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Alteration of soil physical properties and processes after ten years of intercropping with native shrubs in the Sahel

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ABSTRACT

Scarcity of plant available water is a major challenge for rainfed agriculture throughout the Sahel. At two long-term experiments in Central and Southern Senegal, optimized intercropping with native woody shrubs, *Piliostigma reticulatum* (DC.) Hochst or *Guiera senegalensis* J.F. Gmel, (elevated densities and annual coppiced biomass returned to soils) have shown significant improvement of soil-plant-water relations, nutrient availability, and crop yields. The objective was to investigate soil physical properties to develop a mechanistic understanding for the observed improvement of water dynamics due to optimized shrub intercropping. The field experiments had a split-plot factorial design with shrubs as the main factor and fertilizer rate (0, 0.5, 1.0. 1.5 times the recommended addition of N-P-K fertilizer) as the subplot factor. This experiment was carried out at the sites of Keur Matar Arame (Keur Matar) with *G. senegalensis* and Nioro du Rip (Nioro) with *P. reticulatum*. Water retention characteristic, unsaturated hydraulic conductivity, surface evaporation, and surface infiltration were measured in the zero fertilizer treatment. At Keur Matar samples were collected from crop + shrub plots near (< 0.5 m) the shrub canopy (CSn), crop + shrub plots far (> 1 m) from the canopy (CSf) and in crop only plots (CO). At Nioro samples were taken in CSn, CSf, CO, and also from bare soil with no crops or shrubs growing (BS). Infiltration in CO plots compared to CSn plots was 75% and 28% higher at Keur Matar and Nioro, respectively. At Keur Matar water retention was significantly higher at wilting point (-1.5 MPa) in the CSn treatment than in the CSf treatment with values of 0.030 and 0.016 $\mathrm{m^3\,m^{-3}}$, respectively. At Nioro there was no significant difference in wilting point water content between treatments. These results indicate that shrubs slow down soil water as it infiltrates in the sandy soils and that the large additions of shrub biomass over a ten year period has had a small but significant effect on water retention at wilting point. This study highlights the role that shrub presence and biomass additions play in altering centimeter-scale soil properties.

1. Introduction

The Sahel is characterized by intensely degraded agricultural soils that receive minimal organic inputs (Lassaletta et al., 2014) and with very low agricultural productivity (FAO, 2015). When available, soil amendment with crop residue or mulch from woody shrubs, manure, or biochar (Liu et al., 2016; Rawls et al., 2003; Lahmar et al., 2011) can lead to an increase in crop yields (Woomer et al., 2004; Dossa et al., 2012). The addition of biochar (Glaser et al., 2002), crop residue (Michels et al., 1995), or low C:N material such as animal or green manure (Snapp et al., 1998) have been shown to improve soil physical properties, although this is not always the case. Jeffery et al. (2015) reported the lack of an effect on water retention, hydraulic conductivity, and aggregation with the addition of biochar. Soil amended with organic materials can improve soil physical properties by increasing the specific surface area (Pennell et al., 1984), the cation exchange capacity (CEC), aggregation (Kong et al., 2005), and porosity as a result of faunal and microbial activity (Mando et al., 1996; Vadakattu and Germida, 1988), but can also increase the hydrophobicity of soil (Jeffery et al., 2015).

Surface biomass additions in the form of mulch also affect surface energy and water fluxes compared to areas with no added biomass (Chung and Horton, 1987). Mulch reduces the amplitude of daily fluctuations in soil moisture and temperature and can also suppress evaporation (Chung and Horton, 1987; Budelman, 1989). Long-term field studies are needed to investigate how organic carbon material

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additions change soil properties in order to detect management effects. Because such studies are costly and difficult to maintain for long periods, relatively few such studies have been carried out in the semi-arid Sahel (Ouattara et al., 2006). Specifically, little information is available for the Sahel on whether biomass additions affect the availability of water to crops as a result of *in situ* microclimatic effects or whether they change the structure of soils.

The native woody shrubs *G. senegalensis* and *P. reticulatum* grow throughout the Sahel (Le Houérou, 1980) and exist in agricultural fields in the regions of Keur Matar Arame (Keur Matar), and Nioro Du Rip (Nioro) at densities of 239 ± 74.6 and 185 shrubs ha^{-1}, respectively (Kizito et al., 2006; Lufafa et al., 2008). Traditional shrub management in the region consists of coppicing the aboveground biomass and piling and burning it in the fields (Lahmar et al., 2011; Dossa et al., 2012). This study adds to a growing number of studies investigating how using a different technique of coppicing the aboveground shrub biomass, cutting it into a mulch of approximately 5 cm pieces, and spreading and tilling it back into the field affects crop production, soils, hydrology, and microbial activity in this unique agroforestry system (Bright et al., 2017; Debenport et al., 2015; Dossa et al., 2009, 2012, 2013; Kizito et al., 2007). Additionally, the presence of woody vegetation used in agroforestry, particularly in the northern, dry parts of the Sahel, can help battle desertification (Nair, 2012).

In 2001, long-term field studies of intercropping with native woody shrubs and surface mulch additions were established at two experimental stations in Senegal. In 2003 additional shrubs were planted at both sites in CS plots to bring shrub density to 1500 to 1833 *G.senegalensis* plants ha^{-1} at Keur Matar and 1000–1300 *P. reticulatum* plants ha^{-1} at Nioro and all coppiced shrub material was returned to soil after each cutting. Shrubs can increase total soil C (Bright et al., 2017; Dossa et al., 2010; Kizito et al., 2006). While previous studies have shown that the presence of native woody shrubs can lead to increased soil moisture through increased infiltration and microclimatic effects (Kizito et al., 2006, 2007) and the potential for hydraulic redistribution (Kizito et al., 2012), and increased crop yields (Dossa et al., 2012; Bright et al., 2017) this study explores further the mechanisms by which the shrubs alter the soil environment for nearby crops. Our two hypotheses are as follows: (1) Ten years of biomass additions of two native shrubs at two sites will increase available soil moisture at a given water potential beneath and outside of the shrub canopy compared to a control site with bare soil; and (2) ten years of biomass additions from two native shrubs will increase infiltration rates of moisture into surface soil beneath and just outside of (> 1 m) from shrub canopies.

2. Materials and methods

2.1. Site description

The study was conducted at two experimental stations in the villages Keur Matar Arame (14° 46′N, 16° 51′W), and Nioro Du Rip (13° 45 N 15° 47′W) located in the central and southern Peanut Basin of Senegal, respectively. These two sites have been under continuous experimental management since 2003 (Dossa et al., 2012; Kizito et al., 2012, 2007).

The soil at Keur Matar is characterized as a Rubic Arenosol (USDA Psamments) (Michéli et al., 2006; Soil Survey Staff, 2016) and is known locally as the Dior series (Badiane et al., 2000). The majority of the material originates from aeolian deposits emplaced by the Harmattan winds (Renaud, 1961). There is a weak crust at a depth ranging from 3 to 7 cm that is found intermittently throughout the plots, except directly beneath the shrub canopy, but otherwise there is no distinct horizonation. The soil texture measured near Keur Matar is 3% clay, 6% silt, 91% sand, and the soil contains 2150 to 3670 mg kg^{-1} total C, 8.6 to 8.8 mg kg^{-1} total inorganic N, and 12.3 to 13.3 mg kg^{-1} extractable P (Table 1, (Dossa et al., 2012)). The area receives a mean annual rainfall of 450 mm but has large fluctuations in the quantity and timing of rain. The water table lies at a depth of 11 m and the ground surface elevation is 54 m above sea level. The slope of the site ranges from 0 to 1% (Google Inc., 2016). This region is dominated by the native *G. senegalensis* shrub.

The Nioro Du Rip region is predominantly occupied by *P. reticulatum* shrubs on a sandy, lateritic area classified in the FAO system as a fine-sandy, mixed Haplic Ferric Lixisol, which is locally known as Deck-Dior (Badiane et al., 2000; USDA, 2015; Kizito et al., 2006). The texture is 77% sand and 16% silt and 6% clay as reported in Nicou (1986) (notice: these textural results do not add up to 100% in the reference) with a total C content of 2510 to 3140 mg kg^{-1}, and a total inorganic N content of 33 and 25.5 mg kg^{-1} in crop + shrub and crop only treatments, respectively (Table 1, (Bright et al., 2017)). There is no distinct horizonation. The area has unimodal rainfall, 750 mm per annum and a mean annual temperature of 32 °C. The water table lies at approximately 18 m depth, and the field site is 18 m above sea level with a slope of 0–2% (Google Inc., 2016).

2.2. Design and management of experimental plots

Research plots at both sites were established in 2003. Prior to 2003, for at least 50 years the sites were in a crop rotation between *Arachis hypogea* (groundnuts) and *Penisetum glaucum* (pearl millet) under local farmer management with shrubs at their native densities. In 2003 additional shrubs were planted in crop + shrub plots to bring their density to 1500 to 1833 shrubs ha^{-1} at Keur Matar and 1000 to 1300 shrubs ha^{-1} at Nioro (Dossa et al., 2012). The experimental design was split-plot with shrubs as the main-plot factor, and N-P-K fertilizer additions of (0 ×, 0.5 ×, 1x, 1.5 − the recommended rate) as the sub-plot factor. Details of the fertilization practices can be found in (Dossa et al., 2012) for Keur Matar, and (Bright et al., 2017) for Nioro. Subplots measured 6 m × 10 m at Keur Matar, 4.5 m × 10 m at Nioro. Soil cores collected for water retention and unsaturated hydraulic conductivity, and field measurements of infiltration with infiltrometers and dye in this study came from the crop only (CO) plots with zero fertilizer and sole cropping of groundnut (2012) or millet (2013), with no shrub biomass added and crop + shrub which includes shrub biomass (CS). The CS plots were sampled within 50 cm of shrub center referred to as crop + shrub “near” (CSn), and greater than 1 m from shrub center crop + shrub “far” (CSf). Sampling schemes varied slightly by measurement type and are outlined in the following sections.

Fields at both sites were prepared for planting by coppicing all of the shrub material before the arrival of the rainy season late May. The largest diameter of the shrub branches were 2 cm, which was the regrowth since the previous rainy season. Once the aboveground material was cut, the shoots and leaves were further cut into 5–10 cm long pieces and incorporated with a shallow sweep type cultivator under horse traction to a depth of 6 cm. Crops were planted in mid-June to early July at Nioro, and in early to mid-July at Keur Matar. The regrowth of shrub material was coppiced, chopped into 5 cm long pieces, and incorporated into the soil three to four times during the year with the implement outlined above. Shrub biomass was incorporated before planting, after crop emergence, at flowering (depending on year and shrub growth), and at harvest. The surface coverage of the shrub mulch in the crop + shrub plots after the first cutting and incorporation but before planting crops was estimated visually at 40–60%, depending on the plot. Subsequent cuttings produced less biomass and less surface coverage. Annual biomass additions vary widely with a minimum from 2011 to 2015 of 1547 kg ha^{-1} and a maximum of 8609 kg ha^{-1} in the zero fertilizer plots at Nioro (Bright et al., 2017).

2.3. Sample collection and Field measurements

Core samples with an inner diameter of 80 mm and a height of 50 mm were collected for water retention and unsaturated hydraulic conductivity measurement using the dual tensiometer evaporation