmann et al., 2003; Bruun et al., 2012; Kameyama et al., 2012). Overall, it can improve soil fertility, and thereby increase plant yield (Major et al., 2010; Van Zwieten et al., 2010; Jeffery et al., 2011; Zhang et al., 2012; Olmo et al., 2014).

The beneficial effects of biochar on soil nutrient retention are not consistent across all soil types, regions, crops, and biochar types; for example, under some circumstances biochar application

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has decreased crop yield (Van Zwieten et al., 2010; Reverchon et al., 2014; Singla et al., 2014) and increased N_2O efflux (Bruun et al., 2012; Liu et al., 2014; Singla et al., 2014), and in other cases it has had no significant effect on N_2O emissions (Karhu et al., 2011). Pyrolysis temperature can affect biochar physical and chemical properties, such as bioavailable carbon, N and phosphorus, functional group composition, porosity and pore size distribution, which in turn can affect soil and plant nutrient status (Atkinson et al., 2010; Lehmann et al., 2011). Biochar produced at high temperatures may better mitigate N leaching due to greater nitrate absorption capacity (Kameyama et al., 2012; Clough et al., 2013), however, biochars produced at extremely high temperatures (≥600 °C) have been observed to reduce soil aggregation, microbial activity and enzyme activities in coarse-textured and poor organic matter soils, although these effects were not observed in fine textured soils (Gul et al., 2015).

Only one study (Kettunen and Saarnio, 2013) has previously examined the combined effects of biochar amendment and freeze thaw cycles on soil N retention and N_2O emissions. Promisingly, they demonstrated a positive effect of biochar (produced from spruce woodchips at low temperature using slow pyrolysis) in mitigating N losses in response to increased freezing. However, their N leaching and N_2O emissions results were based on a short term laboratory study, and it would be very informative to extend these results and examine the consequences of these effects for subsequent plant N availability or plant growth. Moreover, given that they only examined one type of biochar, there is a need to specifically address variation in biochar production when assessing the potential mitigating effects of soil N losses in response to freezing, and to assess the possible consequences of increases in soil N retention for plant N availability and growth.

We used biochar generated at pyrolysis temperatures ranging from 250 °C to 600 °C to investigate the combined effects of increased soil freezing and biochar addition on soil N retention, plant biomass, soil trace gas losses and N leaching losses. We conducted our experiment over the winter and the following growing season using intact soil-plant mesocosms that were incubated in an agricultural field, then moved to controlled environment chambers to manipulate soil freezing after spring melt. We used ^{15}N labeling to monitor N retention in the soil and plant N uptake. The aims of this study were to examine 1) to what extent biochar addition and biochar pyrolysis temperature affected soil N retention over winter and spring melt, and 2) to what extent the latter affected N availability and plant productivity over the subsequent growing season. We predicted that soil N retention over winter would increase with biochar amendment, and that biochar produced at the highest temperatures would be most effective in mitigating N losses. We also predicted that increased soil N retention in response to biochar addition would correspondently increased plant yield.

2. Material and methods

2.1. Site description

The soil collection and in situ component of our study was conducted in an agricultural field at the Environmental Sciences Western field station in London, Ontario, Canada (43°04′29″N, 81°20′18″W). The soil texture was classified as a well to imperfectly drained silt loam and loam glacial till (Hagerty and Kingston, 1992), with an average pH of 7.44, soil organic matter content of 8.24%, and total C and N contents of 2.84% and 0.22%, respectively; these values increased to means of 4.01% C and 0.25% N with biochar addition (all of the latter values were obtained from the non-enriched samples from the isotope analysis—see below). Mean air temperature at the site was 7.9 °C, with a low monthly mean of −5.6 °C (January), a high monthly mean of 20.8 °C (July), and an average annual precipitation of 1012 mm (Canadian Climate Normals 1981–2010, Environment Canada, National Climate Data and Information Archive). Snowfall generally begins from early to mid-December with snow melt occurring by mid to late March or early April.

2.2. Biochar production

A biomass pyrolysis process was used to produce the biochar samples using a pilot scale horizontal mechanically fluidized reactor (H-MFR) setup in batch configurations (Lago et al., 2015). Pyrolysis is a thermal cracking process carried out in the absence of oxygen. The products are light gases, condensable vapors (bio-oil) and solid biochar. Solid anaerobic digestate (a blend of dairy manure, eggplants, peppers, grape vines, tulip bulbs, animal bedding and corn residues) obtained from a greenhouse company in Ontario, Canada was used as the raw biomass feedstock for the pyrolysis process. The process was carried out at eight different temperatures (250, 300, 350, 400, 450, 500, 550 and 600 °C; chemical properties of the biochar samples are displayed in Table 1; Particle size distribution was determined by dry sieving, and both pH and electrical conductivity were determined using 1:5 (w/v) distilled water extracts; n = 3). For the batch setup, the bio-oil collection system was set up to fractionally separate condensable vapors produced at different reaction temperatures using a lever valve system. The reactor was initially heated and held at 165 °C for one hour to vaporize the water which was collected using a condenser immersed in an ice bath operating at temperatures between 0 and 5 °C. The reactor was then heated from 165 °C to the

Table 1
Chemical and physical properties of the biochar samples. Means ± SEM were compared using Tukey's tests* (n = 3; except the elemental analysis and ash content data, where n = 1).

Pyrolysis temperature (°C)	Elemental analysis (wt. %)				Ash content (wt. %)	Electrical conductivity (µs/cm)	pH	Particle size distribution (%)			
	C	H	N	O				0–0.5 mm	0.5–2 mm	2–4 mm	4–10 mm
250	52.2	5.77	4.75	37.3	7.5	1446 ± 164ab	7.05 ± 0.01a	21.2 ± 7.2a	33.2 ± 1.3ab	25.8 ± 5.4a	13.7 ± 2.3ab
300	54.5	5.40	4.70	35.4	9.9	1039 ± 84a	8.11 ± 0.08b	17.0 ± 2.6a	37.0 ± 1.8b	28.5 ± 2.2a	11.5 ± 1.8ab
350	49.6	4.14	4.33	41.9	9.9	1758 ± 93b	9.01 ± 0.02c	28.7 ± 2.1a	34.5 ± 0.9ab	23.1 ± 1.0a	8.7 ± 0.9a
400	58.8	4.13	5.04	32.0	16.8	1048 ± 64a	9.78 ± 0.01de	16.3 ± 5.0a	38.6 ± 2.4b	33.2 ± 3.8a	10.3 ± 3.1a
450	59.2	3.14	4.81	32.8	16.7	1585 ± 95ab	10.01 ± 0.06f	22.8 ± 1.6a	32.2 ± 1.3ab	28.7 ± 1.1a	11.7 ± 0.9ab
500	56.8	2.89	2.84	37.5	15.7	2620 ± 10c	9.96 ± 0.01ef	15.7 ± 2.7a	34.5 ± 1.3ab	32.4 ± 3.5a	13.5 ± 1.7ab
550	59.3	2.88	3.17	34.7	14.5	3030 ± 181c	9.96 ± 0.01ef	19.3 ± 1.2a	28.1 ± 2.6a	30.7 ± 1.0a	19.8 ± 2.1b
600	61.7	2.26	3.74	32.3	17.5	3957 ± 220d	9.82 ± 0.04e	12.5 ± 2.6a	31.2 ± 1.4ab	34.6 ± 2.1a	20.1 ± 1.0b

* Values within a column followed by the same letter are not significantly different ($P < 0.05$).