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Hydraulic redistribution by two semi-arid shrub species: Implications for Sahelian agro-ecosystems

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ABSTRACT

Hydraulic redistribution is the process of passive water movement from deeper moist soil to shallower dry soil layers using plant roots as conduits. Results from this study indicate that this phenomenon exists among two shrub species (*Guiera senegalensis* and *Piliostigma reticulatum*) that co-exist with annual food crops in Sahelian agro-ecosystems. Real-time measurements were conducted for soil water content, soil water potential and microclimate variables notably; air temperature, relative humidity, wind speed, precipitation and solar irradiance. Additionally, sap flow measurements were conducted in shrub roots using the thermal dissipation technique on intact and coppiced shrubs. Monthly predawn leaf water potential was measured using a portable pressure chamber. Soil water potential (Ψ_s) at the 20 cm depth declined significantly during the dry season with diel changes in Ψ_s of -0.6 to -1.1 MPa. These variations were attributed to passive water release from shrub roots resulting in overnight rewetting of drier upper soil layers. Sap flow measurements on tap and lateral shrub roots indicated daily reversals in the direction of flow. During the peak of the dry season, both positive (toward shrub) and negative (toward soil) flows were observed in lateral shrub roots with sap flow in the lateral roots frequently negative at night and rapidly becoming positive soon after sunrise. The negative sap flow at night in superficial lateral roots and the periodic positive flow in the descending tap roots were indicative of hydraulic redistribution. Hydraulic redistribution may be an important mechanism for drought stress avoidance while maintaining plant physiological functions in both shrubs and neighboring annuals in water-limited environments.

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1. Introduction

The productivity of arid and semi-arid ecosystems is controlled primarily by water dynamics. The relatively recent discovery of hydraulic redistribution (HR) has important implications for understanding ecosystem functioning in these dry environments (Caldwell et al., 1998). Hydraulic redistribution (HR) is the process of passive water movement from relatively moist to drier regions of soil using plant roots as a conduit (Caldwell, 1990; Dawson, 1995; Richards and Caldwell, 1987; Xu and Bland, 1993). It is driven by soil matric potential gradients and modulated by resistance to reverse flow through roots and by rhizosphere resistance to transfer of water from roots to soil. Hydraulic redistribution usually occurs at night when transpiration has diminished sufficiently to allow the water potential in roots to exceed that in the drier upper portions of the soil profile (Scholz et al., 2002). Although movement of water via HR is usually upward from deep, moist soil layers to shallow, dry layers, both downward (Burgess et al., 2001; Smith et al., 1999) and lateral (Bleby et al., 2010; Brooks et al., 2002, 2006) HR have been documented. Downward HR may play an important role in deep soil moisture recharge in arid regions (Leffler et al., 2005; Ryel et al., 2003). Associated benefits of HR for the plants involved may include delaying loss of root xylem conductivity in shallow roots

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(Domec et al., 2004, 2006) and prolonging their nutrient uptake (Caldwell et al., 1998) during dry periods.

Now that more than 60 cases of HR have been reported in woody and herbaceous plants (Jackson et al., 2000), there is reason to expect that its existence is widespread wherever conditions are conducive to its occurrence. Evidence for HR consists largely of time fluctuations of soil water potential showing partial overnight recovery in drier soil layers (Millikin Ishiikawa and Bledsoe, 2000; Richards and Caldwell, 1987), movement of deuterated water as a tracer from roots to soil and neighboring plants (Brooks et al., 2002, 2006; Moreira et al., 2003), and reverse sap flow in roots (Burgess et al., 1998; Scholz et al., 2002; Smith et al., 1999).

Verification of HR requires close observation of other bio-physical processes that could account for altered soil moisture regime in the upper soil layers in the presence of woody shrubs. For instance, near-surface thermal variability can affect water movement within the vadose zone in liquid and vapor phases (Cahill and Parlange, 1998; Milly, 1996; Parlange et al., 1998; Philip and de Vries, 1957). These studies have demonstrated that the presence of temperature gradients in unsaturated soils may also induce water fluxes in gas and liquid phases that can significantly contribute to the water and energy transport processes. However, in a modeling study Ryel et al. (2002) concluded that during summer drought, the amount of water moved by unsaturated flow was typically negligible compared to that moved by HR in an *Artemisia tridentata* stand.

Transfer of water from plants conducting HR to surrounding plants has been documented (Brooks et al., 2006; Caldwell and Richards, 1989; Moreira et al., 2003), but the potential facilitating effects of HR on neighboring plants remain to be evaluated. Although recent studies in the East African savanna indicated that the deeply rooted tree *Acacia tortilis* conducts HR, the facilitative effects of hydraulically lifted water taken up by surrounding grasses were uncertain because soil water potential was consistently lower under the tree crowns than outside the crowns (Ludwig et al., 2003). Lufafa et al. (2009) have shown that two semi-arid shrub species (*Guiera senegalensis* and *Piliostigma reticulatum*) co-exist within row crops and are widely distributed in Senegal. Previous work (Kizito et al., 2006, 2007) has demonstrated that during the dry season, the soil surrounding the shrub shallow roots is substantially moister than soil distant from the shrubs, but these shrubs have not been investigated for their potential to perform HR. The existence of HR among these shrubs could alter hydrological processes enough to significantly impact water balances and improve or stabilize crop productivity by reducing drought stress. We therefore hypothesized the presence of a unique interaction and exchange of water pulses between the semi-arid shrubs and co-occurring annual row crops. Our objectives in this study were to: 1) evaluate the existence and magnitude of hydraulic redistribution by *G. senegalensis* and *P. reticulatum*; and 2) quantify the magnitude of other bio-physical processes potentially responsible for soil water transport during the dry season.

2. Materials and methods

2.1. Study sites

The study was conducted in two different agro-ecological zones in the Peanut Basin of Senegal, West Africa. The region is characterized by temporally and spatially variable unimodal rainfall with episodic droughts and frequent crop failures (Centre de Suivi Ecologique, 2000). The rainy season lasts from July to September, generally as scattered, high intensity, short-duration showers. Air temperature exhibits high diurnal and annual variability. The main annual crops are millet (*Pennisetum glaucum* (L.) R. Br.), groundnuts (*Arachis hypogaea* L.), sorghum (*Sorghum bicolor* (L.) Moench), cowpeas (*Vigna unguiculata* (L.) Walp.) and corn (*Zea mays*) in the southern part of the Peanut Basin. The planting density for peanut is about 130,000 plants ha^{-1}ha (sown as one seed per hole) while that of corn is about 5000 plants ha^{-1}.

The research was conducted at two sites. One study site, Keur Matar Arame (KMA), is located in the northern region (N14°46W 16°51; 43 m above sea level, slope range 0–1%) of the Peanut Basin with a mean annual unimodal precipitation of 450 mm (Fig. 1). The water table at this site lies at 15 m. *G. senegalensis* is the dominant shrub, characteristically 1 m tall with a shrub canopy crown of about 2 m and a highly spreading shallow rooting system in the top 0.45 m and a narrow leading unbranched root to a depth greater than 2.5 m (Kizito et al.,2006). The site has a shrub stand density of 240 shrubs ha^{-1}. The minimum mean annual ambient temperature is 20 °C and a maximum mean annual ambient temperature of 33 °C. The area lies on a leached and disturbed ferruginous sand soil classified as a ferruginous Oxisol (FAO, 1998). The top horizon (0–0.7 m), is sandy with a friable continuous structure and no distinct horizonation with low clay contents of about 5% and scanty organic matter content of 0.5%.

The second study site is located at Nioro, in the southern region (N13°45 W 15°47; 18 m above sea level, slope range of 0–2%) of the Peanut Basin, with a total mean annual unimodal precipitation of 750 mm (Fig. 1). *P. reticulatum* is the predominant shrub occurring at a density of 185 shrubs ha^{-1} with a well developed and fairly deep rooting system (Diack et al., 2000; Kizito et al., 2006). The water table lies at about 12 m below the soil surface. This site has randomly scattered *Cordyla pinnata* and *Prosopis africana* trees in the landscape. The mean annual minimum ambient temperature is 20 °C and the mean annual maximum ambient temperature is

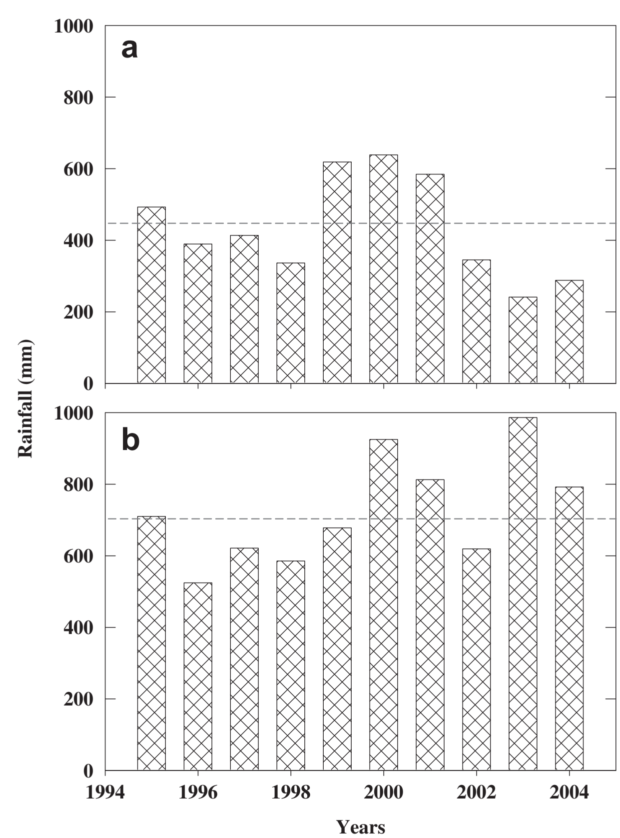

Fig. 1. Decadal cumulative annual rainfall for rain gauges 1995–2004 at (a) KMA and (b) Nioro. Dotted horizontal lines show the decadal average value (After Kizito et al., 2007).

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