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Impact of switchgrass biochars with supplemental nitrogen on carbon-nitrogen mineralization in highly weathered Coastal Plain Ultisols

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HIGHLIGHTS

- Carbon dioxide evolution was increased by the additions of switchgrass biochars and residues.
- Application of switchgrass biochar may cause N immobilization.
- Biochar application may need supplemental N to avoid crop growth retardation.

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ABSTRACT

Although an increase in soil fertility is the most frequently reported benefit linked to adding biochar to soils, there is still a need to pursue additional research that will improve our understanding on the impact of soil fertility enhancement because the effect could vary greatly between switchgrass (*Panicum virgatum*, L) residues (USG) and switchgrass biochars (SG). We hypothesized that SG with supplemental nitrogen (N) would deliver more positive effects on carbon (C) and N mineralization than USG. The objective of this study was to evaluate the effects of USG and SG, with or without supplemental inorganic N fertilizer on C and N mineralization in highly weathered Coastal Plain Ultisols. The application rate for SG and USG based on a corn yield goal of 112 kg ha^{-1} was 40 Mg ha^{-1}. Inorganic N was added at the rate of 100 kg N ha^{-1}, also based on a corn yield of 7.03 tons ha^{-1}. Experimental treatments were: control (CONT) soil; control with N (CONT + N); switchgrass residues (USG); USG with N (USG + N); switchgrass biochars at 250 °C (250SG); SG at 250 °C with N (250SG + N); SG at 500 °C (500SG); and SG at 500 °C with N (500SG + N). Cumulative and net CO_2–C evolution was increased by the additions of SG and USG especially when supplemented with N. Soils treated with 250SG (8.6 mg kg^{-1}) had the least concentration of total inorganic nitrogen (TIN) while the greatest amount of TIN was observed from the CONT + N (19.0 mg kg^{-1}). Our results suggest that application of SG in the short term may cause N immobilization resulting in the reduction of TIN.

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1. Introduction

Through years of extensive research elsewhere, the use of biochars has gained widespread attention as a potential amendment to boost soil fertility (Chan et al., 2008; Novak et al., 2009a; Manya, 2012). While intensive crop production depletes nutrients and reduces organic carbon in soils, biochar produced by pyrolysis has the potential to enhance soil fertility and reduce greenhouse gas emissions. Early studies have shown that biochar contains inorganic nutrients (Chan and Xu, 2009) along with a structural matrix composed of an assemblage of carbon structures, some components are even resistant to microbial oxidation (Lehmann et al., 2011). Everything else being equal, materials added to the soil with a C:N ratio greater than 24:1 will result in a temporary N deficit (immobilization), and those with a C:N ratio less than 24:1 will result in a temporary N surplus.

The fertility of highly weathered Ultisols in the southeastern Coastal Plain region of United States is low. Research has shown organic residues added to soils to improve soil organic carbon content and fertility levels in the southeast Coastal Plain region

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have made minimal gains because materials decompose easily due to the region's sandy-textured soils, warm climate and abundant rainfall (Sigua et al., 2014; Novak and Busscher, 2012). The application of organic residues is critically needed for fertility maintenance of Ultisols as it leads to the formation of humus. Incorporation of crop residues in agricultural systems is an important factor in sustaining soil fertility level and nutrient cycling (Nicolardo et al., 1995; Ambus and Jensen, 1997; Jensen, 1994). Proper management of crop residues for the maintenance of soil fertility cannot be overstressed. Production and export of large amounts of biomass for bioenergy and grain production removes substantial amounts of mineral nutrients from soil (Heggenstaller et al., 2008; Sigua et al., 2004a, 2004b, 2003). Repeated annual harvest of crop residues could reduce soil organic C levels (Sigua and Coleman, 2010; Laird et al., 2009; Sigua, 2009; Sigua et al., 2009).

Applying organic amendments (i.e. biosolids, organic waste, manure, crop residues) to improve soil physical and chemical properties are well known in the literature (Larney and Angers, 2012; Busscher et al., 2011), but the impact of the enhancement varied greatly between amendment sources (Larney and Angers, 2012). The longevity of easily decomposable organic amendments raises the specter of their long-term contribution to soil carbon sequestration and length of duration for the carbon and nitrogen mineralization in the soils. Estimates of net carbon mineralized or converted to CO_2 from biochars decomposition are needed to improve our understanding on both the efficacies of biochars in enhancing soil quality, carbon sequestration and biochar stability in soils. Results of a recent study published by Sigua et al. (2014) showed that feedstock processed into pellets will have lower rate of C mineralization in soils compared with smaller-size (dust; <0.42 mm) biochar particles produced from similar feedstock. Although most soil properties could be improved following application of crop residues and/or pyrolyzed crop residues, there is still a need to pursue additional research that will enhance our understanding of the impact on soil fertility in terms of carbon and nitrogen mineralization because the effect could vary greatly between uncharred and pyrolyzed residues.

With respect to both positive and negative aspect of biochar on short- and long-term functioning in the agroecosystem, there are few studies that dealt with the utilization of crop residues (uncharred) versus pyrolyzed materials from the same feedstock source of plant biomass productivity (Sigua et al., 2014; Novak and Watts, 2013). Gaskin et al. (2010) reported that nitrogen from biochar might not be available to plants. Addition of biochar to soils has been shown to result in slower mineralization of the biochar materials than the uncharred material (Knoblauch et al., 2012) and decrease net N mineralization (Dempster et al., 2012; Castaldi et al., 2012). Inconsistencies between reported effects of biochar derived from pyrolysis of crop biomass and those for other sources suggest additional research is needed. The use of more stable compounds such as carbonized materials from incomplete combustion of organic materials such as black carbon, pyrogenic feedstocks and charcoal could provide a long-term stability for maintaining high levels of soil organic matter and available nutrients in the soil (Glaser et al., 2002). We hypothesized that pyrolyzed switchgrass would deliver more positive effects on carbon and nitrogen mineralization than uncharred switchgrass residues. Understanding the nature of the short-term carbon and nitrogen mineralization and the mechanisms behind it is important for accepting both short- and long-term stability and obtaining reliable estimates of degradation rates. The objective of this study was to evaluate the effects of switchgrass residues and switchgrass biochars, with or without supplemental inorganic nitrogen fertilizer on carbon and nitrogen mineralization in highly weathered Coastal Plain Ultisols.

2. Materials and methods

2.1. Soil and site description

A Norfolk soil (fine loamy, kaolinitic, thermic, Typic Kandiudult) collected from the Clemson University, Pee Dee Research and Education Center, Darlington, South Carolina was used in the study. This soil belongs to the Ultisols order (US Soil Taxonomy) formed in extensively weathered Coastal Plain marine sediments with the clay fraction dominated by kaolinite. The Norfolk soil is a well drained soil located in upland landscape position (Daniels et al., 1999). The collection site has a long history of row crop production (>30 yrs), which in 2007, was converted to switchgrass (*Panicum virgatum*) for biofuel production.

Soils were collected from the top 15 cm and the 15–30 cm layers, respectively. The soil samples were air-dried; and then passed through a 2 mm sieve to remove plant material and large aggregates. Particle size analyses were carried out using the hydrometer method (Soil Characterization Laboratory, The Ohio State University, Columbus, Ohio). Both the Norfolk's Ap and E horizon organic carbon (SOC) and total nitrogen (TN) contents were measured using a LECO TruSpec CN analyzer (LECO Corp., St. Joseph, Michigan). Table 1 summarized some selected soil chemical properties of Norfolk's Ap and E horizons.

2.2. Feedstock selection, biochar pyrolysis and characterization

The switchgrass (*P. virgatum*) feedstock used in this study was obtained by harvesting switchgrass at the Clemson University Pee Dee Research and Education Center. The switchgrass feedstock was processed before pyrolysis by air-drying and grinding to pass a 6-mm sieve. The switchgrass biochars were produced at North Carolina Agricultural and Technical State University as outlined by Novak et al (2013). The biochars were made using slow pyrolysis procedure at 250° and 500 °C under a continual stream of N_2 gas. After recovery from the pyrolyzer, all biochars and the uncharred switchgrass were ground to pass a 0.42-mm sieve using a Wiley Mini-Mill (Thomas Scientific, Swedesboro, NJ, USA). All samples were then further sieved to pass through a 0.25-mm sieve, placed in a sealable plastic bag and stored in a desiccator.

The uncharred switchgrass and switchgrass biochar samples were characterized for their physical and chemical properties that

Table 1
Selected soil chemical properties of soil and chemical properties of switchgrass residues and switchgrass biochars at 250 °C and 500 °C (dry-weight) used in the study.

Soil properties	Ap horizon	E horizon
pH	5.6	5.4
P (mg/kg)	50	10
K (mg/kg)	85	70
Ca (mg/kg)	277	176
Mg (mg/kg)	56	42
Zn (mg/kg)	3.9	2.2
Mn (mg/kg)	11	6
Cu (mg/kg)	0.9	0.4
B (mg/kg)	0.1	0.1
Na (mg/kg)	6	6
CEC (meq	1.8	1.5

Pyrolysis (°C)	pH[a]	Ash[a]	C[a]	H[a]	O[a]	N[a]	O/C	H/C
	——————— g kg^{-1} ———————							
Residues	5.8	22	483	62	427	5.1	0.66	1.53
250	6.4	26	553	60	356	4.3	0.49	1.29
500	9.2	78	844	24	43	3.4	0.04	0.34

[a] Published in Bioenergy Research (Novak et al., 2012).

included pH, ash content and their elemental composition. Selected chemical properties of the uncharred switchgrass and switchgrass biochars are shown in Table 1.

2.3. Experimental treatments, experimental design, biochar incubation and nitrogen mineralization in soils

Experimental treatments consist of the control (CONT) soil, soil with nitrogen (CONT + N), uncharred switchgrass (USG), uncharred switchgrass with nitrogen (USG + N), switchgrass biochars at 250 °C (250SG), switchgrass biochars at 250 °C with nitrogen (250SG + N), switchgrass biochars at 500 °C (500SG), and the switchgrass biochars at 500 °C with nitrogen (250SG + N).

The soil:biochar treatments (described above) were prepared by weighing 400 g of air-dried Norfolk soil taken from 15–30 cm soil depth into a plastic sealable bag and then adding 8.0 g of biochar (equivalent to 40 tons biochar ha^{-1}) for a 2% (w/w) mixture. Each bag was then gently mixed by hand and spread out onto wax paper. Inorganic nitrogen using ammonium nitrate (NH_4NO_3, 37% N) was added at the rate of 100 kg N ha^{-1} (about 0.008 g N per 400 g soils). This amount of nitrogen application was based on standard nitrogen application to attain a 7.03 tons yield of corn ha^{-1}. To the Norfolk soil with biochar added, 20 g of degassed deionized H_2O was added, and the samples were gently mixed using a trowel to obtain a soil moisture content of 10% (w/w or about 40 g of moisture per 400 g of soil). A 50 g portion (corrected for H_2O) of the soil + biochar mixture or soil + switchgrass was transferred into a sterile 250 mL glass incubation bottle (autoclaved) and sealed using a plastic cap equipped with a 3 mm thick Teflon lined silicon septa. After sealing, each incubation bottle was weighed. Unamended Norfolk soil (no switchgrass biochar and switchgrass residues) served as the control. All treatments along with the controls were replicated three times and arranged in a completely randomized design. Additionally, triplicate bottles containing no soil or biochar were assembled for quantifying background CO_2 concentrations in the headspace. All bottles were then placed in an incubator at 25 °C and incubated for 50 days.

Periodically, each bottle was removed from the incubator for headspace gas sampling. Prior to headspace gas sample removal, the head pressure in each incubation vessel was measured and then was pressurized by injecting 5 mL of He. This procedure assured a minimal pressure was created in the vessel in response to removing a 5 mL aliquot of the headspace gas. Subsequently, headspace CO_2 concentrations were corrected for the He addition. The 5-mL headspace sample contained within the gas-tight syringe was then injected into a 10-mL headspace vial capped with 3-mm thick Teflon-lined silicon septa. The headspace vials were then placed into an automatic injector rack of a Combi-Pal auto-sampler installed on a Bruker 450 (Bruker Daltonics, Billerica, Massachusetts) gas chromatograph (GC). The GC oven was run in an isocratic mode at 40 °C. It was equipped with a model 1041 injector operating at 50 °C and 263 kPa. Five-mL of vial headspace gas was injected using a Combi-Pal autosampler equipped with a CTC Analytical headspace syringe. The gas flow proceeded through a 1.8 m long × 1.6 cm outside diameter column packed with 80/110 mesh Hay Sep Q (Varian Inc. Austin, Texas) using He at a flow rate of 55 mL min^{-1}. Carbon dioxide in the sample was detected using a thermal conductivity detector operating at 150 °C with a filament temperature of 200 °C. Headspace CO_2 peaks were corrected for background CO_2 and were then quantified relative to external standards.

After sampling the headspace gas, all incubation bottles were uncapped and remained open for two hours to exchange their past atmosphere with new room air. The bottles were then re-weighed and adjusted back to their initial weight using deionized H_2O, ensuring that any soil moisture lost during headspace gas exchange was replaced adequately.

At the end of the incubation period (50 days), soil samples were taken from each bag for total inorganic nitrogen (NH_4–N + NO_3–N) analyses. The concentration of total inorganic nitrogen (TIN) was extracted with 2 N KCl and analyzed with N Autoanalyzer following the procedures of Mulvaney (1996).

2.4. Data analyses

To determine the effect of uncharred and pyrolyzed switchgrass with or without supplemental inorganic nitrogen on carbon and nitrogen mineralization in Norfolk soil, a single-factor experimental design was followed using SAS PROC ANOVA (SAS Institute, 2000). The mean carbon dioxide-carbon (CO_2–C) concentrations evolved and the amount of TIN in the soils at the end of the incubation period (50 days) were sorted and compared using a Duncan's Multiple Range Test via a SAS PROC ANOVA. Finally, CO_2–C mineralization rate constants were calculated using linear regression analyses. They were tested for significant differences using a SAS PROC ANOVA at a $P < 0.05$ level of significance (SAS Institute, 2000).

3. Results

3.1. Soil cumulative carbon dioxide–carbon evolution

The cumulative amount of CO_2–C evolution was generally higher in soils amended with USG and/or SG with supplemental N than in the control soils (Fig. 1). By the end of day 50, total CO_2–C evolution (mg g^{-1}) from the soil was in the order: USG + N (640) > USG (553) > 250SG + N (208) > 250SG (192) > 500SG + N (66) > CONT (64) > CONT + N (63) > 500SG (51).

Results have shown that addition of supplemental N to soils produced favorable effect by increasing the cumulative amount of CO_2–C evolution. Again, by the end of day 50, the amount of cumulative CO_2–C evolution between soils amended with USG and USG + N was increased by about 16% or from 523 to 640 mg C–CO_2 g^{-1}. The increase in the cumulative amount of CO_2–C evolution in soils that were added with 250SG and 250SG + N was from 192 to 208 mg CO_2–C g^{-1} or about an 8% increase. An increase of about 30% in the cumulative CO_2–C evolution was observed between soils with 500SG (51 mg CO_2–C g^{-1}) and 500SG + N (66 mg CO_2–C g^{-1}). The amount of cumulative CO_2–C from control soil with and without N was almost identical (63 mg CO_2–C g^{-1}).

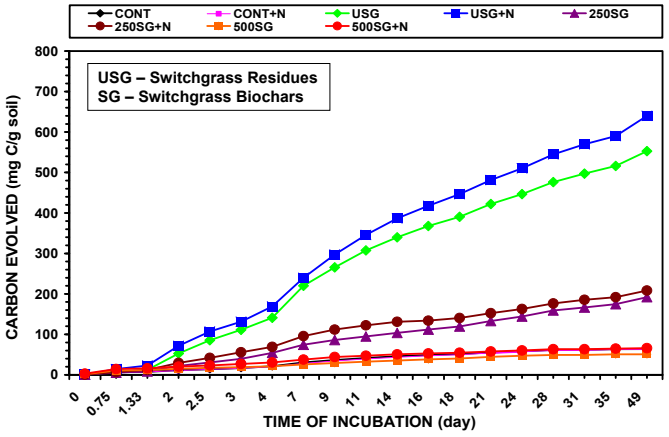

Fig. 1. Cumulative CO_2–C evolved from the mineralization of switchgrass residues and switchgrass biochars with or without supplemental N.

3.2. Soil net carbon dioxide-carbon evolution

Net CO_2–C evolution was significantly affected by switchgrass residues and switchgrass biochars with or without N addition ($p \leq 0.0001$). Overall, soils with USG + N had the greatest net amount of CO_2–C evolved (315 mg g^{-1}) while soils with 500SG had the least amount of CO_2–C evolved of about 31 mg g^{-1} (Fig. 2). The net amount of CO_2–C evolved did not vary significantly among soils treated with 500SG with N (42 mg C–CO_2 g^{-1}) and without N (31 mg C–CO_2 g^{-1}) and control soils with N (36.7 mg C–CO_2 g^{-1}) and without N(35.6 mg C–CO_2 g^{-1}). Similarly, the net amount of CO_2–C evolved between soils treated with 250SG (91 mg C–CO_2 g^{-1}) and soils with 250SG + N (107 mg C–CO_2 g^{-1}) did not vary significantly ($p \leq 0.05$) from each other (Fig. 2).

3.3. Carbon mineralization rates in soils

Carbon mineralization rates in soils varied ($p \leq 0.05$) widely between the control soils and soils with USG and SG with or without added N. The mineralization rate constants shown in Table 2 determined by regression analyses substantiate that USG (33.6 mg g^{-1} day^{-1}) and USG + N (38.1 mg g^{-1} day^{-1}) in soils will decompose faster than 250SG (10.9 mg g^{-1} day^{-1}), 250SG + N (11.8 mg g^{-1} day^{-1}), 500SG (2.8 mg g^{-1} day^{-1}) and 500SG + N (3.5 mg g^{-1} day^{-1}). Although the increase in the rates of CO_2 evolution was not remarkable, both the USG and SG with N addition had higher rates of CO_2 evolution when compared with USG and SG without N. The rate of CO_2 evolution from soils with USG + N was about (38.1 mg g^{-1} day^{-1}) compared with USG alone (33.6 mg g^{-1} day^{-1}). The rates of CO_2 evolutions for 250SG + N and 500SG + N were 11.8 mg g^{-1} day^{-1} and 3.5 mg g^{-1} day^{-1} while the rates of CO_2 evolutions for 250SG and 500SG alone were 10.9 mg g^{-1} day^{-1} and 2.8 mg g^{-1} day^{-1}, respectively (Table 2). There was a slight decrease in the rate of CO_2 evolution from the control soil. Control soils with N had an average CO_2 evolution rate of 3.8 mg g^{-1} day^{-1} compared with 3.9 mg g^{-1} day^{-1} in the control soils without N addition.

3.4. Nitrogen mineralization in the soils

The concentrations of mineralized total inorganic nitrogen (NO_3–N + NH_4–N) in soils amended with USG and SG with or without N are shown in Fig. 3. The concentrations of TIN varied widely ($p \leq 0.001$) among soils amended with USG and SG in combination with N. Of soils amended with SG and/or USG with or without supplemental N, soils treated with 250SG had the least amount of TIN (8.6 mg kg^{-1}) at the end of 50 days soil incubation. The greatest amount of TIN was observed from the control soil with N (19.0 mg kg^{-1}). Overall, the concentrations of TIN were significantly enhanced in soils that were treated with supplemental N (Fig. 3).

Fig. 4 shows the change in the TIN of soils treated with USG and SG in combination with N when compared with the control soil without N addition and the change in TIN of soils amended with USG + N, 250SG + N and 500SG + N when compared with the control soils with supplemental N. Our results have shown that soils amended with USG, USG + N, 250SG, 250SG + N and 500SG had negative concentration of TIN while control soils with N and soils amended with 500SG + N had positive concentrations of TIN at the end of the incubation period. Remarkable results were noted for soils amended with USG and SG in combination with N. When these treatments were compared with the control soils with N, there was a negative result on the concentration of total inorganic N in the soils. Soils treated with USG + N, 250SG + N and 500SG + N had negative decrease of about 5.2%, 4.2% and 0.2% TIN, respectively. Our results suggest that application of SG in the short term can cause N immobilization resulting in the reduction of TIN (Fig. 4).

Table 2
Estimated rate constants for CO_2 evolution in soils amended with switchgrass residues and switchgrass biochars with or without nitrogen.

Treatments	Rate of CO_2 evolution (mg g^{-1} day^{-1})	R^2
Control	3.9	0.97[a]
Control + N	3.8	0.98[a]
USG	33.6	0.98[a]
USG + N	38.1	0.99[a]
250SG	10.9	0.98[a]
250SG + N	11.8	0.98[a]
500SG	2.8	0.98[a]
500SG + N	3.5	0.96[a]

[a] Significant at $p \leq 0.0001$.

4. Discussion

An important aspect of biochar as an amendment that is recently attracting more attention is on how biochar addition contribute to longer term carbon storage (Steinbeiss and Gleixner,

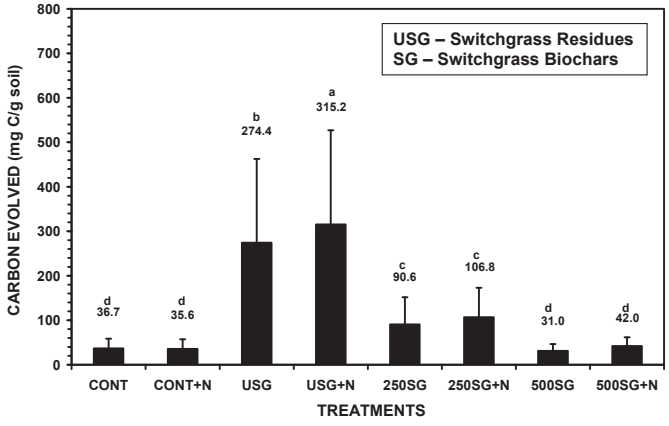

Fig. 2. Net CO_2–C evolution from the mineralization of switchgrass residues and switchgrass biochars with or without supplemental N. Means of carbon evolved are significantly different ($p \leq 0.05$) when letter located at the top of each bar is different.

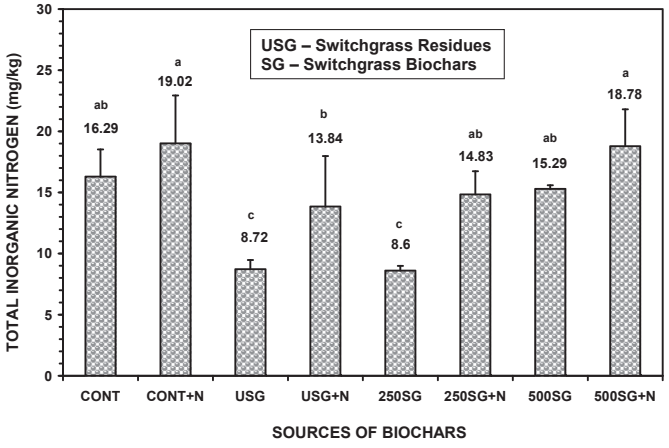

Fig. 3. Total inorganic nitrogen mineralized from switchgrass residues and switchgrass biochars with or without supplemental N. Means of total inorganic nitrogen are significantly different ($p \leq 0.05$) when letter located at the top of each bar is different.

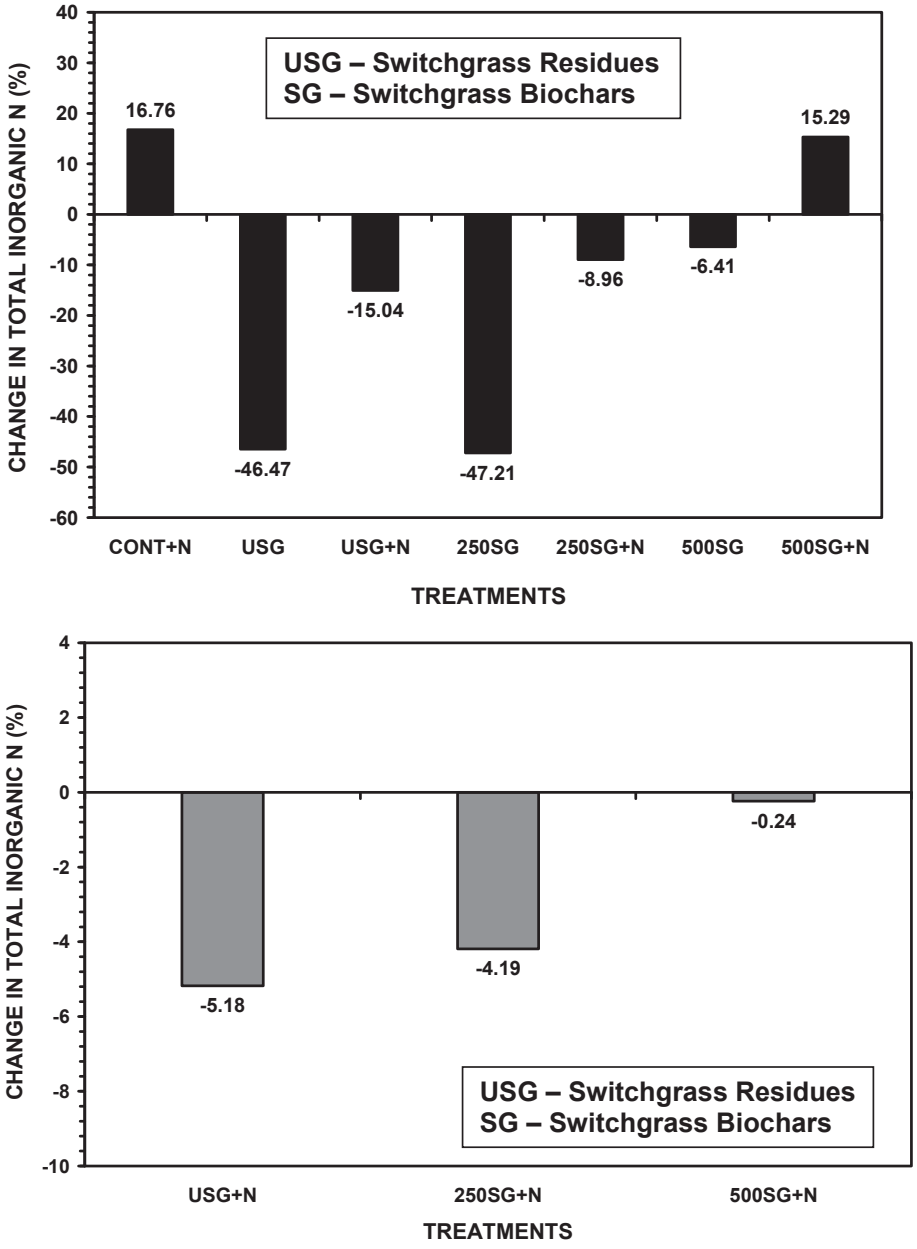

Fig. 4. Comparative changes in the amount of total inorganic nitrogen mineralized from the switchgrass residues and biochars when compared with the control soils with or without supplemental N.

2009; Lehmann, 2007). Turnover times and decomposition rates of biochars in soils and long term storage function are under investigation and results vary widely in the literature. These conditions are due to differences in biochar structure, availability of N species and microbial populations capable of decomposing the biochar. In our present study, we investigated the contrasting effects of switchgrass residues and its conversion to switchgrass biochars on carbon-nitrogen mineralization in a highly weathered Coastal Plain Ultisols.

We hypothesized that SG with or without N would deliver more positive effects on C and N mineralization than USG. Biochar has substantial potential for soil improvement because of its unique physical, chemical and biological properties and their interactions with soil and plant communities. Evidence suggests that biochar application to soil may increase the overall net soil surface area (Chan et al., 2007) and consequently, may improve soil water and nutrient retention (Downie et al., 2009). The ability of SG and/or USG to alter the nutrients during this study appears to be a direct result of nutrients available in the SG and USG themselves, and is also likely influenced by indirect benefits associated with SG and USG properties. The composition of the uncharred feedstock (USG) contained a range of C, H, O, N and S concentrations which are lower than their biochar equivalents (250SG and 500SG). After pyrolysis of uncharred feedstocks (@250 °C and 500 °C), some elements in biochars were concentrated due to loss of volatile materials, while some elements experienced concentration declines (Table 1). The C content of biochars has increased significantly while the H and O contents both decreased with increasing temperature because of carbonization and dehydration reactions during pyrolysis. The resulting C distribution among aliphatic, aromatic and carbonyl group in 250SG and 500SG could have had affected the cumulative and net CO_2–C evolution in our study. Pyrolysis of

uncharred switchgrass in the lower temperature (250 °C) was shown to result in biochars retaining larger portion of their volatile materials which are mostly alipathic-C structures. Pyrolysis at the higher temperature regime (500 °C) resulted in more devolatilization of organic compounds (i.e., aliphatic, O-containing polysaccharides) from the biochar's matrix (Novak et al., 2009b). Higher temperature pyrolysis favors biochars to have mostly of polycondensed aromatic structures which are more stable, less prone to C mineralization and/or decomposition (Novak et al., 2014). As shown in our study, soils with 500SG had the least amount of CO_2–C evolved (31 mg g^{-1}) compared with greatest amount of CO_2–C evolved in USG + N (315 mg g^{-1}).

A number of factors could have affected the C and N mineralization of applied SG and USG in our study. The rapidity and stability with which given biochars or residues are oxidized in the soil will depend on biochars' physical and chemical composition and the physical and chemical conditions of the surrounding soil environment (Stevenson, 1994). In addition, the C:N ratio of the biochars, age of the feedstocks and the degree of disintegration or particle size of the biochars govern the rate of their decomposition. Carbon and N mineralization rates in the soil are a function of the C and N pools available to microorganisms. Typically as C:N ratios increase immobilization of N occurs (Sigua et al., 2014). Additions of biochars or residues to the soil add another dimension to both C and N pools already in the soils. It is well known that biochars produced from manure-based feedstocks have greater ash and N contents than lignocellulosic-based biochars (Cantrell and Martin, 2012; Spokas et al., 2012; Novak, et al., 2009a, 2009b). The type of biochars that we used in our study was produced from lignocellulosic feedstocks (switchgrass) with higher C:N ratio ranging from 129:1 (250SG) to 250:1 (500SG). Other properties of the USG and SG were described in Table 1.

Results of our study suggest that application of USG and SG with or without supplemental N in the short-term caused N immobilization resulting in the reduction of NH_4–N and NO_3–N could be related to the mineralization-immobilization turnover ratio (MIT) of N in the soil. According to the hypothesis of MIT in the soil, incorporation of crop residues like the switchgrass residues in the soil causes a rapid increased in the microbial biomass on and around the residue particles and the soil microbial biomass will act both as a sink for nutrients and as a catalyst for decomposition (Jensen, 1997; Gilmour et al., 1985). Immediately after adding a C substrate to the soil, the energy and growth substrates generated by heterotrophic metabolism will increase microbial biomass and hence the N demand of decomposer populations. The decomposition rate of organic materials added to soil is generally most rapid during the first weeks (Gilmour et al., 1985; Sorensen, 1981). Everything else being equal, materials added to the soil with a C:N ratio greater than 24:1 will result in a temporary N deficit (immobilization), and those with a C:N ratio less than 24:1 will result in a temporary N surplus. Since the average C:N ratio of the switchgrass residues (~94:1) and switchgrass biochars (~194:1) in our study is greater than 24:1, this may have had resulted in N deficit (Fig. 4). The resulting N deficit following incorporation of USG could have had a negative influence on C mineralization in the soil. The recalcitrant nature of biochar suggests that few components contained in biochar would contribute to immobilization of N (DeLuca et al., 2009). Additional research is needed to understand the short- and long-term immobilization and mineralization of applied biochars in the soil. Estimates of net carbon mineralized or converted to CO_2 from biochars decomposition are needed to improve our understanding on both the efficacies of biochars in enhancing soil quality, carbon sequestration and biochar stability in soils (Sigua et al., 2014).

Another possible explanation for the reduction of total inorganic N upon SG addition to the soil is due to the high cation exchange capacity of biochars adsorbing more NH_4–N, thus becoming unavailable for nitrification, resulting in reduced NO_3–N nitrification. Yao et al. (2012) conducted a sorption study, in which most biochars had the capacity for removing NH_4^+ from aqueous solutions, independent of the biochar pyrolysis temperature. Major et al. (2009) mentioned that biochar porosity could contribute to nutrient adsorption. Knowles et al. (2011), Nelissen et al. (2012) and Novak et al. (2010) also observed net NO_3^- immobilization with biochar addition.

5. Summary and conclusion

In summary, switchgrass biochars and switchgrass residues had contrasting effects on nitrogen mineralization in a highly weathered Ultisol in Coastal Plains region. Cumulative and net CO_2–C evolution was increased by the additions of SG and USG especially when supplemented with N. Soils treated with 250SG had the least amount of TIN while the greatest amount of TIN was observed from the CONT + N. Results suggest that application of SG in the short term may cause N immobilization resulting in the reduction of TIN. Our research demonstrates that care has to be taken when applying biochar because it could affect crop growth and productivity as a result of potential N immobilization. Biochar application might in some cases require a supplemental N fertilization to avoid crop growth retardation. As a precautionary measure, there is a need to consider applying biochar some months before the main crop season starts to avoid negative effects of N immobilization on crop performance.

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