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INFLUENCE OF ACACIA TREES ON NEAR-SURFACE SOIL HYDRAULIC PROPERTIES IN ARID TUNISIA

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ABSTRACT

Studies in arid regions have shown that scattered trees strongly influence the environmental conditions under their canopies providing favourable conditions for the recruitment of other plants. The most critical factor controlling plant productivity in arid regions is soil–water availability. Hence, understanding the soil–water relationships below canopy is needed to better comprehend the rehabilitation of degraded land by vegetation. In this study, scattered *Acacia raddiana* trees of three canopy size classes were selected to examine their effect on soil physical properties, soil–water retention curve and saturated and unsaturated hydraulic conductivities of the upper soil layer (0–10 cm). Compared with outside the canopy, below-canopy soils have a higher organic matter content causing a lower bulk density and a higher total porosity. Higher hydraulic conductivities were found below as compared with outside the canopy and the rates increased with increasing canopy size. This could be related to the ratio of water content at field capacity to saturation, suggesting that hydraulic conductivities were mainly driven by macropores and large matrix pores. By improving the near-surface soil hydraulic properties, *A. raddiana* trees can positively affect the water availability for the below-canopy herbaceous cover, which is of crucial importance in water-limited environments.

KEY WORDS: *Acacia raddiana*; below canopy; soil–water; arid lands; Tunisia

INTRODUCTION

Ecosystems with scattered trees occur throughout the world. The origins and ecological roles of scattered trees have been intensively studied at different scales, going from point (microsite) to field (landscape) scale (Manning *et al*., 2006). At point scale, scattered trees may strongly modify the physical environment around their canopies through their effects on biotic and abiotic processes (Shachak *et al*., 2008). Typical changes in environmental conditions underneath their canopy involve a cooler and often wetter microclimate because of the interception of radiation (Mistry, 2000). Stem flow, water uptake through the root system from below and around the tree, and increased infiltration of water into the soil further enhance the concentration of water near trees, especially in otherwise dry environments (Vetaas, 1992; Eldridge & Freudenberger, 2005). Scattered trees often function as ‘nurse plants’ or ‘fertility islands’, in that they facilitate the recruitment of other plants (San José *et al*., 1991; Facelli & Brock, 2000). Positive effects are particularly pronounced in ecosystems where water stress limits plant growth.

In arid to semi-arid regions, water availability in the soil is the most critical factor controlling productivity and reproduction of vegetation (Noy-Meir, 1973; Rodriguez-Iturbe, 2000). On the one hand, vegetation needs water to survive, and thus, the distribution, composition and structure of vegetation communities are directly influenced by spatio-temporal patterns in water availability (Kakembo *et al*., 2012). On the other hand, vegetation exerts a strong effect on hydrological fluxes of the terrestrial-atmospheric system (Asbjornsen *et al*., 2011). In this respect, the facilitating role of scattered trees can only be fully understood by investigating the below-canopy soil–water relations.

Many studies investigated the effects of vegetation patches on infiltration properties. In general, higher soil infiltration rates were observed for vegetated patches compared with interpatch areas. For trees, studies on ecohydrological interactions were mainly executed in semi-arid eucalypt savannas of northeast Australia (Roth *et al*., 2003), arid mulga (*Acacia aneura*) woodlands of central Australia (Dunkerley, 2002) and semi-arid piñon-juniper woodlands of northern New Mexico (e.g. Wilcox *et al*., 2003; Madsen *et al*., 2008). However, little is known about the effects of Acacia trees on soil hydraulic properties in arid and semi-arid regions of Africa. *Acacia tortilis* (Forssk.) Hayne subsp. *raddiana* (Savi) Brenan, for example, is an important woody species in pre-Saharan Tunisia, as it enables to tolerate extreme droughts (mean annual rainfall <200 mm). It is the only forest tree persisting on the edge of the desert and is therefore considered as a keystone species (Le Floc’h & Grouzis, 2003). Hence, understanding the relationship between this keystone species and below-canopy soil hydraulic properties is needed to better comprehend their role in the rehabilitation of degraded land.

We used scattered *A. raddiana* trees of three canopy sizes to examine their effect on soil physical properties, soil–water

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retention curve (SWRC) and saturated and unsaturated hydraulic conductivities. Where most other studies only focus on the infiltration properties, our study investigates the SWRC and the hydraulic conductivity. Therefore, the effects of *A. raddiana* trees on soil physical quality parameters are included. It is hypothesized that (i) scattered *A. raddiana* trees improve soil physical and hydraulic properties underneath their canopy and (ii) these effects will be more pronounced in the longer term, that is, with increasing canopy size.

MATERIALS AND METHODS

Study Site

Bou Hedma National Park (34°39 N and 9°48 E) is located in central Tunisia and covers an area of approximately 16,488 ha. It was designated as a UNESCO Biosphere Reserve in 1977. The main climatic characteristics of the park are an average annual rainfall of 180 mm, an average annual temperature of 17·2 °C and a mean minimum and maximum annual temperature of, respectively, 3·9 °C (December and January) and 38 °C (July and August). The park is characterized by an arid Mediterranean climate with a moderate winter (Le Houérou, 1959). The altitude varies between 90 and 814 m asl. Bou Hedma soils are skeletal in the mountainous area, superficial and stony in the piedmont, and sandy, sandy-loamy to loamy in low-lying flat areas. The park is divided in different zones: three Integral Protection Zones (IPZ) or core areas, two buffer zones and two agricultural zones or transition areas.

The study was conducted in the low-lying flat area of IPZ1. This zone has a total area of 5,114 ha (of which 2,000 ha of plains and 3,114 ha of mountains). IPZ1 is completely fenced to prevent grazing by domestic animals and wild fauna from escaping. *A. tortilis* (Forssk.) Hayne subsp. *raddiana* (Savi) Brenan is a native tree species in the study area. The geographical distribution of *A. raddiana* trees in Tunisia is nowadays limited to the Bou Hedma region. The forest steppe of the Bou Hedma region consists of scattered *A. raddiana* trees associated with several species of grasses and shrubs such as *Rhanterium suaveolens*, *Cenchrus ciliaris*, *Hammada schmittiana*, *Hammada scoparia* and *Salvia aegyptiaca* (Abdallah *et al*., 2012). More perennial grass species such as *C. ciliaris* and *Eragrostis papposa* are found below canopy, whereas open areas are dominated by annual grass species (Abdallah *et al*., 2012). The terminology ‘Acacia forest steppe’ is used to designate preforest formations in arid zones. The region suffered for over a century from overexploitation of natural resources and intensification of agricultural activities. Since 1957, several protective measures and restoration actions are undertaken through area closure and reforestation with *A. raddiana* trees.

Experimental Design

A total of 30 naturally regenerated *A. raddiana* trees was randomly selected in the plain of IPZ1 covering an area of approximately 10 ha. To characterize the *A. raddiana* population present in the park, three crown diameter classes based on the study of Vancoillie *et al*. (2010) were distinguished each containing ten trees: 3–5 m [small crown diameter (SCD)], 5–7 m [medium crown diameter (MCD)] and >7 m [large crown diameter (LCD)]. This attribute was chosen as it can be easily measured, and it is directly related to the area covered by *A. raddiana* trees, that is, the below-canopy microsite. For each canopy size class, crown diameter, basal trunk diameter and tree age are listed in Table I. For those 30 trees, ten per crown diameter class, two locations were distinguished: underneath (canopy) and outside canopy (open), respectively, at 25% of the canopy radius in the northern direction and 10 m away from the canopy edge. This study only focuses on the near-surface soil layer (0–10 cm) as roots of the herbaceous cover are mainly concentrated in the upper layer. Soil texture was determined for all 30 trees underneath and outside the canopy with the pipette method (Gee & Or, 2002) and classified according to the USDA Soil Taxonomy (Soil Survey Staff, 1999), whereas organic matter (OM) was determined according to the Walkley & Black (1934) method. Infiltration measurements underneath and outside the canopy of all 30 trees were performed at the soil surface with a tension disc infiltrometer (Soil Measurement Systems, Tucson AZ, USA) with the infiltration disc (20 cm diameter) separated from the water reservoir. A fine layer of sand was placed on the soil and subsequently saturated in order to ensure good hydraulic contact between the disc and the soil. Three successive matric potentials (ψ) were applied, −0·29, −0·59 and −1·18 kPa, for at least 10 min or until the infiltration rate of three consecutive time intervals was constant.

To obtain the SWRC, undisturbed soil samples of the upper soil layer (0–10 cm) were taken using standard sharpened steel 100 cm^3 Kopecky rings for 21 trees, seven for each diameter class, both underneath and outside the canopy. On those samples, the soil–water content (SWC) was determined at eight matric potentials (−1, −3, −5, −7, −10, −33, −100 and −1,500 kPa) as described by Cornelis *et al*. (2005). The soil bulk density (BD) was determined at −10 kPa following the procedure of Grossman & Reinsch (2002). The total porosity (TP) is calculated by

$$TP = 1 - \frac{\rho_b}{\rho_s} \quad (1)$$

Table I. Means ± SD of *Acacia raddiana* tree attributes with canopy sizes small ($n = 10$), medium ($n = 10$) and large crown diameter ($n = 10$)

	Canopy size SCD	MCD	LCD
Crown diameter (m)	4·1 ± 0·5	5·6 ± 0·4	9·2 ± 1·8
Basal trunk diameter (cm)	19·6 ± 3·0	29·4 ± 3·8	50·1 ± 14·9
Tree age[a] (years)	64 ± 7	88 ± 10	140 ± 37

SCD, small crown diameter; MCD, medium crown diameter; LCD, large crown diameter.
[a]Calculation of tree age based on basal trunk diameter following Noumi & Chaieb (2012).

Where: ρ_s is the particle density of sand equal to 2·65 Mg m^{-3} and corrected for the fraction of organic particles as described by Jury & Horton (2004). The model of van Genuchten (1980) was used to describe the SWRC:

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1 + (\alpha|\psi|)^n}\right]^m \quad (2)$$

Where: θ_r is the residual water content (m^3 m^{-3}), θ_s is the saturated water content (m^3 m^{-3}) and ψ is the matric potential (kPa). Parameters α (kPa^{-1}) and n were estimated using the Retention Curve model of van Genuchten *et al*. (1991) and $m = 1 - 1/n$.

From the obtained SWRC, several important parameters related to soil porosity were calculated. The macroporosity (*MacPor*) and matrix porosity (*MatPor*) parameters express the volume of soil macropores and matrix pores, respectively, and are obtained as

$$MacPor = \theta_s - MatPor \quad (3)$$

$$MatPor = \theta_m \quad (4)$$

Where: θ_m (m^3 m^{-3}) is the volumetric water content of the matrix porosity. To distinguish macropores from matrix pores, a value of $\psi = -5$ kPa, which corresponds with a pore diameter of 0·06 mm, was used similar to Reynolds *et al*. (2007). Soil aeration is represented by the soil air capacity (*AC*) and is defined as

$$AC = \theta_s - \theta_{FC} \quad (5)$$

Where: θ_{FC} (m^3 m^{-3}) is the volumetric water content at field capacity, considered here at $\psi = -10$ kPa (Reynolds *et al*., 2007). The plant-available water capacity (*PAWC*) is often used as an indicator of the soil's capacity to store and provide water that is available to plant roots and is usually defined by

$$PAWC = \theta_{FC} - \theta_{PWP} \quad (6)$$

Where: θ_{PWP} (m^3 m^{-3}) is the volumetric water content at permanent wilting point, which for most practical applications is taken at $\psi = -1{,}500$ kPa (Reynolds *et al*., 2007). Finally, a parameter expressing the soil's capacity to store water relative to the soil's pore volume was calculated. This parameter is known as the relative water capacity (*RWC*) and is defined by Reynolds *et al*. (2007) as

$$RWC = \frac{\theta_{FC}}{\theta_s} \quad (7)$$

The unsaturated hydraulic conductivity and its relation to matric potential was obtained from tension infiltrometer measurements based on the solution of the equation of Wooding (1968) for unconfined steady-state infiltration from a circular pond:

$$\frac{q_h}{\pi R^2} = K(\psi)\left(1 + \frac{4}{\pi R \kappa}\right) \quad (8)$$

Where: q_h is the steady-state flow rate (m^3 s^{-1}), R is the radius of the disc (m), $K(\psi)$ is the hydraulic conductivity (m s^{-1}) and κ (m^{-1}) is a fitting parameter. The two unknowns $K(\psi)$ and κ were derived from tension infiltrometer measurements using the steady-state approach of Logsdon & Jaynes (1993). Their method consists of finding the two unknowns K_s and κ via regression of the data using Equation 8 while substituting Gardner's (1958) hydraulic conductivity function $K(\psi) = K_s\, exp(\kappa\psi)$, where K_s is the field saturated hydraulic conductivity (m s^{-1}).

Data Analysis

To evaluate and compare the different soil physical parameters as influenced by crossed factors canopy size and microsite and factor tree nested in canopy size, a three-way analysis of variance was performed. In case of a significant main effect of canopy size, a Tukey post-hoc test was executed to indicate significant differences among the levels of this factor. The OM contents were lognormally transformed prior to statistical analyses. As is common for *in situ* measurements of hydraulic conductivities (Warrick & Nielsen, 1980), the calculated hydraulic conductivities showed lognormal distributions when subjected to the Kolmogorov–Smirnov test. As a consequence, all statistical analyses were performed on lognormally transformed values. Geometric mean values (*G*) and standard deviation (*SD*) of hydraulic conductivities were calculated using the uniformly minimum variance estimator method developed by Finney (1941). This method was recommended by Parkin *et al*. (1988) as the only acceptable method for lognormally distributed populations with a sample size between four and 20.

RESULTS AND DISCUSSION

Soil Physical Properties

There were no significant ($p > 0.05$) differences in sand and silt fractions between the three canopy size classes and between the two microsites (Table II). For clay, a significant higher ($p < 0.05$) fraction was found underneath compared with outside the canopy (9·1% vs. 8·0%). Between LCD and MCD, a significant difference in clay fraction was noticed (7·6% vs. 9·2%), with SCD having a value of 8·8%. The textural classes were varying between sand, loamy-sand, sandy loam and loam (Soil Survey Staff, 1999). OM content was significantly lower for canopy size SCD compared with MCD (1·1% vs. 1·5%) and LCD (1·1% vs. 1·8%). A significantly higher OM content was found for microsite canopy compared with open (2·1% vs. 0·8%), irrespective of the canopy size. The higher OM content can be related to a greater litter production from leaves and understory vegetation, and improved cycling. Even if litter fall inputs are relatively low in drylands because of constraints in plant productivity (Breckle, 2002), they may be substantially higher underneath the canopy (Cortina & Maestre, 2005). Soil moisture and greater litter production beneath woody canopies lead to greater microbial activity and accumulation of OM (Gutiérrez & Jones, 2006). Furthermore, it was shown in Table II that OM content increased

Table II. Means ± SD of soil physical properties in 0–10 cm soil layer on microsite locations canopy and open for *Acacia raddiana* trees with canopy sizes small ($n = 10$), medium ($n = 10$) and large ($n = 10$) crown diameter

	Microsite	Canopy size			
		SCD	MCD	LCD	Mean
Sand (2,000–50 μm) (%)	Canopy	67·7 ± 11·1	66·2 ± 6·6	68·8 ± 12·4	67·6 ± 10·0
	Open	66·5 ± 14·3	68·9 ± 15·5	70·6 ± 14·2	68·7 ± 14·3
	Mean	67·1 ± 12·5	67·5 ± 11·7	69·7 ± 13·0	
	p-value*	ns, ns, ns			
Silt (50–2 μm) (%)	Canopy	23·3 ± 8·7	24·1 ± 5·1	22·7 ± 9·7	23·4 ± 7·8
	Open	25·0 ± 12·0	22·5 ± 12·4	22·6 ± 12·0	23·4 ± 11·7
	Mean	24·1 ± 10·2	23·3 ± 9·3	22·7 ± 10·6	
	p-value	ns, ns, ns			
Clay (<2 μm) (%)	Canopy	9·1 ± 2·8	9·7 ± 2·1	8·5 ± 3·0	9·1 ± 2·6
	Open	8·5 ± 2·6	8·6 ± 3·4	6·8 ± 2·4	8·0 ± 2·9
	Mean	$8·8^{a,b}$ ± 2·6	$9·2^{b}$ ± 2·8	$7·6^{a}$ ± 2·8	
	p-value	<0·05, <0·05, ns			
BD ($Mg\,m^{-3}$)	Canopy	1·38 ± 0·13	1·37 ± 0·12	1·33 ± 0·11	1·36 ± 0·12
	Open	1·54 ± 0·15	1·51 ± 0·18	1·48 ± 0·13	1·51 ± 0·15
	Mean	1·46 ± 0·16	1·44 ± 0·16	1·41 ± 0·14	
	p-value	ns, <0·01, ns			
TP ($m^3\,m^{-3}$)	Canopy	0·48 ± 0·05	0·48 ± 0·04	0·49 ± 0·04	0·48 ± 0·04
	Open	0·42 ± 0·06	0·43 ± 0·07	0·44 ± 0·05	0·43 ± 0·06
	Mean	0·45 ± 0·06	0·45 ± 0·06	0·46 ± 0·05	
	p-value	ns, <0·01, ns			
OM (%)	Canopy	1·4 ± 0·5	2·1 ± 0·6	2·7 ± 1·1	2·1 ± 0·9
	Open	0·7 ± 0·3	0·9 ± 0·6	0·9 ± 0·2	0·8 ± 0·4
	Mean	$1·1^{a}$ ± 0·5	$1·5^{b}$ ± 0·9	$1·8^{b}$ ± 1·2	
	p-value	<0·01, <0·01, ns			

SCD, small crown diameter; MCD, medium crown diameter; LCD, large crown diameter; BD, bulk density; TP, total porosity, OM, organic matter; ns, not significant.
Means within a row bearing different superscripts (a,b) are significantly different ($p < 0·05$) following Tukey's Honest Significant Difference test.
*Given for canopy size, microsite and canopy size × microsite in that order.

with increasing crown diameter (R^2-adj = 0·330, $p = 0·001$). Accretion of OM when shrubs increase in size was also found by Pugnaire *et al*. (1996) and Tirado & Pugnaire (2003). BD was significantly higher for the open microsite location compared with below canopy (1·51 vs. 1·36 $Mg\,m^{-3}$). Accordingly, TP was significantly lower for interspace compared with canopy (0·43 vs. 0·48 $m^3\,m^{-3}$). The increase of OM in the soil under trees with increasing crown diameter was reflected in a decreasing BD (R^2-adj = 0·543, $p < 0·001$) and hence in an increasing TP (R^2-adj = 0·511, $p < 0·001$).

Table III. Geometric means ± SD of the saturated ($K_{S,G}$) and unsaturated ($K_{\psi,G}$) hydraulic conductivities at soil surface on microsite locations canopy and open for *Acacia raddiana* trees with canopy sizes small ($n = 10$), medium ($n = 10$) and large ($n = 10$) crown diameter

	Microsite	Canopy size			
		SCD	MCD	LCD	Mean
$K_{S,G} \times 10^{-6}\,m\,s^{-1}$	Canopy	4·39 ± 1·56	7·63 ± 5·69	7·39 ± 3·61	6·42 ± 3·81
	Open	3·73 ± 3·00	4·07 ± 2·38	4·37 ± 3·68	4·07 ± 3·13
	Mean	4·12 ± 2·68	5·79 ± 4·30	6·05 ± 4·85	
	p-value*	ns, <0·01, ns			
$K_{\psi,G}$ (−0·29 kPa) × $10^{-6}\,m\,s^{-1}$	Canopy	3·46 ± 1·28	5·87 ± 4·03	5·72 ± 2·55	4·99 ± 2·80
	Open	3·06 ± 2·30	3·40 ± 2·00	3·59 ± 2·86	3·36 ± 2·46
	Mean	3·29 ± 2·00	4·61 ± 3·23	4·77 ± 3·53	
	p-value	ns, <0·01, ns			
$K_{\psi,G}$ (−0·59 kPa) × $10^{-6}\,m\,s^{-1}$	Canopy	2·73 ± 1·08	4·53 ± 2·87	4·43 ± 1·80	3·89 ± 2·09
	Open	2·52 ± 1·76	2·84 ± 1·69	2·96 ± 2·24	2·78 ± 1·93
	Mean	$2·64^{a}$ ± 1·52	$3·68^{a,b}$ ± 2·45	$3·77^{b}$ ± 2·57	
	p-value	ns, <0·01, ns			
$K_{\psi,G}$ (−1·18 kPa) × $10^{-6}\,m\,s^{-1}$	Canopy	1·72 ± 0·80	2·73 ± 1·49	2·69 ± 0·91	2·38 ± 1·21
	Open	1·72 ± 1·03	1·99 ± 1·21	2·02 ± 1·38	1·91 ± 1·21
	Mean	1·72 ± 0·91	2·37 ± 1·44	2·39 ± 1·38	
	p-value	ns, <0·05, ns			

SCD, small crown diameter; MCD, medium crown diameter; LCD, large crown diameter; ns, not significant.
Means within a row bearing different superscripts (a,b) are significantly different ($p < 0·05$) following Tukey's Honest Significant Difference test.
*Given for canopy size, microsite and canopy size × microsite in that order.

Table IV. Means ± SD of soil–water content at eight matric potentials in 0–10 cm soil layer on microsite locations canopy and open for *Acacia raddiana* trees with canopy sizes small ($n = 7$), medium ($n = 7$) and large ($n = 7$) crown diameter

	Microsite	Canopy size			
		SCD	MCD	LCD	Mean
θ (−1 kPa) ($m^3 m^{-3}$)	Canopy	0·39 ± 0·04	0·41 ± 0·04	0·44 ± 0·03	0·41 ± 0·04
	Open	0·38 ± 0·04	0·37 ± 0·03	0·37 ± 0·03	0·37 ± 0·04
	Mean	0·38 ± 0·04	0·39 ± 0·04	0·40 ± 0·05	
	p-value*	ns, <0·01, ns			
θ (−3 kPa) ($m^3 m^{-3}$)	Canopy	0·35 ± 0·03	0·36 ± 0·05	0·40 ± 0·03	0·37 ± 0·04
	Open	0·35 ± 0·04	0·35 ± 0·02	0·34 ± 0·04	0·34 ± 0·03
	Mean	0·35 ± 0·04	0·36 ± 0·04	0·37 ± 0·05	
	p-value	ns, <0·01, ns			
θ (−5 kPa) ($m^3 m^{-3}$)	Canopy	0·31 ± 0·03	0·32 ± 0·05	0·36 ± 0·03	0·33 ± 0·04
	Open	0·31 ± 0·05	0·31 ± 0·03	0·31 ± 0·04	0·31 ± 0·04
	Mean	0·31 ± 0·04	0·32 ± 0·04	0·34 ± 0·05	
	p-value	ns, <0·05, ns			
θ (−7 kPa) ($m^3 m^{-3}$)	Canopy	0·28 ± 0·02	0·29 ± 0·04	0·32 ± 0·04	0·30 ± 0·04
	Open	0·27 ± 0·05	0·27 ± 0·03	0·28 ± 0·05	0·28 ± 0·04
	Mean	0·28 ± 0·04	0·28 ± 0·04	0·30 ± 0·05	
	p-value	ns, <0·05, ns			
θ (−10 kPa) ($m^3 m^{-3}$)	Canopy	0·23 ± 0·02	0·24 ± 0·03	0·25 ± 0·04	0·24 ± 0·03
	Open	0·22 ± 0·05	0·22 ± 0·04	0·23 ± 0·05	0·23 ± 0·05
	Mean	0·23 ± 0·04	0·23 ± 0·04	0·24 ± 0·05	
	p-value	ns, ns, ns			
θ (−33 kPa) ($m^3 m^{-3}$)	Canopy	0·12 ± 0·03	0·14 ± 0·01	0·12 ± 0·03	0·13 ± 0·03
	Open	0·12 ± 0·03	0·11 ± 0·03	0·11 ± 0·02	0·11 ± 0·03
	Mean	0·12 ± 0·03	0·13 ± 0·03	0·11 ± 0·03	
	p-value	ns, <0·05, ns			
θ (−100 kPa) ($m^3 m^{-3}$)	Canopy	0·12 ± 0·02	0·12 ± 0·02	0·10 ± 0·04	0·11 ± 0·03
	Open	0·10 ± 0·03	0·10 ± 0·04	0·09 ± 0·03	0·10 ± 0·03
	Mean	0·11[a] ± 0·03	0·11[a] ± 0·03	0·09[b] ± 0·03	
	p-value	ns, <0·01, ns			
θ (−1,500 kPa) ($m^3 m^{-3}$)	Canopy	0·07 ± 0·02	0·07 ± 0·01	0·06 ± 0·02	0·07 ± 0·02
	Open	0·06 ± 0·02	0·06 ± 0·02	0·06 ± 0·02	0·06 ± 0·02
	Mean	0·06 ± 0·02	0·07 ± 0·02	0·06 ± 0·02	
	p-value	ns, ns, ns			

SCD, small crown diameter; MCD, medium crown diameter; LCD, large crown diameter; θ, water content at given matric potential; ns, not significant.
Means within a row bearing different superscripts (a,b) are significantly different ($p < 0{\cdot}05$) following Tukey's Honest Significant Difference test.
*Given for canopy size, microsite and canopy size × microsite in that order.

Positive effects of OM content on the physical quality of the soil were also reported by Shukla *et al.* (2006).

Soil Hydraulic Conductivity

Saturated ($K_{S,G}$) and unsaturated ($K_{\psi,G}$) hydraulic conductivities were significantly higher underneath compared with outside the canopy (Table III). A significant higher value for unsaturated hydraulic conductivity at −0·59 kPa was found for LCD compared with SCD, with MCD having an intermediate value. In general, increased values in saturated (R^2-adj = 0·129, $p < 0{\cdot}05$) and unsaturated hydraulic conductivities at −0·29 kPa (R^2-adj = 0·143, $p < 0{\cdot}05$), −0·59 kPa (R^2-adj = 0·184, $p < 0{\cdot}05$) and −1·19 kPa (R^2-adj = 0·206, $p < 0{\cdot}01$) were found with increasing canopy size. The saturated values in our study were within the range of sandy to loamy soils (Carsel & Parrish, 1988). Several studies mention higher hydraulic conductivities underneath canopies, particularly under positive head (Lyford & Qashu, 1969; Daryanto *et al.*, 2013), following natural rainfall (Reid *et al.*, 1999; Bhark & Small, 2003) and with tension infiltrometers (Shafer *et al.*, 2007; Caldwell *et al.*, 2008). Improved infiltrability under vegetation canopies may be due to a number of factors, including higher OM content

Table V. van Genuchten parameters θ_r, θ_s, α and n obtained by fitting to water retention data in 0–10 cm soil layer on microsite locations canopy and open for *Acacia raddiana* trees with canopy sizes small ($n = 7$), medium ($n = 7$) and large ($n = 7$) crown diameter

		θ_r ($m^3 m^{-3}$)	θ_S ($m^3 m^{-3}$)	α (kPa^{-1})	n (−)
Canopy					
	SCD	0·07	0·40	2·04	1·92
	MCD	0·07	0·43	2·58	1·75
	LCD	0·07	0·44	1·54	2·23
Open					
	SCD	0·06	0·39	1·91	1·90
	MCD	0·07	0·38	1·61	2·23
	LCD	0·06	0·37	1·49	2·22

SCD, small crown diameter; MCD, medium crown diameter; LCD, large crown diameter; θ_r, residual water content; θ_S, saturated water content; α and n, parameters of the van Genuchten model.

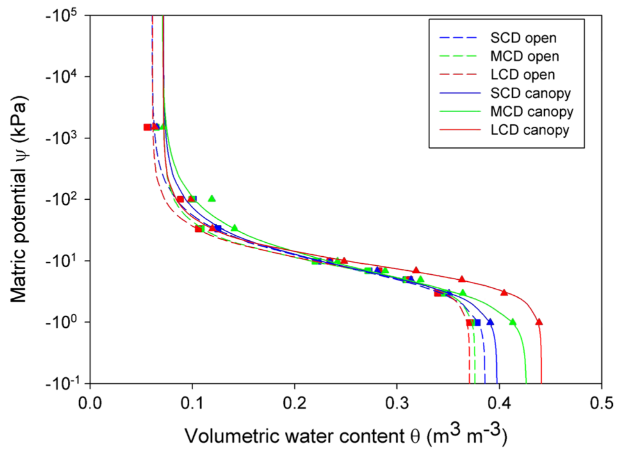

Figure 1. Soil–water retention curves for microsite locations canopy (solid line) and open (dashed line) with observations of mean soil–water content (standard deviation is mentioned in Table IV) at eight matric potentials (canopy: triangles; open: squares) in 0–10 cm soil layer for *Acacia raddiana* trees with canopy sizes small (SCD) ($n=7$), medium (MCD) ($n=7$) and large crown diameter (LCD) ($n=7$). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

(Wang *et al*., 2009), protection of the soil by leaf-litter creating aggregation and a more developed network of macropores (Dunkerley, 2000).

Soil–Water Retention

Soil–water content was significantly higher underneath compared with outside the canopy at all matric potentials except −10 and −1,500 kPa (Table IV). Increased values of SWC with increasing canopy size were found in the wet range, that is, for matric potentials −1 kPa (R^2-adj = 0·203, $p<0·05$), −3 kPa (R^2-adj = 0·255, $p<0·05$), −5 kPa (R^2-adj = 0·220, $p<0·05$) and −7 kPa (R^2-adj = 0·147, $p<0·05$). Increasing OM content resulted in higher water retention values at low suctions −1 kPa (R^2-adj = 0·299, $p<0·001$), −3 kPa (R^2-adj = 0·224, $p<0·01$), −5 kPa (R^2-adj = 0·202, $p<0·01$) and −7 kPa (R^2-adj = 0·208, $p<0·01$), and at high suctions −10 kPa (R^2-adj = 0·198, $p<0·01$), −33 kPa (R^2-adj = 0·242, $p<0·01$), −330 kPa (R^2-adj = 0·157, $p<0·01$) and −1,500 kPa (R^2-adj = 0·244, $p<0·01$). This is in agreement with Garba *et al*. (2011), who stated that OM can play an important role in water retention capacity of sandy-soils, such as those in the Sahel. The soil–water retention parameters derived according to the van Genuchten model are listed in Table V. The residual water content (θ_r) was in the same range for all canopy sizes underneath and outside the canopy, amounting to 0·07 m^3 m^{-3}. The SWC at saturation (θ_S) increased from SCD over MCD to LCD in the range from 0·40 to 0·44 m^3 m^{-3} underneath the canopy. Parameters α and n showed corresponding values, indicating a corresponding shape of the water retention curve, irrespective of the canopy size or microsite (Figure 1).

Soil Physical Quality

Matrix porosity (MatPor), macroporosity (MacPor) and AC showed significantly higher values underneath compared with outside the canopy (Table VI). Furthermore, a significant interaction effect between canopy size and microsite was found for AC. No significant differences in PAWC and RWC were found between the three canopy size classes

Table VI. Means ± SD of soil physical quality parameters in 0–10 cm soil layer on microsite locations canopy and open for *Acacia raddiana* trees with canopy sizes small ($n=7$), medium ($n=7$) and large ($n=7$) crown diameter

		Canopy size			
	Microsite	SCD	MCD	LCD	Mean
MatPor (m^3 m^{-3})	Canopy	0·31 ± 0·03	0·32 ± 0·04	0·36 ± 0·03	0·33 ± 0·04
	Open	0·31 ± 0·05	0·31 ± 0·03	0·31 ± 0·05	0·31 ± 0·04
	Mean	0·31 ± 0·04	0·31 ± 0·04	0·34 ± 0·05	
	p-value*	ns, <0·05, ns			
MacPor (m^3 m^{-3})	Canopy	0·09 ± 0·03	0·11 ± 0·02	0·08 ± 0·02	0·09 ± 0·02
	Open	0·08 ± 0·01	0·07 ± 0·01	0·06 ± 0·03	0·07 ± 0·02
	Mean	0·08 ± 0·02	0·09 ± 0·03	0·07 ± 0·03	
	p-value	ns, <0·01, ns			
AC (m^3 m^{-3})	Canopy	0·16^{a,b} ± 0·03	0·18^{b} ± 0·03	0·19^{b} ± 0·04	0·18 ± 0·03
	Open	0·16^{a,b} ± 0·02	0·16^{a,b} ± 0·02	0·14^{a} ± 0·03	0·15 ± 0·03
	Mean	0·16 ± 0·03	0·17 ± 0·03	0·16 ± 0·04	
	p-value	ns, <0·01, <0·05			
PAWC (m^3 m^{-3})	Canopy	0·17 ± 0·02	0·17 ± 0·03	0·19 ± 0·02	0·17 ± 0·03
	Open	0·17 ± 0·04	0·16 ± 0·02	0·18 ± 0·05	0·17 ± 0·04
	Mean	0·17 ± 0·03	0·16 ± 0·03	0·18 ± 0·04	
	p-value	ns, ns, ns			
RWC (−)	Canopy	0·59 ± 0·06	0·57 ± 0·04	0·56 ± 0·09	0·57 ± 0·06
	Open	0·57 ± 0·08	0·58 ± 0·06	0·63 ± 0·10	0·59 ± 0·08
	Mean	0·58 ± 0·07	0·57 ± 0·05	0·59 ± 0·10	
	p-value	ns, ns, ns			

SCD, small crown diameter; MCD, medium crown diameter; LCD, large crown diameter; MatPor, soil matrix porosity; MacPor, soil macroporosity; AC, soil air capacity; PAWC, plant-available water capacity; RWC, relative water capacity; ns, not significant.
Means within a row bearing different superscripts (a,b) are significantly different ($p<0·05$) following Tukey's Honest Significant Difference test.
*Given for canopy size, microsite and canopy size × microsite in that order.

or between the two microsites. Values of PAWC were comparable because of similar values of SWC at both field capacity and permanent wilting point (Table IV). With increasing canopy size, an increase in MatPor was found (R^2-adj = 0·217, $p < 0·05$). This can be related to increased values of OM content (R^2-adj = 0·197, $p < 0·01$). Hence, larger amounts of water are conducted at lower (more negative) matric potentials resulting in higher unsaturated conductivity values (Table III). RWC was negatively correlated with values of saturated (R^2-adj = 0·170, $p < 0·05$) and unsaturated hydraulic conductivities at −0·29 kPa (R^2-adj = 0·180, $p < 0·05$), −0·59 kPa (R^2-adj = 0·200, $p < 0·05$) and −1·19 kPa (R^2-adj = 0·191, $p < 0·05$). This suggests that hydraulic conductivities are mainly driven by the ratio of water content at field capacity to saturation. As both macropores and large matrix pores are responsible for soil–water flow under saturated and near-saturated conditions, that is, for example, during an intensive rainfall event, more infiltration into the soil profile will occur underneath the canopy compared with interspaces between trees. In accordance, Cerdà (1997) found less ponding and surface runoff at vegetated patches compared with bare patches (interspaces) for a semi-arid area in south-east Spain.

CONCLUSIONS

Compared with interspace sites between trees, below-canopy soils have a higher OM content causing a lower BD and a higher TP. The better structured soil under canopy habitats resulted in higher saturated and unsaturated hydraulic conductivities and the rates increased with increasing canopy size. This could be related to the ratio of water content at field capacity to saturation, suggesting saturated and near-saturated hydraulic conductivities are mainly driven by macropores and large matrix pores. By improving the near-surface soil hydraulic properties, *A. raddiana* trees can positively affect the water availability for the below-canopy herbaceous cover, which is of crucial importance in water-limited environments. Differences in hydraulic properties underneath and outside the canopy underline their importance in the development of hydrological models on a field scale. Further research is needed to investigate the effect of distance from stem and the effect of wind direction on the soil hydrological properties. This can provide useful information on how to upscale ecosystem processes from point to field scale and to investigate the benefits of incorporating spatial variability in hydrological models.

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