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# Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil

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## HIGHLIGHTS

- Short-term field study conducted comparing soil quality under HA, WTR, and biochar.
- Biochar significantly increased soil-C and $N_2$-surface area and reduced bulk density.
- Only WTR significantly increased soil microporous surface area compared to control.
- Cumulative $N_2O$ emission was significantly decreased in the biochar-amended soil.
- WTR and HA resulted in net soil C losses and biochar as a soil C gain.

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## ABSTRACT

Short and long-term impacts of biochar on soil properties under field conditions are poorly understood. In addition, there is a lack of field reports of the impacts of biochar on soil physical properties, gaseous emissions and C stability, particularly in comparison with other amendments. Thus, three amendments – biochar produced from oak at 650 °C, humic acid (HA) and water treatment residual – (WTR) were added to a scalped silty-loam soil @ 0.5% (w/w) in triplicated plots under soybean. Over the 4-month active growing season, all amendments significantly increased soil pH, but the effect of biochar was the greatest. Biochar significantly increased soil-C by 7%, increased sub-nanopore surface area by 15% and reduced soil bulk density by 13% compared to control. However, only WTR amendment significantly increased soil nanopore surface area by 23% relative to the control. While total cumulative $CH_4$ and $CO_2$ emissions were not significantly affected by any amendment, cumulative $N_2O$ emission was significantly decreased in the biochar-amended soil (by 92%) compared to control over the growing period. Considering both the total gas emissions and the C removed from the atmosphere as crop growth and C added to the soil, WTR and HA resulted in net soil C losses and biochar as a soil C gain. However, all amendments reduced the global warming potential (GWP) of the soil and biochar addition even produced a net negative GWP effect. The short observation period, low application rate and high intra-treatment variation resulted in fewer significant effects of the amendments on the physicochemical properties of the soils than one might expect indicating further possible experimentation altering these variables. However, there was clear evidence of amendment–soil interaction processes affecting both soil properties and gaseous emissions, particularly for biochar, that might lead to greater changes with additional field emplacement time.



## 1. Introduction

Soil degradation and nutrient depletion are a global concern. Soil restoration techniques to increase soil organic matter (SOM), and stability of soil carbon (C) are required to increase productivity and minimize risks of soil degradation and environmental pollution. To this end, impacts of a range of agricultural and industrial by-products (waste materials) and composts have been studied as soil amendments to enhance soil physical properties (SerraWittling et al., 1996; Sikora and Yakovchenko, 1996; Wells et al., 2000; Zebarth et al., 1999), availability

*Abbreviations:* AC, ash content; AWC, available water capacity; BD, bulk density; C, carbon; CEC, cation exchange capacity; EC, electrical conductivity; GHG, greenhouse gas; GMD, geometric mean diameter; GWP, global warming potential; HA, humic acid; MRT, mean residence time; MWD, mean weight diameter; OM, organic matter; P, phosphorus; PR, penetration resistance; SA, surface area; SOM, soil organic matter; VM, volatile matter; WHC, water holding capacity; WSA, water stable aggregate; WTR, water treatment residual.

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of plant nutrients (Tejada et al., 2001), increase SOM concentrations and populations of beneficial microbes (Freixo et al., 2002; Lal and Kimble, 1997; Madrid et al., 2007; Reeves, 1997; von Lutzow et al., 2002), and decrease incidences of plant pathogens (Abawi and Widmer, 2000). A range of environmentally-friendly industrial and agricultural by-products have also been tested for their ability to minimize losses of nutrients by leaching and transport of soil contaminants and nutrients such as phosphorus (P) in water runoff (Agyin-Birikorang and O'Connor, 2007; Glaser et al., 2002; Smith et al., 2004). Humic acid (HA), water treatment residual (WTR) and biochar are considered to be among the most promising soil amendment materials for serving these broad ranging purposes.

Humic substances, consisting of HA and fulvic acid, are the dark colored heterogeneous complex organic components of soil that are important to soil fertility. They are formed naturally from plant and animal residues by decomposition and re-synthesis processes (Senesi and Plaza, 2007). Application of HA may improve soil characteristics by buffering pH, chelating micronutrients (Kudeyarova, 2007; Mackowiak et al., 2001; Motojima et al., 2012), and increasing cation exchange capacity (CEC) and available water capacity (AWC) of soil (Senesi and Plaza, 2007; Sharif et al., 2002; Soler-Rovira et al., 2010; Tahir et al., 2011). Coal-derived HA substances, the type used in this study, can increase water retention, AWC and aggregate stability of degraded soils (Piccolo et al., 1996). Despite the consensus that HA could be a promising soil amendment, limited field-scale research has been carried out to understand the effects of HA on soil physical properties, greenhouse gas (GHG) emissions and stability of soil C.

The WTRs, by-products of the water clarification process, may be another effective environmental remedient. For example, application of WTR reduced P leaching from a coastal sandy soil (Ippolito et al., 2011), and water soluble P concentration in a manure-impacted soil (Agyin-Birikorang et al., 2007). Application of WTRs can have positive benefits in regard to (i) reducing heavy metal runoff (Fan et al., 2011; Mahmoud, 2011), (ii) enhancing soil physical quality (Hsu and Hseu, 2011; Park et al., 2010), and (iii) increasing crop yield (Hsu and Hseu, 2011; Mahdy et al., 2009; Oladeji et al., 2009; Park et al., 2010; Titshall and Hughes, 2009). Soil application of WTRs increased pH, aggregate stability, porosity, water holding capacity (WHC), and saturated hydraulic conductivity, and decreased bulk density (BD) in a range of soils (Hsu and Hseu, 2011; Park et al., 2010) with attendant improvements in crop growth (Hsu and Hseu, 2011; Mahdy et al., 2009; Oladeji et al., 2009). While WTR amendment might be expected to decrease SOM degradation via sorptive protection, data on GHG emissions and stability of C in WTR-amended soil are lacking.

The term 'biochar' refers to the solid carbonaceous product of pyrolyzed biomass that is intentionally produced for use as a soil amendment. Considerable progress has been made in understanding its properties, sorption ability, and effects on plant growth when applied to soils. For example, biochar amendments can increase soil pH, base saturation, available nutrient content, nutrient retention and CEC (Glaser et al., 2002; Moreira et al., 2005; Mukherjee and Zimmerman, 2013; Tiessen et al., 1994), and decrease Al toxicity (Glaser et al., 2002; Kishimoto and Sugiura, 1985; Tryon, 1948). Addition of hardwood-derived biochar to sandy and loamy soils was shown to effectively increase CEC 1.5 times and base saturation nine times, and significantly increase available K, Ca, Mg, total N and P (Glaser et al., 2002; Tryon, 1948). Seed germination, plant height and crop yield were doubled following miombo wood-derived biochar amendment (Chidumayo, 1994; Glaser et al., 2002). Several column leaching studies with biochar-amended soils have shown enhanced nutrient release after biochar addition (Laird et al., 2010a; Mukherjee and Zimmerman, 2013), though these results varied strongly with biochar and soil type. While available information shows that the use of biochar can increase soil surface area (SA) (Laird et al., 2010a; Laird et al., 2010b; Liang et al., 2006), decrease BD (Chen et al., 2011; Jones et al., 2010; Laird et al., 2010b), and increase WHC (Jones et al., 2010; Laird et al., 2010b; Uzoma et al., 2011), there is a lack of data on the effects of biochar on soil physical properties under field conditions or these parameters measured in conjunction with crop yields (Mukherjee and Lal, 2014a).

Among the three amendments, HA, WTR and biochar, only biochar has been studied widely for its effects on GHG emissions and these have mainly been laboratory incubation studies that do not necessarily replicate native processes including rhizosphere processes, bioturbation and aggregation and effects of weathering (Kuzyakov et al., 2009). In general, biochar $CO_2$ emissions have been found to increase with heating temperature and duration (Zimmerman, 2010), but also varied with biomass and climate (Jones et al., 2011; Mukherjee and Lal, 2014a; Scheer et al., 2011; Zimmerman et al., 2011). Some studies have also reported reduction in $N_2O$ emissions from biochar-amended soils, perhaps due to increases in soil aeration (Castaldi et al., 2011; Rogovska et al., 2011; Zhang et al., 2012a). However, both increased (Rondon et al., 2005; Spokas et al., 2009; Spokas and Reicosky, 2009) and decreased $CO_2$ emissions (Liu et al., 2011) have been reported from biochar-amended soils. Similarly, $CH_4$ emission from soil may be either enhanced or suppressed by biochar addition (Liu et al., 2011; Rondon et al., 2006; Rondon et al., 2005).

It is difficult to compare the relative benefits of different amendment types because few studies have simultaneously examined a wide range of soil and plant responses to a number of materials. In addition, only a few field studies have monitored changes in soil physical properties with biochar amendment (Mukherjee and Lal, 2014a) and several drawbacks of biochar in this context are recently reported (Mukherjee and Lal, 2014a). Thus, a field study was conducted over 16 weeks, comparing the effects of biochar with two other non-traditional amendments (WTR and HA) on the characteristics of a simulated degraded soil, and GHG emissions under soybean (*Glycine max*). The biochar chosen for this study, oak (*Quercus lobata*) charred at 650 °C (oak-650), has the potential to improve soil conditions based on previous studies (Mukherjee and Zimmerman, 2013; Mukherjee et al., 2011). It is hypothesized that HA (with a high complexation ability) and WTR (with high pH and SA) will improve soil characteristics, and positively impact C stability and soil fertility. Specific objectives of the study were to: (i) assess changes in soil properties over a short time horizon, (ii) understand the relationship between the evolved physicochemical characteristics of the amended soil and GHG emission, and (iii) evaluate the relative short-term effects of these amendments on global warming potential (GWP).

## 2. Materials and methods

### 2.1. Materials and field measurements

A field experiment was conducted at the Waterman Farm of The Ohio State University, Columbus, Ohio (40°02′00″N, 83°02′30″W) from June 25th to October 8th, 2012 under a Crosby (fine, mixed, mesic, Aeric Ochraqualf) silt loam soil (Abid and Lal, 2009). Previous studies conducted at this research site found that on average, about half of the annual $CO_2$ efflux occurs, during the experimental period of time, a single summer growing season (Datta et al., 2013; Shrestha et al., 2009; Shrestha et al., 2013; Ussiri and Lal, 2009; Ussiri et al., 2009), as the ground is frozen or covered by snow during much of the rest of the year.

Commercial coal-derived HA was obtained from Sigma Aldrich, MO, USA and aluminium WTR was collected from a water treatment plant located in Columbus, Ohio. Biochar was produced from oak wood (5 × 5 × 30 cm pieces), collected in Gainesville, Florida, by combustion for 3 h at the peak temperature of 650 °C in a lidded container sealed loosely to allow smoke to exit. Detailed information on biochar preparation and chemical and physical characteristics of the freshly prepared oak-650 biochar have been presented elsewhere (Kasozi et al., 2010; Mukherjee et al., 2011; Zimmerman, 2010). The coarse size fraction