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Differences in biomass and water dynamics between a cotton-peanut rotation and a sweet sorghum bioenergy crop with and without biochar and vinasse as soil amendments

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A B S T R A C T

Land use conversion of row crops to bioenergy cropping systems in the southeastern United States (U.S.) creates concerns associated with water use and NO_3-N leaching. Production of energy from biomass is associated with large amounts of byproducts generated during biofuel processing. Biochar and vinasse are two nutrient rich byproducts that could be land-applied to bioenergy crops to reduce reliance on synthetic fertilizer. However, effects on water dynamics of applying these byproducts to support biomass production is poorly understood, particularly when bioenergy crops replace traditional row crops. Thus, this study aimed to compare a cotton (*Gossypium hirsutum* L.)-peanut (*Arachis hypogaea* L.) rotation to sweet sorghum [*Sorghum bicolor* (L.) Moench] receiving annual applications of biochar and vinasse, on biomass yield, crop evapotranspiration, water use efficiency (WUE), NO_3-N leaching, and soil volumetric water content. A field study was conducted from 2013 to 2015 to assess the following treatments: cotton + 150 kg N ha^{-1} (COT), peanut + 30 kg N ha^{-1} (PEA), and sweet sorghum receiving one of the following i) 30 kg N ha^{-1} (S30); ii) 30 kg N ha^{-1} + biochar (S30B); iii) 30 kg N ha^{-1} + vinasse (S30V); and iv) 150 kg N ha^{-1} (S150). Similar aboveground dry matter yields were obtained in 2013 and 2015 for cotton and all sweet sorghum treatments and were on average 19 Mg ha^{-1} for both years. S30 and S150 achieved similar yields. Sweet sorghum and COT exhibited the highest WUE (~5 g kg^{-1}). S30B increased soil moisture retention at 0–0.2 m depth 36, 29, and 24% in 2013, 2014, and 2015, respectively. Biochar incorporated at 0.15 m soil depth increased soil moisture retention down to 0.4 m. Low N rate application combined with biochar in S30B could represent an alternative management practice to minimize N leaching, recycle nutrients, and increase soil water retention if sweet sorghum were to be widely adopted by farmers in the southeastern U.S.

1. Introduction

Cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) are two major row crops generally grown in rotation in the southeastern United States (U.S.). Total area in 2016 dedicated to production of these crops was about 1.07 million ha combining Alabama, Florida, and Georgia (NASS, 2016). This rotational cropping system could potentially be replaced by bioenergy crops in order to meet the production goal of 36 billion gallons of ethanol by 2022 established in the Energy Independence and Security Act (Sissine, 2007). Changing species in agricultural systems to bioenergy crops will not only impact biomass productivity, but also could potentially alter the provisioning of ecosystem services, such as regulation of water cycle to support crop evapotranspiration, carbon (C) and nitrogen (N) fluxes, erosion control, and biodiversity (Werling et al., 2014) in ways that are poorly understood. For instance, the excessive removal of biomass in bioenergy crops poses detrimental effects on soil and water quality due to minimum amounts of crop residue left in the field after harvest (Blanco-Canqui, 2013), whereas in the majority of conventional cropping systems only the plant component with economic importance is harvested

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and remaining plant biomass is either left on the surface or incorporated into the soil, which reduces soil evaporative losses and recycle nutrients back to the soil (Laird, 2008).

Sweet sorghum [*Sorghum bicolor* (L.) Moench], an annual crop, is a promising biofuel candidate species because of its high agronomic performance with low fertilizer requirements compared with other row crops, and adaptability to environmental conditions typical of the southeastern U.S. (Erickson et al., 2011). Additionally, sweet sorghum for feedstock has demonstrated potential as a dedicated bioenergy crop due to its versatility to fit thermal and chemical biomass conversion platforms for biofuel and energy generation (Rooney et al., 2007). Sweet sorghum has been reported to potentially produce between 70 and 80 Mg total fresh biomass ha^{-1} in the southeastern U.S. (Erickson et al., 2012; Fedenko et al., 2015). Evidence suggests that sweet sorghum has physiological mechanisms to regulate its metabolism to withstand high soil salinity, drought, and flooding for longer periods than other biofuel crops such as sugarcane (*Saccharum* spp.) and corn (*Zea mays* L.) (Vasilakoglou et al., 2011). Significant research has been carried out on sweet sorghum management practices in the southeastern U.S. assessing its performance under low N and K input levels (Adams et al., 2015a), different planting dates (Erickson et al., 2011), and planting arrangements and densities to maximize biomass yield and make production compatible with equipment and practices of existing cropping systems such as sugarcane (Adams et al., 2015b). These studies consistently demonstrated the high versatility of sweet sorghum to a myriad of management practices and stress conditions with minimum yield loss. Consequently, sweet sorghum is a good candidate crop to be grown as a dedicated bioenergy crop for lignocellulosic biofuel production (Zegada-Lizarazu and Monti, 2012).

The increasing demand for renewable energy from lignocellulosic crops to accomplish national energy goals (US-DOE, 2009) is coupled with increased production of mineral-rich residues (i.e. byproducts) from the conversion of biomass to fuels either by biochemical or thermochemical processes. Bioenergy facilities processing feedstocks (i.e. sugarcane, starch crops, lignocellulosic material) to constituent sugars that are subsequently fermented to ethanol also produce a fermentation residue commonly called vinasse (Wilkie et al., 2000), and production of biogas from plant biomass generates a solid residue named biochar (Lehmann and Joseph, 2009). Both of these byproducts are nutrient-rich but if not properly managed, may adversely affect ecosystem services, through eutrophication and soil and water pollution.

Limited information exists regarding the effects of land-applying cellulosic vinasse on productivity of dedicated bioenergy crops and ecosystems services such as maintenance of soil fertility, soil moisture retention, and preservation of water quality (Gell et al., 2011; Power, 2010), but positive reports on the application of sugarcane vinasse complementing mineral fertilization for sugarcane indicate benefits for crop yield (Gomez and Rodriguez, 2000). Conversely, biochar literature has grown exponentially in the last decade with a strong focus on carbon sequestration and agronomic benefits attributed to amelioration of specific soil constraints that depress crop productivity (Liu et al., 2013). Some of the benefits reported for biochar application to soil include compaction reduction (Hardie et al., 2014), increase in soil moisture content (Glaser et al., 2002) and stimulation of larger root length density in the soil layers where it is applied (Reyes-Cabrera et al., 2017). Therefore, biochar application could increase sweet sorghum productivity and resilience to abiotic stresses such as drought.

Vinasse and biochar residues could be used to supplement sweet sorghum nutritional requirements and increase the productivity of the bioenergy cropping system through nutrient recovery potentially reducing reliance on synthetic fertilizers. Thus, there is a clear need to assess ecosystem services offered by sweet sorghum grown for bioenergy, especially when vinasse and biochar residues are land-applied as a nutrient recovery strategy. Therefore, the objectives of this study were to compare aboveground biomass production between a traditional cotton-peanut rotation and a sweet sorghum monoculture grown for feedstock. Furthermore, we evaluated the effects of land application of vinasse and biochar residues to sweet sorghum on aboveground biomass accumulation, soil moisture dynamics, and NO_3-N leaching. The hypotheses tested were that i) land application of biochar and vinasse residues combined with minimum N fertilization rate could meet sweet sorghum nutrient requirement for high biomass productivity, ii) land application of biochar and vinasse residues to sweet sorghum will increase soil water-holding capacity, and iii) sweet sorghum receiving land application of biochar and vinasse residues will reduce NO_3-N leaching compared with cotton, peanut, and sweet sorghum fertilized with commercial N sources.

2. Materials and methods

2.1. Site description and experimental design

A field experiment was conducted at the West Florida Research and Education Center, University of Florida, near Jay, FL (30° 46′ N, 87° 08′ W) from 2013 to 2015. The soil was a Dothan fine sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudult) with 74% sand, 16% silt, 10% clay, 2% organic matter, pH 6, and 5.43 mg NH_3-N kg^{-1} and 0.95 mg NO_x-N kg^{-1}. Field capacity and wilting point were 0.18 and 0.08 $cm^3\ cm^{-3}$, respectively. The experimental site was maintained fallow for three years before experiment initiation, and previously was under a conventional cotton-cotton-peanut rotation.

The experiment was established in a randomized complete block design with four replications. Treatments consisted of different cropping systems: i) cotton + 150 kg N ha^{-1} (COT); ii) peanut + 30 kg N ha^{-1} (PEA); iii) sweet sorghum monoculture + 30 kg N ha^{-1} (S30); iv) sweet sorghum monoculture + 30 kg N ha^{-1} + 5 Mg biochar ha^{-1} (S30B); v) sweet sorghum monoculture + 30 kg N ha^{-1} + 8 Mg vinasse ha^{-1} (S30V); and vi) sweet sorghum monoculture + 150 kg N ha^{-1} (S150). Sweet sorghum monocultures are not a desirable production approach when considering negative long-term effects on productivity, integrated pest management, and soil health. However, in order to adequately assess the effect of fermentation residues on biomass and water dynamics, we had to implement a continuous sweet sorghum system to avoid confounding effects associated with rotation. Additionally, PEA was fertilized with 30 kg N ha^{-1} annually in order to ensure that we had a common NO_3-N leaching rate baseline for all plots and treatments for comparison purposes. However, we recognize that N fertilization for peanut is not commonly done. All phases of the conventional cotton-peanut rotation were present in all years. Plots were 110 m^2 (10 m by 11 m) and separated by 9 m buffer areas that were maintained fallow.

2.2. Cultural practices

The experimental area was disk-tilled to 0.15-m soil depth before planting each year. Cotton (PHY 333 WRF), peanut (Georgia-06G), and sweet sorghum (M81E), were sown on 28 May 2013; 17 June 2014; and 2 June 2015. Crops were planted utilizing 0.9-m inter-row spacing, and intra-row plant spacing was 10, 5, and 5 cm for cotton, peanut, and sweet sorghum, respectively. Seeds were planted at 2-cm depth for all crops.

Each year, all plots received an initial rate of 30 kg N ha^{-1} from 16-4-8 N-P_2O_5-K_2O blended granular fertilizer broadcasted after planting. S150 and COT treatments were fertilized with additional 120 kg N ha^{-1} as ammonium sulfate [$(NH_4)_2SO_4$] 45 days after the first N application. Weeds were controlled in all plots mechanically or with the use of herbicides based on recommended practices for the area (Ferrell et al., 2015a,b,c).

Land application rates of biochar and vinasse residues to S30B and S30V were calculated from reported sweet sorghum dry matter yield in the region equivalent to 16 Mg $ha^{-1}\ yr^{-1}$ (Erickson et al., 2012), and biomass conversion efficiency to energy using pyrolysis and