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Biochar and Soil Heat and Water Flow

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Mini Review

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Abstract

Biochar has been identified as a soil amendment and potential tool for mitigating climate change and sequestering carbon in soils. Over the last fifteen years, scientific literature devoted to the use biochar as a soil amendment has increased significantly. However, researchers have acknowledged shortcomings in data availability and the need for additional studies. Specifically, studies related to the impact of biochar on soil physical properties and processes are limited compared to those that have evaluated the effects of biochar on soil chemical and biological processes. Most studies that have evaluated the effects of biochar on soil physical properties often have examined biochar's effects on soil bulk density, porosity, and water retention. Limited attention has been given to the effect of biochar on soil heat and water flow. The lack of studies related to the effect of biochar on soil heat and water flow has prompted the writing of this mini-review. This mini-review provides a critical review of studies that have examined the effect of biochar on soil temperature and soil moisture, coupled heat and water transfer, and thermal properties. Due to the importance of soil heat and water flow for a number of physical, biological, and chemical properties and processes that occur in the soil future, direction for studies to evaluate the effect of biochar on soil heat and water flow is provided.

Keywords: Biochar; Soil; Heat; Water; Thermal

Introduction

Agriculture is currently faced with the trilemma of helping to provide solutions to the global grand challenges of increased food and energy production for an increasing population while preserving environmental sustainability. In an effort to lessen our dependence on finite fossil fuel resources and to reduce the threat of global climate change due to greenhouse gas emissions, the United States has become interested in renewable biofuel energy resources. Thermochemical transformation of lignocellulosic materials, known as biomass into liquid energy products, has been touted as a way to secure America's energy future through the production of renewable biofuels and to reduce the threat of global climate change. Potential biomass feedstocks include perennial plant species, crop residues, harvested wood and forestry residues, and municipal and industrial wastes [1,2]. Pyrolysis, the heating of biomass with little or no oxygen, has been identified as a simple, inexpensive, and robust process for producing biofuels [3]. The pyrolysis process for producing biofuels results in the production bio-oil, syn-gas, and biochar.

Biochar, a product of the pyrolysis process, has been identified as a soil amendment and a potential tool for climate change mitigation through the sequestration of carbon in soil. Further, biochar has been proposed as a key component for developing sustainable agronomic-biomass- bioenergy production systems [4]. The application biochar as a soil amendment has been studied to determine its impact on soil properties. Many studies have highlighted the potential of biochar to reduce the emission of greenhouse gases [5-8]. Trace gas emissions (methane and nitrous oxide) were also found to be reduced due to the application of biochar [9]. Biochar related studies have investigated the potential of biochar for absorbing heavy metals organic chemicals, and bacteria in soil [10-12]. Numerous studies have also investigated the effect of biochar on various components of soil quality. Laird et al. [4] found that biochar amendments increased organic C by 69% and cation exchange capacity up to 20% in a Midwestern agricultural soil.

Due to its unique physical properties, high surface area and low bulk density, biochar is thought to improve a range of soil physical properties such as total porosity, pore-size distribution, soil bulk density, soil moisture content, water holding capacity, and plant available water. Gaskin [13] found significant differences in the amount of water retained in soils to which biochar was applied at a rate of 88 t ha^{-1} compared to those of non-amended soils in the matric potential range of -0.01-0.20 MPa. In a study on the impacts of biochar application on sand-based turfgrass rootzones, Brockhoff et al. [14] found that saturated hydraulic conductivity decreased as biochar concentrations increased, thereby improving overall water storage. In a laboratory study, Ibrahim et al. [15] investigated the effect of conocarpus biochar additions on soil the soil hydraulic properties of a sandy loam soil and found that biochar additions reduced soil water evaporation and improved soil water retention.

While these studies highlight the potential impacts biochar may have on soil physical properties, overall, studies regarding the impact of biochar on soil physical properties and processes compared to those related to the impact of biochar amendments on soil chemical and biological properties are still limited [16,17]. Studies on the impact of biochar on soil physical properties have been limited to laboratory settings and sieved repacked soils where values of soil moisture retention and hydraulic conductivity could be an artifact of soil packing. Specifically, there is a lack of information regarding the impact of biochar on heat and water transfer near the soil surface. This has resulted in a crucial knowledge gap related to the impact of biochar on soil thermal and moisture regimes of in-situ agricultural soils.

Biochar and Soil Temperature and Soil Moisture

Knowledge of fluctuations of soil temperature and soil moisture is critical to understanding many physical, chemical, and biological processes in soil and plant science. In soil, many hydraulic properties, such as the infiltration rate and hydraulic conductivity, vary with soil temperature and soil moisture. It has been long recognized that the amount of water present in the soil and the soil temperature affect soil microbial activity. Degradation of agricultural pesticides by microbes is influenced by soil temperature and water content. Soil temperature and water content also affect the emission of greenhouses gases from soil. Perhaps, the largest influence soil temperature and soil moisture have is on plant growth and development. Seed germination is extremely dependent on soil temperature and soil moisture. The germination rate of seeds decreases with soil temperatures. The soil temperature can also influence the mechanism by which water is transported to seeds during the germination process. The uptake of plant nutrients and water occur with an optimum soil temperature range. Plant growth is also dependent on the available soil moisture which can vary with soil and atmospheric conditions.

Changes in soil temperature and soil moisture due the application of biochar can be critical to a number of physical, chemical, and biological processes that occur in the near surface soil environment. However, most studies have only focused on the effects of biochar application on soil surface albedo and soil temperature. The surface albedo, the fraction of shortwave solar radiation reflected by the soil surface, plays a major role in the energy balance because the majority of the energy partitioned at the soil surface originates from shortwave solar radiation [18]. Soil surface albedo was reduced by 80% after application of biochar in plots treated with biochar at rates of 30 to 60 t ha^{-1} compared to control in bare soil conditions [19]. Similarly, Verheijen et al. [20] and Meyer et al. [21] found reductions in soil surface albedo with increasing application rates of biochar to soil. Soil surface albedo and soil temperature was affected due the application of biochar in separate studies by Zhang et al. [22] and Usowicz et al. [23]. Zhang et al. [22] found when compared to the control biochar application lowered the soil temperature in high temperature soils and increased the temperature in low temperature soils. Only one study has examined the effect of biochar application on soil temperature and soil moisture distributions.

Ventura et al. [24] found soil surface temperature increased in plots amended with biochar at application rates of 30 and 60 t ha^{-1} with respect to a non-amended control plot, while no differences in soil temperature were detected at a soil depth of 7.5 cm. The authors further note no differences in soil moisture distributions were found between the biochar amended plots and the non-amended control plots. Prediction of soil thermal and moisture regimes requires knowledge of heat and moisture transfer. Analysis of soil thermal and moisture regimes often considers heat and water transfer processes separately. Heat and water transfer processes in soil are interrelated, particularly near the soil surface.

Biochar and Coupled Heat and Water Transfer in Soil

Coupled heat and water transfer has long been recognized to occur in unsaturated soil near the surface in processes such as evaporation. Diurnal fluctuations in net radiation and air temperature are responsible for coupled heat and water transfer. During the night the soil surface cools, which results in an upward thermal gradient and the transfer of heat to the surface from the warm subsoil. A drop in the temperature below the dew-point temperature can cause water vapor to condense at the soil surface, which liberates more heat. Water also moves upward from the subsoil to re-wet the soil near the surface that dried the previous day. Thermal gradients are reversed in the morning as solar radiation warms the soil surface. Liquid water near the soil surface vaporizes and is transported into the atmosphere while taking large quantities of heat with it. Water vapor is driven by the thermal gradient from the soil surface simultaneously with evaporation from the warmer soil above. This dynamic and intricate cycle begins again as the sun goes down. Although the importance of coupled heat and water transfer in unsaturated soil is well known, studies examining the effect of biochar on coupled heat and water transport in soil are lacking. An improved understanding of coupled heat and water transfer and how they are altered due to the addition of biochar is needed to understand the effect of biochar on agrophysical, plant, and microbial processes in the near surface soil environment.

Biochar and Soil Thermal Properties

The simultaneous movement of heat and water in soil are strongly related to soil thermal properties [25]. Knowledge of soil thermal properties is critical for understanding the partitioning of energy and the transfer of heat and water at and near soil surfaces. Soil thermal properties include thermal conductivity, volumetric heat capacity, and thermal diffusivity. The soil thermal conductivity describes the ability of a soil to transmit heat. Soil thermal diffusivity describes the rate at which temperature change transmits through a soil. Volumetric heat capacity is related to a soil's ability to store heat. Soil thermal properties are affected by soil mineralogy, air-filled porosity, soil structure, water content, bulk density, and organic matter [26-28]. The application of biochar to soil can lead to changes in soil bulk density, porosity, and water holding capacity. These changes can potentially lead to alteration of soil thermal properties and subsequently affect the movement of heat and water in the near surface soil environment. However, only a few studies have investigated the effect of biochar on soil thermal properties.

The few studies [22,23,25] that have examined the effects of biochar on soil thermal properties have indicated the application of biochar to soil can lead to reductions in soil thermal conductivity. Zhao et al. [25] found that when compared to a non-amended soil, the application of corncob biochar to a sandy loam soil at two different rates decreased soil thermal conductivity and soil thermal diffusivity by 0.3 to 32.2% and 0.6 to 21.5%, respectively. In a separate field study, Zhang et al. [22] found after five years soil thermal conductivity decreased significantly by 3.48% and 7.49% for biochar application rates of 4.5 and 9.0 t ha^{-1} when compared to a non-amended control soil. Likewise, Usowicz et al. [23] found the addition of biochar at application rates of 11, 22, and 33 t ha^{-1} reduced soil thermal conductivity and diffusivity compared to a control soil. Alterations in soil thermal properties in the previously cited studies were attributed to the characteristics of the biochar and changes in bulk density and water content due to the addition of biochar. For example, Zhao et al. [25] noted a strong positive relationship between soil thermal conductivity and bulk density and between soil thermal conductivity and water content. Further, they noted soil thermal conductivity decreased with increasing amounts of biochar leading to a strong negative relationship between soil thermal conductivity and biochar amount.

Conclusion

The limited literature indicates the application of biochar to soil can influence soil temperature and soil moisture and alter soil thermal properties in the near surface soil environment. However, studies examining the effect of biochar on coupled soil heat and water transfer are non-existent. Understanding the potential effects of biochar on soil thermal properties and the movement of heat and water in soil is critical for understanding the effect of biochar on chemical, biological and physical processes that occur near the soil surface. Future studies across different soils are needed to fully understand the effects of biochar on soil thermal properties and the movement of heat and water near the soil surface. Specifically, the application of biochar to soil and its potential to alter soil thermal properties and soil physical properties such as bulk density, porosity, and soil water content warrant detailed investigations designed to evaluate temporal and spatial changes in these properties and their effects on coupled heat and water transfer in the near surface soil environment.

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