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Changes in soil hydraulic properties, soil moisture and water balance in *Acacia senegal* plantations of varying age in Sudan

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ABSTRACT

The effects of *Acacia senegal* trees on soil moisture (*SM*) and hydraulic properties in relation to plantations age and associated changes in soil organic carbon (SOC) were investigated and compared to grasslands at two sites in Sudan. Soil hydraulic properties were computed using pedotransfer functions based on texture and SOC, and SM measured using TDR. The measured SM data was used to parametrize a simple daily water balance model in which Hortonian runoff was calculated using the SCS runoff curve number (*CN*) method and evapotranspiration calculated using crop coefficients, K_c, adjusted to seasonal values using *NDVI*. Measured *SM* was higher in the grasslands than plantations, but increased with plantation age, reflecting a similar trend in plantation SOC and plant available water capacities. The modelling resulted in lower runoff from the plantations, increased infiltration, evapotranspiration, reduced drainage and lower *SM*, as shown by measurements. Greater *SM* contents in the grasslands were attributed to lower evapotranspiration and resulted in greater drainage fluxes compared to the plantations. The study highlighted the need for more empirical studies on the effect of tree density and cover on rainfall-runoff relationships, infiltration, evapotranspiration and drainage in drylands, especially those of the drier parts of semi-arid Africa.

1. Introduction

Arid and semi-arid areas (drylands) are characterized by low and erratic rainfall and high potential evapotranspiration, resulting in limited soil water availability for plant growth and productivity (Kurc and Small, 2007; García et al., 2013; Nicholson, 2011). The Sahel of Africa has experienced recurrent droughts from the 1960s to the 1980s (UNEP, 2012; WMO, 2005), which, combined with population growth and associated disturbances such as cutting trees for fuelwood and charcoal production, cultivation and overgrazing, has considerably reduced the cover and density of trees and significantly contributed to land degradation (Doso, 2014; Dregne, 2002; Tiessen et al., 1998; UNEP, 2012) as indicated by reduced soil organic matter (SOM) contents (FAO, 2004; Lal, 2004). A further result of reduced tree cover in drylands has been an increase in runoff and erosion while infiltration is reduced (WMO, 2005; Zuazo and Pleguezuelo, 2008). In addition, the removal of trees and associated reduction in SOM results in reduced soil moisture contents (FAO, 2004; Wang et al., 2013). The loss of vegetation cover also encourages the formation of soil crusts, which inhibits infiltration and favours surface runoff (Abu-Awwad, 1997; Zuazo and Pleguezuelo, 2008). Reversing the trend of tree removal in the Sahel and associated loss in SOM may therefore be expected to result in increased infiltration and soil moisture retention and contents (Ilstedt et al., 2007; Wang et al., 2013; Zuazo and Pleguezuelo, 2008). However, planting trees in drylands is often discouraged because of concerns that they would intensify evapotranspiration and water shortages (Farley et al., 2005; Malagnoux et al., 2007). On the other hand, a recent study in the semi-arid West African Sahel indicated that intermediate tree cover and densities can actually increase infiltration, drainage and groundwater recharge (Ilstedt et al., 2016). But few studies to investigate the effects of tree cover on the water balance have been carried out in the eastern Sahel region. This gap in our knowledge about this extensive region is partly related to a lack of available meteorological and hydrological data, including soil moisture data (Feddema, 1998; Nicholson, 2011).

The few studies available for the Sudan have focused on the water use (evapotranspiration) of *Acacia senegal* trees in agroforestry (Gaafar et al., 2006; Raddad and Luukkanen, 2007), the results of which showed that both *A. senegal* and crops used water from the same depth, which is not the intended aim of agroforestry. The water balance modelling study by Starr and Alam (2015) focused on the differences in

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the long-term mean annual water balance across the entire Sudanese woodland Savanna zone in relation to the long-term mean annual rainfall and soil type. However, the effect of trees on SOM contents and hydraulic properties and subsequently on daily soil moisture contents during dry and wet seasons were not included in their study. Ardö et al. (2008) compared the fluxes of CO_2 for a sparse woodland savanna site in Sudan during a wet and dry season in relation to water availability and showed that the mean daily net ecosystem exchange strongly responded to small changes in plant available soil water contents.

The aims of this study were to investigate changes in soil moisture during 2011 and 2012 in *A. senegal* plantations of varying age (biomass and cover) in two sites in semi-arid Sudan and to compare the results with those in adjacent grasslands, to evaluate the effects of soil organic carbon (SOC) on soil hydraulic properties, to use the soil moisture data to help validate a water balance model, and finally to compare and evaluate the water balances of the plantations and grasslands. We hypothesized that increases in tree biomass and cover and associated increases in SOC contents would reduce surface runoff during the rainy season and thereby increase infiltration, plant available water capacity, and soil moisture contents compared to open grasslands. We further hypothesized that these effects would increase with increasing plantation age. The rationale for the study was that increasing or at least maintaining tree cover would not only favour carbon sequestration, but also improve the hydraulic properties of the soil and water availability.

2. Material and methods

2.1. Study sites

The study was conducted at two sites in the North Kordofan state, Sudan: El Demokeya forest reserve (13°16′ N, 30°29′ E, 560 m a.s.l.), which is an experimental site managed for gum arabic research by El Obeid Agricultural Research Station, and El Hemaira forest (13°19′ N, 30°10′ E, 570 m a.s.l.) owned and managed by farmers for gum arabic production (Fig. 1). The topography at El Demokeya site is very gently sloping eastwards and is flat at El Hemaira.

The vegetation at both sites falls within the low rainfall woodland savanna (Ayoub, 1998; FAO, 2006). Rainfall varies greatly in the amount and distribution from year to year, but mostly falls from July to September. Total rainfall for 2011 and 2012, when this study was carried out, was 347 and 406 mm, respectively. The daily mean minimum and maximum temperatures over the same two years was 21 and 35 °C, respectively. The soils at both sites are sandy ($\geq$90% sand) Arenosols, developed in aeolian deposits and without clear differentiation of pedogenic horizons (Ayoub, 1998; FAO, 1995). They are locally known as "*Qoz*" soils and known to have low SOC and nutrient contents and water holding capacity (El Tahir et al., 2009; Olsson and Ardö, 2002).

At both study sites, plantations of *Acacia senegal* (L.) Willd. have been established. At El Demokeya the plantations are 15 and 24-years-old (in 2011) and at El Hemaira 7, 15 and 20-years-old. The initial tree density was approximately 400 trees ha^{-1} (5 × 5 m spacing), but the density is now considerably lower due to disturbance (cutting, wind throw, grazing and natural mortality), particularly at El Demokeya site. Current tree densities are 117–167 trees ha^{-1}at El Demokeya and 177–327 trees ha^{-1} at El Hemaira site. Corresponding canopy cover values are 16–31% at El Demokeya and 20–28% at El Hemaira (Abaker et al., 2016). The ground vegetation is dominated by grasses and some herbs (Fig. 2).

2.2. Sample plots

In 2011, three circular plots (17.8 m radius; 0.1 ha) were established in each of the plantations at both sites. Within each plantation age, the plots were within 150–500 m of each other. In addition, three square plots were located in an adjacent grassland area at both sites to serve as control sites. The grassland plots were 50 × 50 m at El Demokeya and 30 × 30 m at El Hemaira, the difference in size being due to the difference in the area of grassland at the two sites.

2.3. Soil sampling and soil moisture measurements

Soil samples were taken from all 15 plantation plots and 6 grassland plots. For each of the plantation plots, samples from depths of 0–10,

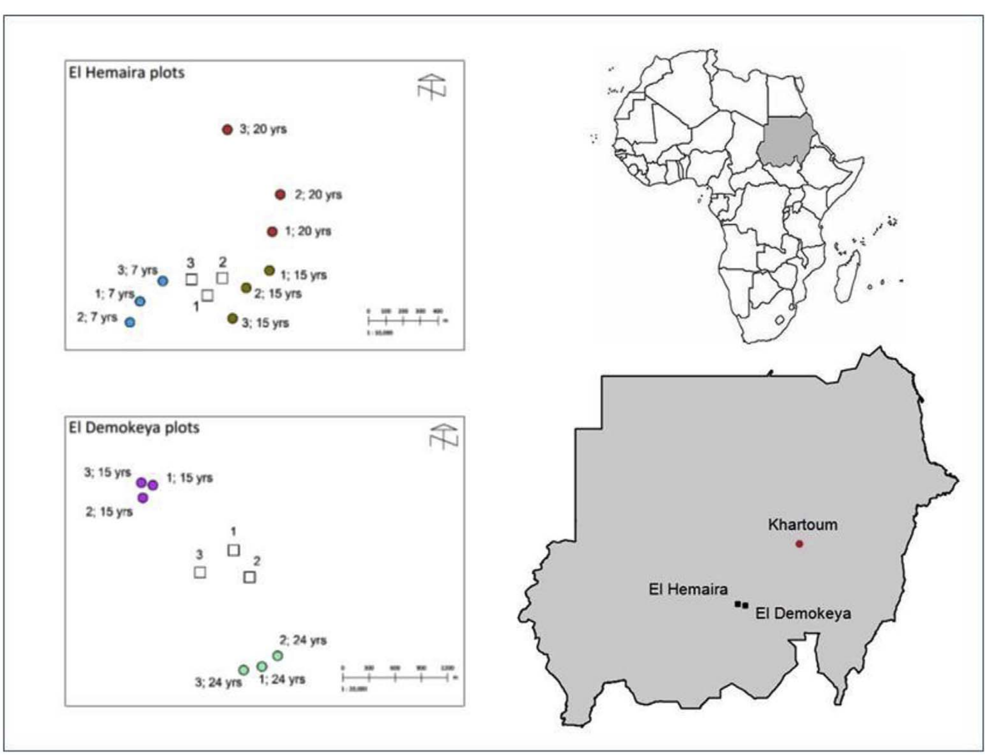

Fig. 1. Map showing location of study sites and plots.