View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Ghent University Academic Bibliography

Influence of Acacia canopy cover on soil hydraulic properties in an arid zone of Tunisia

M. De Boever[1,2], Wim M. Cornelis[1,2], Mohamed Ouessar[3], Donald Gabriels[1,2]

(1) Ghent University, Department of Soil Management, Coupure Links 653, Ghent, Belgium, e-mail: Maarten.DeBoever@UGent.be
(2) Ghent University, UNESCO Chair on Eremology, Coupure Links 653, Ghent, Belgium
(3) Institut des Région Arides, Médenine, Tunisia

Abstract

Studies in arid regions have shown that scattered trees play an important role in reducing the negative effects of climate and soil aridity. They strongly influence the environmental conditions under their canopies. Scattered trees often function as 'fertility islands', in that they provide favourable conditions for the recruitment of other plants. The most critical factor controlling plant productivity in arid regions is water availability in the soil. Hence, understanding the soil-water relationships of nursed ecosystems is of crucial importance. The objective of this study was to investigate the facilitating role of Acacia trees on the herbaceous layer in a forest steppe ecosystem in the Bou Hedma National Park in central Tunisia. To identify the soil-water relations, the soil-water retention curve and the hydraulic conductivity of the upper soil layer (0-10 cm) were determined. Two habitats were distinguished: canopy and interspace, respectively underneath and outside the canopy of Acacia trees. The field saturated hydraulic conductivity (K_{fs}) was higher underneath compared to outside the canopy (8.03 vs. 5.14 x 10^{-6} m s^{-1}). This could be related to the shift in the wet range of the soil-water retention curve, suggesting K_{fs} was driven by greater macroporosity. By improving the soil hydraulic properties, Acacia trees have a strong influence on the water availability within the nursed ecosystem. Therefore, scattered trees can play a central role in the restoration of degraded drylands. Differences in hydraulic properties underneath and outside the canopy underline the importance of incorporating the spatial variability when developing hydrological models on a field scale.

Keywords: Acacia, canopy, soil water, arid zones, 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 strongly influence their abiotic environment. Typical changes in environmental conditions underneath their canopy involve a cooler and often wetter microclimate due to the interception of radiation and precipitation (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 and 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 and Brock, 2000). Facilitation appears to be an essential process, not only for survival, growth, and fitness in some plants (Tirado and Pugnaire, 2003; Aerts *et al.*, 2006, 2007), but also for diversity and community dynamics in many ecosystems (Pugnaire *et al.*, 1996; Abdallah *et al.*, 2008). The 'fertility island' effect of scattered trees further enhances their ability to act as central points of ecosystem recovery from which plant succession may radiate outwards into other parts of a given landscape (Toh *et al.,* 1999).

The most critical factor controlling plant productivity and reproduction in arid to semiarid regions is water availability in the soil (Noy-Meir, 1973; Rodriguez-Iturbe, 2000). On the one hand, plants need water to survive, and thus, the distribution, composition and structure of plant communities are directly influenced by spatiotemporal patterns in water availability. On the other hand, plants exert a strong effect on hydrological fluxes of the terrestrial-atmospheric system (Asbjornsen, 2011). In this respect, the facilitating role of scattered trees can only be fully understood by investigating the soil-water relations of the nursed ecosystem. The soil-water retention curve and the hydraulic conductivity are the most important hydraulic properties when describing these ecohydrological interactions but many studies only focus on the infiltration properties (Dunkerley, 2002; Bedford and Small, 2008; Caldwell et al., 2008; Madsen et al., 2008; Wine et al., 2012).

In this study, the effect of scattered trees on both hydraulic properties was investigated. Measurements were conducted at the microsite scale, distinguishing between the habitats canopy and interspace respectively underneath (0.5 m from stem) and outside (10 m from stem) the canopy of scattered trees. Subsequently, the importance of incorporating the spatial variability of hydraulic properties caused by scattered trees in hydrological models was evaluated.

Study area

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. The park was designated as a UNESCO Biosphere Reserve in 1977. The altitude varies between 90 and 814 m above sea level. Bou Hedma soils are skeletal in the mountainous area, superficial and stony in the piedmont, and sandy to sandy-loamy in low-lying flat areas. The park is divided in different zones: three Integral Protection Zones (IPZ) or core areas, two buffer zones (BZ) and two agricultural zones (AZ) or transition areas. The study was conducted in the low-lying flat area of IPZ1 (Fig. 1.). This zone has a total area of 5,114 ha (of which 2,000 ha plains and 3,114 ha mountainous zones). IPZ1 is completely fenced to prevent grazing by domestic animals and wild fauna from escaping.

The central and the southern part of Tunisia have an arid climate characterized by an extremely irregular spatiotemporal rainfall pattern, a limited amount of precipitation (maximum 350 mm per year), a limited number of rainy days (15 to 40 days per year) and a high average annual temperature ranging from 18 to 21 °C (Abdelkebir, 2005). The main climatic characteristics of the park are: an average rainfall of 180 mm, an average temperature of 17.2 °C, and a mean minimum and maximum temperature of respectively 3.9 °C (December and January) and 38 °C (July and August). The park is characterised by an arid Mediterranean climate with a moderate winter (Le Houérou, 1959).

Acacia raddiana is an important woody species in pre-Saharan Tunisia, which is able 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 and Grouzis, 2003). Nowadays, its geographical distribution is limited to the Bou Hedma region. The terminology 'Acacia forest steppe' is used to designate preforest formations in arid zones (Zaafouri *et al.*, 1996). The forest steppe of the Bou Hedma region suffered for over a century from overexploitation of natural resources and intensification of agricultural activities. Through reforestation and protection programs, the original vegetation is gradually restored. Vancoillie *et al.* (2010) found a mean density of 8 trees per hectare (maximum 95 trees per ha) for 2009, which is similar to the tree density between 1900 and 1925 (4 to 25 trees/ha) as described by Zaafouri *et al.* (1996).

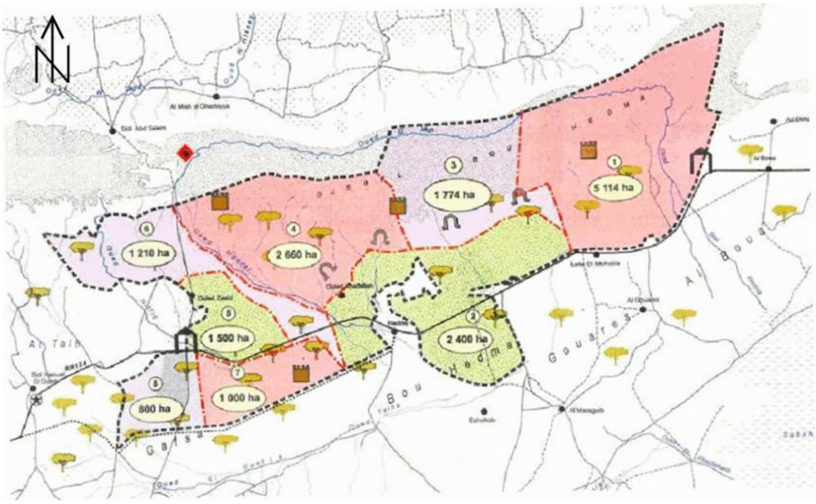

Fig. 1: Map of Bou Hedma National Park with different management zones. The study area lies within zone marked with number 1, i.e. IPZ1.

Materials and methods

Two sub-habitats were distinguished in the study area: tree-covered and open areas, respectively underneath and outside the canopy of Acacia trees. Soil texture was determined using laser diffraction and classified according to the USDA Soil Taxonomy (1951), whereas organic matter measurements were based on the Walkley and Black (1934) method.

Infiltration and soil water retention characteristics were determined for five trees. Measurements underneath and outside the canopy took place respectively at 0.5 and 10 m in the northern direction of each stem. Hydraulic properties underneath and outside the canopy were determined using discrete measurements of infiltration rates. Measurements were performed with a tension disk infiltrometer (Soil Measurement Systems, Tucson AZ, USA) with the infiltration disk (20 cm diameter) separated from the water reservoir. A fine layer of sand was placed on the soil in order to ensure hydraulic contact between the disk 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.

At each measurement location, an undisturbed soil sample of the upper soil layer (0-10 cm) was taken using standard sharpened steel 100-cm³ Kopecky rings. On these samples, five underneath and five outside the canopy, the soil water retention curve was determined at eight matric potentials (-1, -3, -5, -7, -10, -33, -100 and -1500 kPa) using the hanging water-column method on a sand box apparatus (Eijkelkamp Agrosearch Equipment, Giesbeek, the Netherlands) for matric potentials between -1 and -10 kPa, and with pressure chambers (Soilmoisture Equipment, Santa Barbara, CA) for matric potentials between -33 and -1500 kPa. After weighing the soil samples at equilibrium for the matric potential -10 kPa, subsamples were taken and the moisture content on mass basis was determined after oven drying at 105 °C for 24 h as detailed by Cornelis *et al.* (2005). It should be noted that none of the samples was subjected to shrinking upon drying on the sand box apparatus. This enabled the calculation of bulk density following the procedures of Grossman and Reinsch (2002). Moisture content on mass basis (θ_m) for the sample at each matric potential, as well as the volumetric water content (θ_v) were determined using the relationship:

$$\theta_v = \theta_m \frac{\rho_b}{\rho_w} \qquad [1]$$

where ρ_b is the bulk density of the soil (Mg m^{-3}) and ρ_w is the density of water (Mg m^{-3}). The total pore volume TPV is calculated by:

$$TPV = 1 - \frac{\rho_b}{\rho_s} \qquad [2]$$

where ρ_s is the particle density of sand and equal to 2.65 Mg m^{-3}. The model of van Genuchten (1980) was used to describe the soil water retention curve:

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1+(\alpha|\psi|)^n}\right]^m \qquad [3]$$

where θ_r is the residual water content (m^3 m^{-3}), θ_s is the saturated water content (m^3 m^{-3}), ψ is the matric potential (kPa). Parameters α (m^{-1}) and n are estimated using the Retention Curve model (RETC) of van Genuchten *et al.* (1991) and $m = 1 - 1/n$. From the obtained soil water retention curve several important parameters related to the soil porosity can be calculated. The macroporosity (*MacPOR*) and matrix porosity (*MatPOR*) parameters define the volume of soil macropores and matrix pores, respectively, and are defined as:

$$MacPOR = \theta_s - MatPOR \qquad [4]$$

$$MatPOR = \theta_m \qquad [5]$$

where θ_m (m^3 m^{-3}) is the volumetric water content of the matrix porosity. To distinct macropores from matrix pores, values of ψ = -1 kPa, -5 kPa and -10 kPa are used which correspond with pore diameters of 0.3, 0.06 and

0.03 mm respectively (Jarvis *et al.*, 2002; Hall *et al.*, 1977). In this study θ_m was defined as the equilibrium volumetric soil water content at ψ = -5 kPa similar to Reynolds *et al.* (2007). Soil aeration is represented by the soil air capacity (*AC*) and is defined as:

$$AC = \theta_s - \theta_{FC} \quad [6]$$

where θ_{FC} (m^3 m^{-3}) is the field capacity, which is the volumetric water content at ψ = -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:

$$PAWC = \theta_{FC} - \theta_{PWP} \quad [7]$$

where θ_{PWP} (m^3 m^{-3}) is the permanent wilting point, which for most practical applications corresponds to the volumetric water content at ψ = -1500 kPa (Reynolds *et al.*, 2007). Finally, a parameter expressing the soil's capacity to store water relative to the soil's pore volume can be calculated. This parameter is known as the relative water capacity (*RWC*) and is defined by Reynolds *et al.* (2007) as:

$$RWC = \frac{\theta_{FC}}{\theta_s} \quad [8]$$

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

$$\frac{q_h}{\pi R^2} = K(\psi)\left(1 + \frac{4}{\pi R \kappa}\right) \quad [9]$$

where q_h is the steady-state flow rate (m^3 s^{-1}), R is the radius of the disk (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 can be found from tension infiltrometer measurements using the steady-state approach of Logsdon and Jaynes (1993). Their regression method consists of finding the two unknowns K_s and κ via regression of the data using Eq. [9] while substituting Gardner's (1958) hydraulic conductivity function $K(\psi) = K_s\, exp(\kappa\psi)$, where K_s is the saturated hydraulic conductivity (m s^{-1}).

To evaluate and compare the different hydraulic parameters underneath and outside the canopy, a statistical procedure was performed. As is common for in situ measurements of hydraulic conductivities (Warrick and Nielsen, 1980), the calculated hydraulic conductivities showed a lognormal distribution. As a consequence, all statistical analyses were performed on lognormally transformed hydraulic conductivities. The mean (*m*), standard deviation (SD), and coefficient of variation (CV) 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. Before executing one-way ANOVA to look for significant differences between underneath and outside the canopy, a modified Levene test was performed to check the assumption of equal variances (homoscedasticity).

Results and discussion

In a first step, physical and chemical characteristics of the two habitats, canopy and interspace, were compared (Table 1). There were no significant differences ($p>0.05$) in sand, silt and clay fractions between the two habitats. According to the USDA classification, a sandy loam texture was found for both habitats. The bulk density (BD) and total pore volume were respectively lower and higher underneath compared to outside the canopy. The organic matter (O.M.) underneath the canopy was significantly higher ($p<0.05$) than outside.

Table 1: Physical and chemical characteristics of the two habitats, canopy and interspace (n=5).

Habitats	Sand (2000-50 µm) (%)	Silt (50-2 µm) (%)	Clay (<2 µm) (%)	BD (Mg cm^{-1})	TPV (m^3 m^{-3})	O.M. (%)	Texture
Canopy	65.3	30.4	4.3	1.41	0.47	2.37[a]	Sandy loam
	(6.8)	(5.2)	(3.5)	(0.08)	(0.03)	(0.43)	
Interspace	73.0	23.0	4.0	1.54	0.42	0.96[b]	Sandy loam
	(9.2)	(7.9)	(1.5)	(0.12)	(0.05)	(0.28)	

In a second step, the geometric mean of the saturated hydraulic conductivity ($K_{S,G}$) and the unsaturated hydraulic conductivities ($K_{\psi,G}$) of the two habitats were compared (Table 2). A higher mean $K_{S,G}$-value was found underneath compared to outside the canopy (8.03 vs. 5.14 x 10^{-6} m s^{-1}). Differences in unsaturated hydraulic conductivities between the two habitats decreased from lower to higher matric potentials, indicating that mainly the largest macropores are responsible for increased water infiltration. Enhanced infiltrability underneath the canopy of scattered trees can be due to a number of factors which improve the soil structure, including elevated levels of organic matter and lower bulk density under vegetation as was found in Table 1. Furthermore, the variation in mean hydraulic conductivities outside the canopy was remarkably higher compared to underneath the canopy. High coefficients of variation outside the canopy were due to extreme high rates of water infiltration at one measurement location.

Table 2: Geometric mean saturated ($K_{S,G}$) and unsaturated ($K_{\psi,G}$) hydraulic conductivities with coefficients of variation (CV) for the two habitats, canopy and interspace (n=5).

Habitats	$K_{S,G}$ x 10^{-6} m s^{-1}	CV (%)	$K_{\psi,G}$ (-0.29 kPa) x 10^{-6} m s^{-1}	CV (%)	$K_{\psi,G}$ (-0.59 kPa) x 10^{-6} m s^{-1}	CV (%)	$K_{\psi,G}$ (-1.18 kPa) x 10^{-6} m s^{-1}	CV (%)
Canopy	8.03	34	6.12	30	4.68	26	2.75	20
Interspace	5.14	82	4.18	77	3.40	72	2.26	62

In a third step, the mean soil water content was determined at eight matric potentials for the two habitats canopy and interspace (Table 3). Significant higher ($p<0.05$) water retention data were found underneath compared to outside the canopy for matric potentials ranging between -1 and - 5 kPa. As a value of -5 kPa was used to distinct macropores from matrix pores, higher values of soil water retention underneath the canopy can be related to greater macroporosity.

Table 3: Mean soil water content with standard deviations at eight matric potentials for the two habitats, canopy and interspace (n=5).

Habitats	θ (-1 kPa)	θ (-3 kPa)	θ (-5 kPa)	θ (-7 kPa)	θ (-10 kPa)	θ (-33 kPa)	θ (-100 kPa)	θ (-1500 kPa)
					m^3 m^{-3}			
Canopy	0.43[a]	0.40[a]	0.35[a]	0.30	0.22	0.10	0.08	0.05
	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)
Interspace	0.36[b]	0.32[b]	0.29[b]	0.26	0.21	0.10	0.07	0.05
	(0.03)	(0.03)	(0.03)	(0.04)	(0.04)	(0.02)	(0.02)	(0.01)

The soil water retention curves for the two habitats canopy and interspace were established using the van Genuchten model. Table 4 lists the mean values of the fitted van Genuchten parameters to the water retention data for the two habitats. The soil water content at saturation (θ_S) was higher underneath compared to outside the canopy (0.44 vs. 0.36 m^3 m^{-3}). This is a direct result of the increased total pore volume underneath the canopy. The residual water content was similar for both habitats. Also parameters α and n showed corresponding values, indicating similar shape of the water retention curve underneath and outside the canopy.

Table 4: van Genuchten parameters θ_r, θ_s, α and n obtained by fitting to water retention data for the two habitats, canopy and interspace (n=5).

Habitats	θ_r[1]	θ_S[1]	α[1]	n[1]
	m^3 m^{-3}		m^{-1}	-
Canopy	0.06	0.44	1.62	2.30
Interspace	0.05	0.36	1.60	2.25

[1] θ_r is the residual water content, θ_S the saturated water content, α and n are parameters of the van Genuchten model.

The resulting soil water retention curves for both habitats are given in Figure 2. Especially in the wet range of the soil water retention curve, with matric potentials between 0 and -10 kPa, higher values of soil water content were found underneath compared to outside the canopy. The increase in water retention at low matric potentials can be attributed to the improved soil structure underneath the canopy. In the dry range of the soil water retention curve, with matric potentials between -10 and -1500 kPa, similar values of soil water content were found for both habitats.

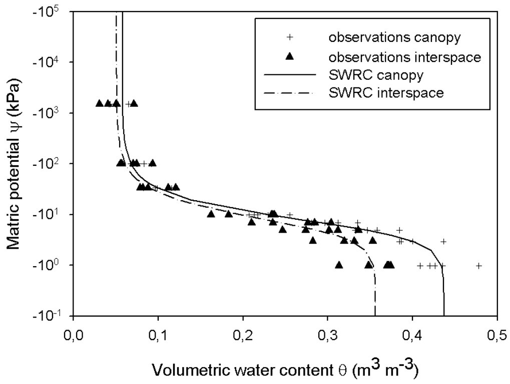

Fig. 2: Soil water retention curves with observation points for the two habitats canopy and interspace (n=5).

In a final step, the soil physical quality parameters for the two habitats canopy and interspace are given in Table 5. Compared to outside the canopy, soil matrix porosity was significantly higher ($p<0.05$) underneath the canopy suggesting its ability to conduct larger amounts of water at lower matric potentials. However, a non-significant increase in macroporosity was found underneath the canopy. The soil air capacity was significantly higher underneath compared to outside the canopy indicating a higher level of soil aeration. The PAWC was similar due to close values of soil water retention at field capacity and at permanent wilting point for both habitats. The RWC was lower underneath compared to outside the canopy due to higher water content at saturation whereas the water content at field capacity remained practically the same.

Table 5: Soil physical quality parameters for the two habitats, canopy and interspace (n=5).

Habitats	MatPor[1]	MacPor[1]	AC[1]	PAWC[1]	RWC[1]
	$m^3\ m^{-3}$				-
Canopy	0.32^a	0.12	0.21^a	0.17	0.51
	(0.02)	(0.02)	(0.02)	(0.01)	(0.03)
Interspace	0.28^b	0.08	0.15^b	0.16	0.59
	(0.04)	(0.03)	(0.03)	(0.04)	(0.09)

[1] MatPor is the soil matrix porosity, MacPor the soil macroporosity, AC the soil air capacity, PAWC the plant-available water capacity and RWC the relative water capacity.

Conclusions

This study shows that Acacia trees have a positive influence on the soil hydraulic properties. By improving the soil hydraulic properties, Acacia trees have a strong influence on the water availability within the nursed ecosystem. Although Acacia trees do not affect the plant available water content, other vegetation will benefit through better aeration and infiltration capacity. Therefore, scattered trees can play a central role in the restoration of degraded drylands.

Differences in hydraulic properties underneath and outside the canopy underline the importance of incorporating the spatial variability when developing hydrological models on a field scale. Further research will be carried out to investigate the effect of tree age, distance from stem, and direction on the soil hydrological properties. Additionally, the extent of influence of Acacia trees on those properties outside the canopy will be determined. 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.

References

Abdallah, F., Noumi, Z., Touzard, B., Belgacem, A.O., Chaieb, M., 2008. The influence of *Acacia tortilis* (Forssk.) subsp. *raddiana* (Savi) and livestock grazing on grass species composition, yield and soil nutrients in arid environments of South Tunisia. Flora 203, 116-125.

Abdelkebir, H., 2005. Elaboration de la carte des aménagements CES et de lutte contre l'ensablement dans l'observatoire de Haddej Bou Hedma par la technique de SIG. Thesis, Université de Jendouba, Ecole Supérieure des Ingénieurs de l'Equipement Rural de Medjez-El-Bab, 83 p.

Aerts, R., Maes, W.H., November, E., Negussie, A., Hermy, M., Muys, B., 2006. Restoring dry Afromontane forest using bird and nurse plant effects: Direct sowing of Olea europaea ssp cuspidata seeds. Forest Ecology and Management 230, 23-31.

Aerts, R., Negussie, A., Maes, W.H., November, E., Hermy, M., Muys, B., 2007. Reforestation of dry afromontane forest using pioneer shrubs as nurse-plants for Olea europaea ssp cuspidata. Restoration Ecology 15, 129-138.

Asbjornsen, H., Goldsmith, G.R., Alvarado-Barrientos, M.S., Rebel, K., Van Osch, F.P., Rietkerk, M., Chen, J., Gotsch, S., Tobón, C., Geissert, D.R., Gómez-Tagle, A., Vache, K., Dawson, T.E., 2011. Ecohydrological advances and applications in plant-water relations research: a review. Journal of Plant Ecology 4, 3-22.

Bedford, D.R., Small, E.E., 2008. Spatial patterns of ecohydrologic properties on a hillslope-alluvial fan transect, central New Mexico. Catena 73, 34-48.

Caldwell, T.G., Young, M.H., Zhu, J.T., McDonald, E.V., 2008. Spatial structure of hydraulic properties from canopy to interspace in the Mojave Desert. Geophysical Research Letters 35, 6 pp.

Cornelis, W.M., Khlosi, M., Hartmann, R., Van Meirvenne, M., De Vos, B., 2005. Comparison of unimodal analytical expressions for the soil-water retention curve. Soil Science Society of America Journal 69, 1902-1911.

Dunkerley, D., 2002. Systematic variation of soil infiltration rates within and between the components of the vegetation mosaic in an Australian desert landscape. Hydrological Processes 16, 119-131.

Eldridge, D.J., Freudenberger, D., 2005. Ecosystem wicks: woodland trees enhance water infiltration in a fragmented agricultural landscape in eastern Australia. Austral Ecology 30, 336-347.

Facelli, J.M., Brock, D.J., 2000. Patch dynamics in arid lands: localized effects of *Acacia papyrocarpa* on soils and vegetation of open woodlands of south Australia. Ecography 23, 479-491.

Finney, D.J., 1941. On the distribution of a variate whose logarithm is normally distributed. Supplement Journal of the Royal Statistical Society 7, 155-161.

Gardner, W.R., 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science 85, 228-232.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility, in: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Physical methods. SSSA Madison Wisconsin, USA, 201-228.

Hall, D.G.M., Reeve, M.J., Thomasson, A.J., Wright, V.F., 1977. Water retention, porosity and density of field soils. Soil Survey Technical Monograph No. 9, Rothamsted, Harpenden, U.K., 75p.

Jarvis, N.J., Zavattaro, L., Rajkai, K., Reynolds, W.D., Olsen, P.A., McGechan, M., Mecke, M., Mohanty, B., Leeds-Harrison, P.B., Jacques, D., 2002. Indirect estimation of near-saturated hydraulic conductivity from readily available soil information. Geoderma 108, 1-17.

Le Floc'h, E., Grouzis, M., 2003. *Acacia raddiana*, un arbre des zones arides à usages multiples, in: Grouzis, M., Le Floc'h, E. (Eds.), Un arbre au désert. *Acacia raddiana*. Paris, IRD éditions, 21-58.

Le Houérou, H.N., 1959. Recherches écologiques et floristiques sur la végétation de la Tunisie méridionale. Institut de Recherches Sahariennes de l'Université d'Alger, Alger, 520 p.

Logsdon, S., Jaynes, D., 1993. Methodology for determining hydraulic conductivity with tension infiltrometers. Soil Science Society of America Journal 57, 1426-1431.

Madsen, M.D., Chandler, D.G., Belnap, J., 2008. Spatial gradients in ecohydrologic properties within a pinyon-juniper ecosystem. Ecohydrology 1, 349-360.

Manning, A.D., Fischer, J., Lindenmayer, D.B., 2006. Scattered trees are keystone structures – Implications for conservation. Biological Conservation 132, 311-321.

Mistry, J., 2000. Savannas. Progress in Physical Geography 24, 601-608.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Annual Review of Ecology, Evolution, and Systematics 4, 25-51.

Parkin, T.B., Meisinger, J.J., Starr, J.L., Chester, S.T., Robinson, J.A., 1988. Evaluation of statistical estimation methods for lognormally distributed variables. Soil Science Society of America Journal 52, 323-329.

Pugnaire, F.I., Haase, P., Puigdefabregas, J., 1996. Facilitation between higher plant species in a semiarid environment. Ecology 77, 1420-1426.

Reynolds, W., Drury, C., Yang, X., Fox, C., Tan, C., Zhang, T., 2007. Land management effects on the near-surface physical quality of a clay loam soil. Soil and Tillage Research 86, 316-330.

Rodriguez-Iturbe, I., 2000. Ecohydrology: a hydrologic perspective of climate–soil–vegetation dynamics. Water Resources Research 36, 3-9.

San José, J.J., Farinas, M.R., Rosales, J., 1991. Spatial patterns of trees and structuring factors in a Trachypogon savanna of the Orinoco Llanos. Biotropica 23, 114-123.

Tirado, R., Pugnaire, F.I., 2003. Shrub spatial aggregation and consequences for reproductive success. Oecologia 136, 296-301.

Toh, I., Gillespie, M., Lamb, D., 1999. The role of isolated trees in facilitating tree seedling recruitment at a degraded sub-tropical rainforest site. Restoration Ecology 7, 288-297.

USDA. 1951. Soil survey manual. U.S. Department of Agriculture Handbook No. 18. U.S. Gov. Print Office, Washington, DC.

Vancoillie, F., Delaplace, K., De Wulf, R., Gabriels, D., De Smet, K., Ouessar, M., Belgacem, A.O., Taamallah, H., 2010. Estimation of *Acacia tortilis* tree attributes in Bou-Hedma, Tunisia: an object-based approach. Proceedings ForestSat 2010.

van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892-898.

van Genuchten, M.T., Leij, F.J., Yates, S.R., 1991. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils, Version 1.0. EPA Report 600/2-91/065, U.S. Salinity Laboratory, USDA, ARS, Riverside, California.

Vetaas, O.R., 1992. Micro-site effects of trees and shrubs in dry savannas. Journal of Vegetation Science 3, 337-344.

Walkley, A., Black, I.A., 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromatic acid titration method, Soil Science 37, 29-37.

Warrick, A.W., Nielsen, D.R., 1980. Spatial variability for soil physical properties in the field, in: Hillel, D. (Ed.), Applications of soil physics. Academic Press, Toronto, 319-344.

Wine, M.L, Ochsner, T.E., Sutradhar, A., Pepin, R., 2012. Effects of eastern redcedar encroachment on soil hydraulic properties along Oklahoma's grassland-forest ecotone. Hydrological Processes 26, 1720-1728.

Wooding, R.A., 1968. Steady infiltration from a shallow circular pond. Water Resources Research 4, 1259-1261.

Zaafouri, M.S., Zouaghi, M., Akrimi, N., Jeder, H., 1996. La fôret steppe a *Acacia tortilis* sbssp. *raddiana* var. *raddiana* de la Tunisie aride: dynamique et évolution. Actes du séminaire international. Acquis scientifiques et perspectives pour un développement durable des zones arides. Jerba, 5-6-7 Décembre 1996, 258-271.