Influence of scattered Acacia trees on topsoil physico-chemical properties and water balance in arid soils

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Invloed van solitaire Acaciabomen op de fysico-chemische eigenschappen en waterbalans van de bodemtoplaag in aride bodems.

Illustration on the cover: View of an integral protected zone of Bou Hedma National Park with an Acacia forest steppe ecosystem (Photo source: Maarten De Boever).

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Voorwoord

Het begon in 2009 toen ik besloten had mijn project rond kleurstabiliteit van rundvlees aan de vakgroep Dierlijke Productie bij prof. Stefaan De Smet niet te verlengen. Ik was van mening dat als ik toen niet zou terugkeren naar mijn 'bodem-roots', nog niet vermoedend dat ik in de toekomst onderzoek zou voeren naar de wortelzone, het nooit meer zou gebeuren. Zo gezegd zo gedaan nam ik de koe bij de horens en stapte naar de controlekamer van de windtunnel aan de faculteit Bio-ingenieurswetenschappen om daar prof. Donald Gabriels te ontmoeten. Ik had horen waaien (veel stof kwam er gelukkig niet aan te pas) dat dit de te strikken man was met tal van projecten rond bodemdegradatie en bodemerosie. De kans zat er dus dik in dat hij iemand nodig had om een studie in het buitenland op te volgen. Na een warm onthaal en het bespreken van vele mogelijke pistes werd mijn 'lot' toen vastgelegd. Ik ging in het najaar naar Tunesië om in het nationaal park van Bou Hedma het veldwerk van de masterstudenten Ken en Kevin voort te zetten. Het was een heus avontuur om als groentje tussen niets-begrijpende parkwachters met meetapparatuur het Acaciaparadijs op het warmste moment van de dag te betreden. Door gebrek aan financiële middelen was dit project helaas van korte duur.

Het was pas in het najaar van 2010 dat ik opnieuw aan de horizon van de vakgroep Bodembeheer verscheen toen er een vacature rond grofstofmetingen in de havens van Gent en Antwerpen was uitgeschreven door prof. Wim Cornelis. Ik herinnerde mij hem van het vak bodemfysica dat hij op meesterlijke wijze doceerde (en van de moeilijke examenvragen). Ik wist dus niet of dit de perfecte match ging worden maar ik kon vrijwel meteen aan de slag dus ik twijfelde geen seconde. Prof. Gabriels was toen nog steeds de resident van de windtunnel en zijn enthousiasme om het onderzoek in Tunesië voort te zetten was springlevend. Het duurde even voor een doctoraatsonderzoek ter sprake kwam, maar uiteindelijk kwamen prof. Cornelis, prof. Gabriels en ik tot een akkoord om de piste van de Acaciabomen in relatie tot de bodemeigenschappen en het microklimaat in het nationaal park van Bou Hedma verder uit te spitten.

Het werden vier fantastische jaren met verscheidene bezoeken aan het park en tal van opportuniteiten om congressen te organiseren en bij te wonen, op korte buitenlandse missies te gaan (met het bezoek aan Dubai als hoogtepunt), gras te maaien en te betreden, stofplaatjes te bereiden en grof stof te tellen, prototypes van grofstofmeters te testen, de windtunnel te bedienen en praktische oefeningen te geven. Het resultaat van dit onderzoek staat nu mooi neergepend in dit proefschrift. Het realiseren ervan was echter niet mogelijk geweest zonder de steun van tal van mensen waarvoor ik dan ook graag een dankwoordje uitbreng.

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Gedurende mijn periode als medewerker aan Universiteit Gent zijn veel buitenlandse collega's de revue gepasseerd. De meesten van hen hebben ondertussen hun doctoraat behaald. Mijn oprechte dank gaat uit naar Raciel, Reza, Gunjan, Martin en Paiwan om mij in te wijden in deze toch wel bijzondere wereld.

Naast de inspanning was er zeker nood aan ontspanning. Voor sport kon ik rekenen op mijn eigen loopbenen bij de Kouterlopers en op de pittige fietsmomenten bij de Eendagsvliegers. Op vlak van vrijwilligerswerk kon ik mij volledig uitleven als financieel beheerder binnen het Bouwcomité van Chiro Scheldering. De frustraties uit mijn lichaam blazen, deed ik als trompettist bij the ArtBridge. Om de gedachten echt te verzetten en soms volledig kwijt te spelen, kon ik terecht bij mijn maten, les amis de dimanche, Oudstreiders, ManaMa-vriendjes en vriendjes-van-Anne (waaronder enkelen zich afvroegen waarom die ene Acaciaboom nu toch zo speciaal is).

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Maarten,

16 februari 2015.

Summary

More than two billion hectares of degraded land worldwide are suitable for rehabilitation through forest and landscape restoration. There is growing awareness for mosaic restoration, in which forest and trees are combined with other land uses, as well as for restoration based on planting forest bridges, in which disparate clumps of woods are connected to form one large ecosystem. In addition, many drylands worldwide have recently experienced or are currently undergoing an increase in the density and cover of woody plants leading to decreases in pastoral productivity and ecosystems colonized by non-native woody plants. As such, not only from a land restoration point of view, but also from a land degradation perspective, understanding the impact of woody vegetation on dryland ecosystems is emphasized.

Scattered woody plants can function as 'nurse plants' or 'fertile islands', facilitating the recruitment of other plants. Positive effects are particularly pronounced in harsh environments such as arid and semiarid regions, where water and nutrient availability in the soil are the most critical factors controlling productivity and reproduction of vegetation. To understand how trees and shrubs can be used as central points of ecosystem recovery from which plant succession may radiate outwards into other parts of a given landscape, their impact on the near-surface soil physical, soil hydraulic and soil chemical properties needs be investigated along a gradient from canopy to interspace. Furthermore, in the context of (re)forestation programs their restoration potential should be studied in function of tree age.

The study was conducted in Bou Hedma National Park in central Tunisia with an arid Mediterranean climate. The park is completely fenced and consists of a forest steppe covered with scattered *Acacia raddiana* trees in combination with a woody and herbaceous ground vegetation. The general objective was to investigate the facilitating role of scattered *A. raddiana* trees on the productivity of the herbaceous ground vegetation by examining their impact on the near-surface soil physical, hydraulic and chemical properties as well as the water balance of the near-surface soil layer, where uptake of water and nutrients by herbaceous roots takes place. Thereby, a distance gradient (both horizontally and vertically) and tree age were taken into account.

In a first part of the doctoral study the impact of scattered *A. raddiana* trees on the near-surface soil physical and hydraulic properties was studied in function of tree age (3 age groups: ca. 65, 90 and ≥110 years old). The study was conducted for 30 *A. raddiana* trees on a microsite scale in a binary way, i.e. at locations underneath and outside the canopy, to investigate whether there was a link with the ecological studies conducted in Bou Hedma National Park. Improved soil physical properties in the top 10 cm soil were found underneath their canopy irrespective of tree age. This was reflected in significantly higher values for total porosity (TP) and significantly lower values for bulk density (BD). In addition, soil physical quality indicators like matrix porosity, macroporosity and air capacity were significantly higher below canopy. The better structured soils underneath the canopy resulted in significantly higher saturated and unsaturated hydraulic

conductivities and significantly higher values of soil-water retention. Saturated and near-saturated hydraulic conductivities were mainly driven by macropores and large matrix pores. The impact of scattered *A. raddiana* trees on the soil physical and soil hydraulic properties became more pronounced with increasing tree age. Significant changes in organic matter (OM), BD, TP, hydraulic conductivities, soil-water content values at low suctions and matrix porosity were found. Higher hydraulic conductivities and higher water retention in the below-canopy soil can positively affect the water availability for the herbaceous vegetation. This is in accordance with recent ecological studies conducted in Bou Hedma National, showing higher species density and biomass production of the herbaceous layer below canopy. However, to understand the impact of scattered *A. raddiana* trees on the soil hydraulic properties on a field scale and their interaction with the herbaceous vegetation, spatial patterns in those properties need to be considered.

In second part of the doctoral study the impact of scattered *A. raddiana* trees on the near-surface soil physical and hydraulic properties in function tree age was studied considering a distance gradient from underneath to outside the canopy (25%, 75%, 125% and 175% of the canopy radius and 10 m away from the canopy) in the four compass directions to account for spatial patterns. For 15 *A. raddiana* trees, greatest differences in soil physical properties in the top 10 cm soil were found between the microsite closest to the tree stem and the other microsites irrespective of tree age. Significant changes in OM, TP, BD and soil-water content at saturation and near-saturation were observed with increasing distance from the tree stem. Enhanced soil physical properties may be mainly due to higher OM levels. Significant changes in OM were observed with increasing tree age. Differences in saturated hydraulic conductivities for the four compass directions were not consistent between tree age groups and were considered as site-specific variations. For the unsaturated hydraulic conductivities, no differences between the compass directions were observed. In accordance with the soil physical properties, saturated and unsaturated hydraulic conductivities were highest closest to the tree stem and significantly decreased with longer distance from the tree stem. Although enhanced soil physical and hydraulic properties were found up to 175% and 125% respectively, especially for the trees older than 75 years with a medium or large crown diameter, the differences were not significant outside the canopy. A spatial pattern in soil physical and hydraulic properties exists between canopy and open microsites and developing hydrological models considering a gradient from underneath to outside the canopy could exploit this spatial pattern.

In a third part of this doctoral study the 'fertile island' effect of scattered *A. raddiana* trees was investigated in function of tree age considering a distance gradient in both horizontal and vertical direction to account for spatial patterns. For 15 *A. raddiana* trees, greatest differences in soil nutrient levels in the top 10 cm soil were found between the microsite closest to the tree stem and the other microsites irrespective of tree age. Levels of OM, total N, exchangeable K^+ and extractable P significantly decreased with longer distance from the tree stem as well as with increasing soil depth. Significantly higher nutrient levels near the stem were found up to a soil depth of 20 cm. Changes in nutrient levels were largely driven by greater litter inputs from leaves and vegetation cover. Significantly higher levels of OM, total N, exchangeable K^+ and extractable P were found with increasing tree age. Although higher levels of OM, total N, exchangeable K^+ and extractable P were found up to 175% of the canopy radius, especially for trees older than 75 years with a medium or large crown diameter, the differences were not significant outside the canopy. A spatial structure in soil chemical properties exists between canopy and open microsites. When combined with information on spatial patterns in soil physical and soil hydraulic properties as previously found, the interaction between scattered *A. raddiana* trees and the herbaceous ground vegetation can be investigated more profoundly.

In a final part of the doctoral study the impact of a single *A. raddiana* tree on the near-surface soil-water balance and the productivity of the herbaceous vegetation was studied along a gradient from underneath to outside the canopy based on a spatial pattern in soil physical and hydraulic properties as was previously found. Hydrus-1D was used to simulate the soil-water balance and the actual transpiration of the herbaceous vegetation. Soil-water availability improved both underneath and outside the canopy up to 175% of the canopy radius as was reflected by higher water content after rainfall events available for longer periods. Greater water availability below canopy can be related to the improved near-surface soil physical and hydraulic properties. In addition, a more favourable microclimate, i.e. higher relative humidity and lower air and soil temperature, was found below canopy, reducing non-productive evaporative losses. The actual transpiration of the herbaceous vegetation was higher underneath compared to outside the canopy for both a dry and a normal year. Consistent with the stress-gradient hypothesis, the difference in actual transpiration between microsites underneath and outside the canopy was more pronounced during a dry year. In addition, water was used more efficiently below canopy as per unit biomass production less water was transpired. Incorporating spatial patterns of soil hydraulic properties in hydrological models when applied on ecosystems with scattered trees provided useful information with regard to the extent of influence on water availability in the soil outside the canopy. However, the improved soil-water availability outside the canopy was strongly reduced due to higher evaporative water losses. Hence, the positive impact of *A. raddiana* on the actual transpiration of the herbaceous layer was mainly occurring underneath their canopy.

Scattered *A. raddiana* trees improve the near-surface soil physical, hydraulic and chemical properties mainly underneath their canopy. However, improved soil hydraulic properties were also found outside the canopy, especially for trees older than 75 years with a medium or large crown diameter, as was reflected in higher soil-water availability. Due to high evaporative losses, soil-water availability was strongly reduced and higher actual transpiration was only found below canopy. Nevertheless, ephemeral annuals can benefit from higher soil-water availability outside the canopy as they complete their life cycle during a short period. The facilitating role of scattered *A. raddiana* trees regarding the productivity of the herbaceous layer is therefore not only limited to the area below canopy. Scattered *A. raddiana* trees can act as important central points of ecosystem recovery from which plant succession may radiate outwards into other parts of a given landscape. They possess a valuable restoration potential especially in drier years when their impact on the productivity of the herbaceous layer was more pronounced. This study confirms the findings of other ecological studies conducted in Bou Hedma National Park showing significantly higher plant cover and productivity of the herbaceous vegetation below canopy and a tree-plant interaction which increased with more drought stress.

Samenvatting

Wereldwijd is meer dan 2 miljard hectare gedegradeerd land geschikt voor herstel door bos- en landschapsrestauratie. Er is een groeiende belangstelling voor mozaiekrestauratie, waarbij bos en bomen worden gecombineerd met andere landgebruiken. Bovendien is er belangstelling voor restauratie gebaseerd op het aanplanten van boomviaducten, waarbij van elkaar afgescheiden delen bos met elkaar worden verbonden tot één groot ecologisch geheel. Verschillende droogtegebieden waren recentelijk of zijn momenteel onderhevig aan een toenemende densiteit en bedekking met houtachtige planten. Dit kan leiden tot een afname in productiviteit van de kruidachtige vegetatie en tot ecosystemen die gekoloniseerd worden door niet-inheemse houtige plantensoorten. Niet enkel vanuit het perspectief van landschapsrestauratie, maar ook omwille van landschapsdegradatie, is het belangrijk om de impact van houtachtige vegetatie op ecosystemen in droogtegebieden te bestuderen.

Solitaire bomen en houtachtige planten kunnen als ‘vruchtbare eilandjes’ functioneren, die de vestiging van andere vegetatie kunnen bewerkstellingen. Positieve effecten zijn vooral uitgesproken in onherbergzame omgevingen, zoals aride en semi-aride gebieden, waar water- en nutriëntenbeschikbaarheid in de bodem als meest kritische factoren voor de productiviteit en reproductie van bodemvegetatie kunnen beschouwd worden. Om een volledig beeld te krijgen van de wijze waarop bomen en houtachtige planten kunnen ingezet worden als centrale punten voor ecosysteemrestoratie van waaruit bodemvegetatie naar andere delen van het landschap kan oprukken, is het noodzakelijk hun impact op de bodemfysische, -hydraulische en -chemische eigenschappen te onderzoeken langs een gradiënt vanaf de stam. In de context van (her)bebossings-campagnes wordt hun restauratiepotentieel in functie van de leeftijd van de boom bestudeerd.

De doctorale studie werd uitgevoerd in het nationaal park van Bou Hedma in centraal Tunesië met een aried mediterraan klimaat. Het park is volledig omheind en bestaat uit een bos-steppe ecosysteem van solitaire *Acacia raddiana* bomen en een houtachtige en kruidachtige bodemvegetatie. Het algemene objectief van de studie was de faciliterende rol van *A. raddiana* bomen op de productiviteit van de kruidachtige bodemvegetatie na te gaan. Dit kan door hun impact te evalueren op de bodemfysische, -hydraulische en -chemische eigenschappen alsook op de waterbalans van de toplaag, waar de opname van water en nutriënten door wortels van de kruidachtige vegetatie plaatsvindt. Hierbij werd een afstandsgradiënt (zowel horizontaal als verticaal) en de leeftijd van de bomen in rekening gebracht.

In een eerste deel van de studie werd het effect van solitaire *A. raddiana* bomen op de bodemfysische en -hydraulische eigenschappen van de toplaag bestudeerd in functie van de leeftijd van de boom (3 leeftijdsgroepen: ca. 65, 90 en ≥110 jaar). De studie werd uitgevoerd voor 30 *A. raddiana* bomen op microsite-schaal, nl. onder en buiten de kroon, zodat het verband met andere ecologische studies uitgevoerd op deze schaal in het nationaal park van Bou Hedma kon onderzocht worden. Er werden betere bodemfysische

eigenschappen vastgesteld in de 10 cm toplaag onder de kroon dan buiten de kroon en dit ongeacht de leeftijd van de boom. Dit uitte zich in een significant hogere totale porositeit (TP) en een significant lagere bulkdichtheid (BD). Daarnaast werden onder de kroon hogere waarden van de bodemfysische kwaliteitsindicatoren matrixporositeit, macroporositeit en bodemluchtcapaciteit vastgesteld. De beter gestructureerde bodems onder de kroon resulteerden in een significant hogere verzadigde en onverzadigde hydraulische geleidbaarheid en in significant hogere bodemwaterretentie. Verzadigde en onverzadigde hydraulische geleidbaarheden werden bijgevolg voornamelijk gestuurd door macroporiën en grote matrixporiën. De positieve invloed van solitaire *A. raddiana* bomen op de bodemfysische en -hydraulische eigenschappen was sterker met toenemende leeftijd van de boom. Significante trends in organisch materiaal (OM), BD, TP, hydraulische geleidbaarheden, matrixporositeit, bodemwatergehaltes bij lage zuigspanningen werden vastgesteld. Door de betere hydraulische geleidbaarheid en waterretentie in de bodemtoplaag onder de kroon wordt de waterbeschikbaarheid voor de kruidachtige bodemvegetatie positief beïnvloed. Dit bevestigde de resultaten van recent uitgevoerde ecologische studies in het nationaal park van Bou Hedma waarbij een hogere bodembedekkingsgraad en biomassaproductie van de kruidachtige vegetatie onder de kroon werd vastgesteld. Om de impact van *A. raddiana* bomen op de bodemhydraulische eigenschappen op veldschaal te bestuderen en hun interactie met de kruidachtige bodemvegetatie te begrijpen, dienen ruimtelijke patronen van bodemeigenschappen in beschouwing genomen te worden.

Daarom werd in een tweede deel van de studie de impact van solitaire *A. raddiana* bomen op de bodemfysische en -hydraulische eigenschappen van de bodemtoplaag bestudeerd, volgens een afstandsgradiënt van onder naar buiten de kruin (25%, 75%, 125% en 175% van de kroonradius alsook 10 m van de kroon) en dit in de vier kompasrichtingen. Voor 15 *A. raddiana* bomen werden de grootste verschillen in bodemfysische eigenschappen in de 10 cm toplaag gevonden tussen de microsite dichtst bij de stam en de andere microsites ongeacht de leeftijd van de boom. Significante trends in OM, TP, BD en bodemwatergehalte bij lage zuigspanningen werden vastgesteld met toenemende afstand van de stam. Verbeterde bodemfysische eigenschappen kunnen verband hebben met hogere OM-gehaltes. Een significante stijging in OM werd vastgesteld met toenemende leeftijd van de boom. Verschillen in verzadigde hydraulische geleidbaarheden in de vier kompasrichtingen werden beschouwd als site-specifieke variaties. Voor de onverzadigde hydraulische geleidbaarheden werden geen verschillen tussen de kompasrichtingen aangetroffen. In overeenstemming met de bodemfysische eigenschappen, was de verzadigde en onverzadigde hydraulische geleidbaarheid het hoogst dichtbij de stam en deze nam significant af verder van de stam. Niettegenstaande betere bodemfysische en -hydraulische eigenschappen in de 10 cm toplaag werden waargenomen tot een afstand van respectievelijk 175% en 125% van de kroonradius, in het bijzonder voor bomen ouder dan 75 jaar met een middelmatige tot grote kroondiameter, werden er geen significante verschillen buiten de kroon vastgesteld. Ruimtelijke patronen in bodemfysische en -hydraulische eigenschappen zijn aanwezig tussen de microsites onder en buiten de kroon. Het ontwikkelen van hydrologische modellen waarbij rekening wordt gehouden met een afstandsgradiënt kan bijgevolg dit ruimtelijk patroon incorporeren.

Niet alleen waterschaarste maar ook een beperkte nutriëntenbeschikbaarheid kan de plantengroei in aride en semi-aride gebieden beperken. In een derde deel van de studie werd het ‘vruchtbare eilandjes’-effect van solitaire *A. raddiana* bomen in functie van de leeftijd van de boom bestudeerd volgens een gradiënt in zowel horizontale als verticale richting. Voor 15 *A. raddiana* bomen werden de grootste verschillen in nutriëntengehalten aangetroffen tussen de microsite dichtst bij de stam en de andere microsites ongeacht de leeftijd van de boom. Een significante daling in OM, totale stikstof, uitwisselbare kalium en extraheerbare fosfor werd vastgesteld met toenemende afstand van de stam alsook met toenemende diepte in de bodem terwijl de concentraties van deze nutriënten toenamen met de leeftijd van de boom. Veranderingen in nutriëntenconcentraties werden in verband gebracht met de aanvoer van strooisel afkomstig van bladval en bodemvegetatie. Niettegenstaande betere bodemchemische eigenschappen in de 10 cm toplaag werden opgetekend tot een afstand van 175% van de kroonradius, in het bijzonder voor bomen ouder dan 75 jaar met een middelmatige tot grote kroondiameter, werden geen significante verschillen buiten de kroon vastgesteld. Voorspelbare ruimtelijke patronen in bodemchemische eigenschappen zijn aanwezig tussen de microsites onder en buiten de kroon. In combinatie de ruimtelijke patronen in bodemfysische en -hydraulische eigenschappen, kan de interactie tussen solitaire *A. raddiana* bomen en de kruidachtige bodemvegetatie op geïntegreerde wijze onderzocht worden.

In een laatste deel van de studie werd de impact van *A. raddiana* op de waterbalans van de bodemtoplaag en op de productiviteit van de kruidachtige bodemvegetatie onderzocht rekening houdende met een afstandsgradiënt vanaf de stam gebaseerd op ruimtelijke patronen in bodemfysische en -hydraulische eigenschappen zoals eerder vastgesteld. Hydrus-1D werd gebruikt om de bodemwaterbalans en de actuele transpiratie van de bodemvegetatie te simuleren. De waterbeschikbaarheid in de 40 cm bodemtoplaag verbeterde zowel onder als buiten de kroon tot een afstand van 175% van de kroonradius. Dit uitte zich in een hoger vochtgehalte in de bodem dat voor een langere periode beschikbaar was na een neerslagbui. Verhoogde waterbeschikbaarheid in de bodem onder de kruin kan gerelateerd worden aan de verbeterde bodemfysische en -hydraulische eigenschappen. Daarenboven werd een gunstiger microklimaat, met name hogere relatieve vochtigheid en lagere lucht- en bodemtemperatuur, vastgesteld onder de kroon waardoor niet-productieve waterverliezen via evaporatie gereduceerd werden. De actuele transpiratie van de kruidachtige bodemvegetatie was hoger onder de kroon vergeleken met buiten voor zowel een droog als een nat jaar. Samenhangend met de stress-gradiënt-hypothese, was het verschil in actuele transpiratie tussen de microsites onder en buiten de kruin meer uitgesproken gedurende het droog jaar. Daarenboven werd het water door de bodemvegetatie meer efficiënt gebruikt onder de kroon aangezien per eenheid biomassaproductie minder waterverbruik optrad. Het gebruik van een afstandgradiënt in hydrologische modellen toegepast op ecosystemen met solitaire bomen verschafte bruikbare informatie met betrekking tot hun impact op de waterbeschikbaarheid in de bodem zowel onder als buiten de kroon. De verbeterde waterbeschikbaarheid in de bodemtoplaag buiten de kroon werd echter sterk gereduceerd door hoge waterverliezen door bodemevaporatie. Hogere waarden van actuele transpiratie van de kruidachtige bodemvegetatie werden dus voornamelijk onder de kroon vastgesteld.

Solitaire *A. raddiana* bomen hebben een positieve invloed op de bodemfysische, -hydraulische en -chemische eigenschappen voornamelijk onder hun kroon. Verbeterde hydraulische eigenschappen werden echter ook buiten de kroon vastgesteld, voornamelijk voor bomen ouder dan 75 jaar met een middelmatige tot grote kroondiameter. Dit resulteerde in een hogere waterbeschikbaarheid in de toplaag. De waterbeschikbaarheid buiten de kroon werd echter sterk gereduceerd door evaporatie van de bodem. Hogere waarden van actuele transpiratie door de bodemvegetatie werden bijgevolg enkel onder de kroon geobserveerd. Desondanks de verhoogde bodemevaporatie kunnen eenjarige planten genieten van de verhoogde waterbeschikbaarheid in de bodem buiten de kroon, aangezien zij hun levenscyclus voltooien in een korte periode. De faciliterende rol van solitaire *A. raddiana* bomen met betrekking tot de productiviteit van de kruidachtige bodemvegetatie is bijgevolg niet enkel beperkt tot de zone onder de kroon. Solitaire *A. raddiana* bomen kunnen optreden als belangrijke centrale punten van waaruit plantsuccessie kan optreden naar andere delen van een landschap. *A. raddiana* bomen bezitten een waardevol restauratiepotentieel, in het bijzonder in droge jaren met een meer uitgesproken positieve impact op de productiviteit van de bodemvegetatie. Deze studie bevestigt de resultaten van verscheidene ecologische studies uitgevoerd in het nationaal park van Bou Hedma waarbij een hogere bedekkingsgraad en productiviteit van de bodemvegetatie onder de kroon werd geobserveerd en deze boom-plant interactie was meer uitgesproken met toenemende droogtestress.

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ΔSWC	change in soil-water storage
AC	air capacity
AI	aridity index
ANOVA	analysis of variance
BD	bulk density
CD	compass direction
CS	canopy size
D	depth
D_d	deep drainage
E_a	actual evaporation
EC	electrical conductivity
ET_a	actual evapotranspiration herbaceous layer
ET_p	potential evapotranspiration reference crop
ET_c	potential evapotranspiration herbaceous layer
FAO	Food and Agriculture Organization of the United Nations
FLR	forest landscape restoration
G	geometric mean
gs2013	growing season 2012/2013
gs2014	growing season 2013/2014
h	pressure head
IBRD	International Bank for Reconstruction and Development
ICP-AES	inductively coupled plasma atomic emission spectroscopy
IPCC	Intergovernmental Panel on Climate Change
IPZ	integral protection zone
ƙ	macroscopic capillary length
$K(\psi)$	unsaturated hydraulic conductivity
K_S	saturated hydraulic conductivity
$K_{S,G}$	geometric mean value of saturated hydraulic conductivity
$K_{\psi,G}$	geometric mean value of unsaturated hydraulic conductivity
l	Mualem (1976) pore-connectivity parameter
LCD	large crown diameter
M	microsite
MacPor	macroporosity
MatPor	matrix porosity
MCD	medium crown diameter
MVG	Mualem-van Genuchten model
n	pore size distribution index, van Genuchten (1980) fitting parameter
N	number of observations/pairs
NS	Nash-Sutcliffe index
ns	not significant
OM	organic matter
P	rainfall

PAWC	plant available water capacity
q_h	steady state flow rate
R	runoff
r	disk radius of tension infiltrometer
R^2	coefficient of determination
R^2-adj	adjusted coefficient of determination
RETC	retention curve model of van Genuchten *et al.* (1991)
RMSE	root mean square error
RWC	relative water capacity
S	sink term related to plant water uptake
s.e.m.	standard error of the mean
SCD	small crown diameter
SD	standard deviation
SGH	stress-gradient hypothesis
SWC	soil-water content
SWC_0	initial soil-water content
SWRC	soil-water retention curve
t	time
T_a	actual transpiration
TP	total porosity
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development programme
UNEP	United Nations Environment Programme
VWC	volumetric water content
z	radial and vertical space coordinate
α	inverse of air-entry value, van Genuchten (1980) fitting parameter
θ_{FC}	volumetric water content at field capacity
θ_m	volumetric water content of the matrix porosity
θ_{obs}	observed water content
θ_{PWP}	volumetric water content at permanent wilting point
θ_r	residual volumetric water content
θ_S	volumetric water content at saturation
θ_{sim}	simulated water content
μ	mean of lognormally transformed values
ρ_b	bulk density
ρ_s	particle density
σ^2	variance of lognormally transformed values
ψ	matric potential
$\Psi(x)$	power series

Chapter 1. Introduction

1.1 A new paradigm for land restoration

'*Forests keep drylands working*' was the UNCCD slogan for 2011, which was the International Year of Forests. Forests are critical to the eradication of poverty in drylands, according to the UNCCD's Secretariat. Forest and tree cover prevent land degradation and desertification by stabilizing soils, reducing water and wind erosion, and maintaining water and nutrient cycling in soils. They are also the first step towards restoring and rehabilitating drylands and protecting them from desertification and drought. Both restoration and rehabilitation seek to repair ecosystems. However, whereas restoration focuses on the conservation of indigenous biodiversity and ecosystem structure and dynamics, rehabilitation aims at raising ecosystem productivity for the benefit of local people (Aronson *et al.*, 1993).

More than two billion hectares of degraded land worldwide are suitable for rehabilitation through forest landscape restoration (FLR). Sayer *et al.* (2003) defined FLR as a process of forest restoration that aims to regain ecological integrity and enhance human wellbeing in degraded forest landscapes. This approach requires that individual elements of a land-use mosaic should not be viewed in isolation. Of that two billion hectares, 1.5 billion hectares would be best suited to mosaic restoration, in which forest and trees are combined with other land uses, including agroforestry and smallholder agriculture (World Resources Institute, 2010). The other 500 million hectares are suited for restoration of closed forests. There is growing awareness for a new paradigm for forest restoration suggesting to focus on planting forest corridors, i.e. connecting otherwise disparate clumps of woods to form one large ecosystem, instead of exclusively prioritizing the expansion of existing medium-to-large size forest fragments.

Restoration through tree planting should not only be considered as replacing lost trees but rather as improving the productivity of landscapes in a sustainable way. Hence, forestation is taken to a next level (Buckingham, 2014). In the last two decades, significant land recovery and improvement have occurred in drylands. In many cases, local communities have taken charge of it. For instance, farmer-managed natural regeneration and agroforestry techniques, such as planting of 'fertilizer trees' on farmlands and grazing lands, have already been adopted in many regions (UNCCD, 2012). That even a single tree can make the difference is proven by the positive trend in African agriculture applying farmer-managed re-greening, i.e. protecting and managing trees that regenerate spontaneously on their farms. Such techniques have contributed to the restoration of millions of hectares across Africa (Reij, 2012).

Not only from a land restoration point of view, but also from a land degradation perspective, the importance of ecosystems with scattered trees or shrubs can be underlined. Many drylands worldwide have recently experienced or are currently experiencing an increase in the density and cover of woody plants (Bond *et al.*, 2003; Potts *et al.*, 2010), leading to dramatic declines in pastoral productivity in many systems (e.g., Oba *et al.*, 2000; Van Auken, 2009). In this context, the term woody encroachment is defined as 'the increase in density, cover and biomass of woody or shrubby plants' (Van Auken, 2000, 2009). Moreover, these woody plants can be non-native invasive species. Dramatic invasions of many species of trees and shrubs the last decades around the world have ensured that woody plants are now among the most widespread and damaging of invasive organisms (Richardson and Rejmánek, 2011). Many tree invasions occur in areas that were formerly treeless or at least where native woody plants very seldom dominate vegetation formations such as grasslands and (semi)arid riparian areas (Rundel *et al.*, 2014).

The apparent mechanisms behind this phenomenon range in the spatial scale from local-to-regional (e.g., increases in grazing and reductions in fire frequency) and regional-to-global (e.g., changes in N deposition, atmospheric CO_2 concentration and climate; Sankaran and Anderson, 2009). Long periods of heavy grazing suppress grass production, and the resulting decline in grass fuel loads can alter the frequency and severity of wildfire, which exerts a controlling feedback effect on shrubs (D'Odorico *et al.*, 2012). Increasing atmospheric CO_2 may favour the establishment of C_3 shrubs at the expense of C_4 grasses, and deep-rooted C_3 shrubs may be more physiologically active in dry conditions than shallow-rooted C_4 grasses (Throop *et al.*, 2012).

The ecological and economic consequences of woody encroachment have received little research emphasis beyond pastoral impacts, despite evidence suggesting that encroachment can have positive impacts on multiple ecosystem functions (Eldridge *et al.*, 2011; Maestre *et al.*, 2009) or ecosystem 'multifunctionality' (Maestre *et al.*, 2012). An emerging view is that encroaching shrubs, whether occurring in isolated patches or as extensive shrublands, can cause a state transition from historical grass dominance to an alternative, but stable state (Standish *et al.*, 2009). Ecosystem multifunctionality in this altered stable state may still remain high (D'Odorico *et al.*, 2012), even where herbaceous productivity is sparse or patchy. These 'novel systems' (Bridgewater *et al.*, 2011), characterised by a greater cover and density of woody plants, are more strongly resistant to human-induced disturbances than the original systems from which they were derived (Standish *et al.*, 2009).

Of particular interest are the similarities in ecosystem multifunctionality between these shrublands and scattered trees. For example, shrubs may also moderate surface micro-climate, reduce nutrient loss from erosional processes, enhance nutrient inputs via N fixation (Lajtha and Schlesinger, 1986), increase soil structure, stability and the infiltration of water (Howard *et al.*, 2012), and provide essential habitat for a range of shrub-obligate taxa (Daryanto and Eldridge, 2012; Eldridge *et al.*, 2011; Howard *et al.*, 2012; Maestre *et al.*, 2009). Shrubs can also hasten the recovery of degraded systems by facilitating seedling establishment (Padilla and Pugnaire, 2006) due to their ability to moderate the effects of drought, and extremes of fire, salinity and frost (Booth *et al.*, 1996; Richmond and Chinnock, 1994).

Positive effects of scattered trees are particularly pronounced in harsh environments, such as drylands, where water and nutrient availability in the soil are the most critical factors controlling productivity and reproduction of vegetation (Noy-Meir, 1973; Rodriguez-Iturbe, 2000). Facilitation of scattered trees regarding the growth of the below-canopy vegetation may occur through a more favourable microclimate (Moro *et al.*, 1997; Breshears *et al.*, 1998), improved soil chemical properties and nutrient availability (Belsky, 1994; Ludwig *et al.*, 2004; Eldridge and Wong, 2005; Wilson, 2002) and enhanced infiltration of rainwater (Caldwell *et al.*, 2008; Dunkerley, 2002).

Ecohydrology, i.e. the study of the interplay between ecological and hydrological processes, of drylands is strongly coupled to available water (Rodriguez-Iturbe, 2000). On the one hand, vegetation needs water to survive, and thus, the vegetation communities are directly influenced by spatiotemporal 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 (Asbjornson *et al.*, 2011). To formulate soil-water relationships as affected by scattered trees, soil hydraulic properties, i.e. the soil-water retention and hydraulic conductivity, are required as essential inputs (Cornelis *et al.*, 2005). Hence, in addition to the determination of water infiltrating properties in the soil, the amount of water retained by the soil needs to be investigated. To our knowledge, ecohydrological studies only focus on the infiltration properties (e.g., Tobella *et al.*, 2014; Caldwell *et al.*, 2008; Madsen *et al.*, 2008, Wilcox *et al.*, 2003; Dunkerley, 2002) apart from one study (Mapa, 1995) where infiltration properties were evaluated in combination with the soil-water retention.

To have better insight in the role of scattered trees in the rehabilitation and restoration of degraded drylands, and more specific their interactions with the below-canopy vegetation, focus needs to be put on their impact on the near-surface soil layer where uptake of water and nutrients by herbaceous roots takes place. Uncertainty in the spatial heterogeneity of these interactions however, affect our ability to upscale observed processes. At the microsite scale, i.e. at locations underneath or outside the canopy of scattered trees, only point-scale information can be obtained. However, to understand the impact of scattered trees on a field scale, one should investigate whether spatial structure does exist from underneath to outside the canopy. Only few studies include the distance gradient when investigating the soil hydraulic properties (Caldwell *et al.*, 2008; Madsen *et al.*, 2008) or soil chemical properties (e.g., Belsky *et al.*, 1994; Belsky *et al.*, 1989) as affected by scattered woody plants.

1.2 Background of this study

Drylands have moved more into the centre of attention thanks to UNCCD and the Convention to Combat Desertification was adopted by the international community in 1994. UNESCO, with its 'Arid Zones' Programme, has helped to pave the way for the recognition of the importance of drylands (Schaaf *et al.*, 2013).

This is why UNESCO and the United Nations University (UNU) joined forces to elaborate the Sustainable Management of Marginal Drylands (SUMAMAD) Project in late 2001. Their aim was to create an inter-regional research cum development project so that the expertise on dryland management can be shared among scientist and national resources managers the world over. Thanks to funding provided by the Flemish Government of Belgium to UNESCO, the SUMAMAD project started in 2002 in its first phase, and has completed its second phase in 2013 by involving dryland specialists from Belgium, Bolivia, Burkina Faso, China, Egypt, India, the Islamic Republic of Iran, Jordan Pakistan and Tunisia (Schaaf *et al.*, 2013).

In the second phase of the SUMAMAD project, from 2009 till 2013, the Bou Hedma Biosphere Reserve (part of the network of Biosphere Reserves of UNESCO) in central Tunisia was included as an extra project site beside the Zeuss-Koutine watershed in southern Tunisia. In this period, intensive field studies were performed in Bou Hedma National Park which belongs to the Bou Hedma Biosphere Reserve.

In the Bou Hedma region, an important tree species of arid and semiarid regions in northern Africa is found, i.e. *Acacia tortilis* (Forssk.) Hayne subsp. *raddiana* (Savi) Brenan. It is the only forest tree persisting on the edge of the Sahara desert, and is therefore considered as a keystone species (Le Floc'h and Grouzis, 2003). The terminology 'Acacia forest steppe' is used to designate forest formations in arid zones such as the Bou Hedma region consisting of scattered Acacia trees in combination with ground cover vegetation.

Bou Hedma National Park was selected to investigate the effect of scattered trees on the ground cover vegetation on a field scale. As the park is completely fenced, disturbance from external factors such as grazing by cattle and human interventions are excluded. Several reforestation programs with *A. raddiana* seedlings were executed in the fenced park since the 1950s. Hence, important information concerning their impact on the near-surface soil hydraulic and chemical properties both underneath and outside their canopy in function of tree age can be derived. From the 2000 ha of plains in Bou Hedma National Park, an area of 10 ha with naturally regenerated and planted *A. raddiana* trees was selected for our study.

Several ecological studies were conducted in Bou Hedma National Park investigating the effect of scattered *Acacia raddiana* trees on the below-canopy herbaceous layer. The aspect of interaction between tree and understory layer was discussed in detail in the dissertations of Noumi (2010) and Abdallah (2010) with point-scale studies in a binary way, i.e. at locations underneath and outside the canopy, on species composition and richness, plant cover and productivity of the herbaceous layer and soil nutrients.

As water availability is the most critical factor in arid zones, the effect of scattered *A. raddiana* trees on the soil hydraulic properties needs to be considered to understand their impact on the below-canopy herbaceous layer. An ecohydrological study needs to be executed in a binary way in order to investigate whether a link is present between the soil hydraulic properties from our study and the findings from the studies of Noumi (2010) and

Abdallah (2010). In order to study the impact of scattered *A. raddiana* trees on a field scale and to determine whether a predictable structure is present, spatial patterns in soil chemical and hydraulic properties need to be investigated from underneath to outside the canopy. A distance gradient will be considered in our study and the extent of influence of scattered trees on the soil properties outside the canopies of scattered *A. raddiana* trees will be examined. In a final step, spatial patterns in soil hydraulic properties will be considered in a hydrological model to simulate the soil-water balance.

Findings from the study conducted in Bou Hedma National park might be useful for other dryland ecosystems with scattered trees or shrubs, systems based on agroforestry and management of sites undergoing woody encroachment or invasion of non-native species. To trigger landscape-level transformations, awareness raising amongst farmers and policy makers on the benefits for scaling-up re-greening is needed (Reij, 2012). Hence, the importance of studying the impact of scattered trees on dryland ecosystems on a field scale is emphasized.

1.3 General and specific objectives

The general objective of this study was to investigate the facilitating role of scattered *A. raddiana* trees on the productivity of the herbaceous ground vegetation by examining their impact on the soil physical, hydraulic and chemical properties as well as the water balance of the near-surface soil layer, where uptake of water and nutrients by herbaceous roots takes place. Thereby, a distance gradient (both horizontally and vertically) and the effect of tree age were taken into account. The specific objectives were to investigate the influence of scattered *A. raddiana* trees on:

- the near-surface soil hydraulic properties in function of tree age, and their link with the herbaceous vegetation;
- spatial patterns in near-surface soil physical and hydraulic properties in function of tree age;
- spatial patterns (both horizontally and vertically) in near-surface soil nutrient levels in function of tree age;
- the near-surface soil-water balance and the actual transpiration of the herbaceous vegetation.

1.4 Outline of the dissertation

A schematic scheme of the dissertation is given in Figure 1.1. After the introduction, Chapter 2 gives a general overview of the drylands in the world. In Chapter 2, drylands are classified based on the aridity index, their geographical distribution, the threats they face from natural and human induced processes, their role in mitigating the global effects of climate change and their provided ecosystem services. In addition, focus is put on their climatic and vegetative characteristics, and their soil and land use types. Chapter 3 gives a general description of *A. raddiana* trees with their taxonomy, their botanical properties and their ecological and phenological characteristics. It also includes the surviving strategies of *A. raddiana* trees in water-limited environments and their coexistence with herbaceous vegetation. This chapter ends with the geographical distribution of *A. raddiana* trees and a detailed description of the study site Bou Hedma National Park. Chapter 4 focuses on the near-surface soil physical and hydraulic properties on a microsite scale, i.e. underneath and outside the canopy of scattered *A. raddiana* trees, and their relation with the herbaceous vegetation is investigated. In Chapter 5 the impact of scattered *A. raddiana* trees on the near-surface soil physical and hydraulic properties in function tree age is studied considering a distance gradient in the four compass directions to account for spatial patterns. The impact of scattered *A. raddiana* trees on the soil physical and hydraulic properties is examined on a field scale and their extent of influence outside the canopy is examined. Chapter 6 investigates spatial patterns in soil nutrient levels in the near-surface soil layer as affected by scattered *A. raddiana* trees in function of tree age. Spatial patterns are accounted for by considering a distance gradient in both horizontal and vertical direction. The impact of scattered *A. raddiana* trees on the soil chemical properties is examined on a field scale and their extent of influence outside the canopy is examined. In Chapter 7, the influence of *A. raddiana* on the near-surface water balance is studied along a gradient from underneath to outside the canopy and put in relation with the actual transpiration of the herbaceous vegetation. This dissertation concludes with Chapter 8, which presents general discussion from the entire study, provides a synthesis of major results, and offers a brief outlook and recommendations.

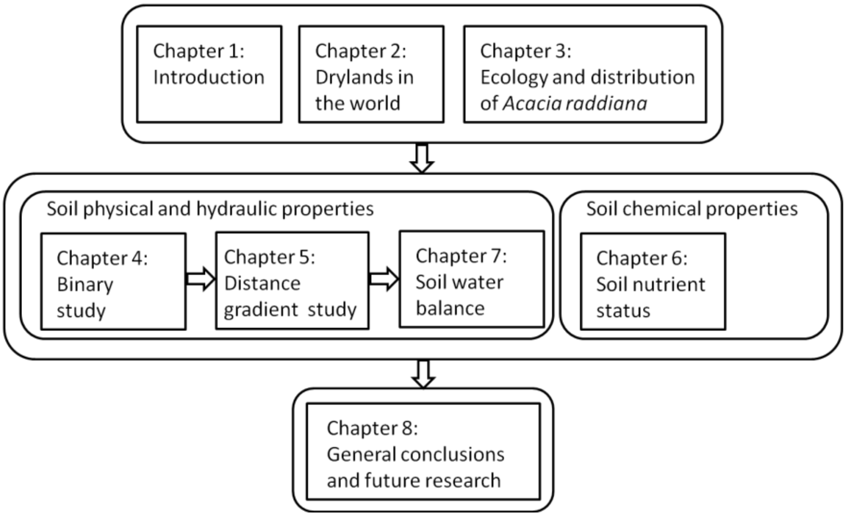
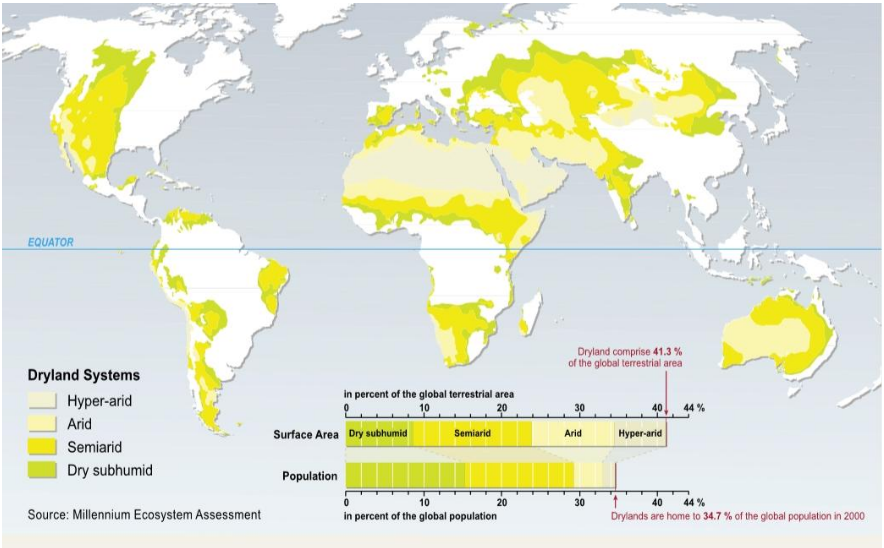


Figure 1.1 Schematic overview of the dissertation

Chapter 2. Drylands in the world: an overview

2.1 Introduction

Drylands are home to over 2 billion people living in some 100 countries and cover more than 40% of the earth's surface. Drylands are found on every continent but are most extensive in Africa and Asia (Figure 2.1). Most drylands are located in developing countries and approximately 90% of dryland people live in developing countries (Safriel *et al.*, 2005).



Source: Millennium Ecosystem Assessment

Figure 2.1 The world's drylands (Millennium Ecosystem Assessment, 2005)

Drylands are under constant threat from multiple stresses and challenges, which occur as a result of a complex interplay of natural processes such as weather variability, recurrent and unpredictable droughts and the concomitant floods caused by the typically short and heavy intervening rains as well as human induced processes including land degradation and desertification caused by unsustainable and inadequate land use practices on a fragile resource base of low fertility (Millennium Ecosystem Assessment, 2005).

2.2 Aridity

Drylands are considered to be areas where rainfall is less than the potential moisture losses through evaporation and transpiration (FAO, 2004). According to the World Atlas of Desertification (UNEP, 1992), drylands have an aridity index (AI), i.e. the ratio of average annual precipitation to potential evapotranspiration, less than 0.65.

Drylands can be further subdivided into: hyperarid deserts ($AI<0.05$), arid ($0.05<AI<0.20$), semiarid ($0.20<AI<0.50$), and dry subhumid zones ($0.50<AI<0.65$) (Figure 2.1). Of the total land area of the world, the hyperarid zone covers 6.6%, the arid zone 10.6%, the semiarid zone 15.2%, and the dry sub-humid zone 8.7% (Safriel *et al.*, 2005). Therefore, drylands cover about 40% of the total area of the world.

Annual rainfall in hyperarid zones is low, rarely exceeding 200 mm. The rains are infrequent and irregular, sometimes with no rain during long periods of several years. True nomadic pastoralism is frequently practiced. Arid zones are characterised by pastoralism and farming with irrigation and water harvesting. There is high rainfall variability, with annual amounts of winter and summer rains not exceeding 200 and 400 mm respectively. Semiarid and dry subhumid zones can support rain-fed agriculture with more or less sustained levels of production. Sedentary livestock production also occurs. Annual precipitation varies for semiarid and dry subhumid zones respectively from 200-500 and 500-700 mm, with winter rains, and respectively from 400-600 and 600-800 mm with winter rains (UNEP, 1992).

2.3 Land use

Despite the difficulties of living in drylands, people have successfully inhabited these areas for thousands of years (UNDP/UNCCD, 2011). Drylands played a central role in the development of human societies (Middleton, 2009). Historically, dryland livelihoods have been based on a mixture of hunting, gathering, cropping, and animal husbandry. This mixture varied in time, place, and culture. The harsh and unpredictable climate combined with changing socio-economic and political factors has forced dryland inhabitants to be flexible in land use (Millennium Ecosystem Assessment, 2005).

Inhabitants of drylands in Africa have learnt to cope with permanent water scarcity, inter- and intra-seasonal rainfall and the recurrent weather-related risks (IAASTD, 2009). However, as a result of high poverty rates, changing socio-economic and political circumstances and demographic growth, traditional coping strategies are increasingly becoming insufficient. Unsustainable land management practices, including over-grazing, over-cultivation, illegal and excessive fuel wood collection and poor irrigation technologies, among others, have become prevalent, often due to institutional or tenurial barriers (UNCCD/UNDP/UNEP, 2009). In Africa for example, 25% of the already fragile drylands have been further degraded in the recent past in a process often referred to as 'desertification' (UNEP, 2006).

Cultivated lands are a substantial part of the dryland landscape. About 44% of all cultivated systems worldwide are located within drylands, especially in dry subhumid areas (Figure 2.2). Conversion of rangelands to cultivated lands, especially in arid and semiarid drylands, leads to trade-offs in long-term sustainability of services and livelihood generation for people. Although urban systems occupy a relatively small fraction (2%) of the area of drylands, they contain a large and rapidly increasing fraction (nearly 45%) of the dryland population (Millennium Ecosystem Assessment, 2005).

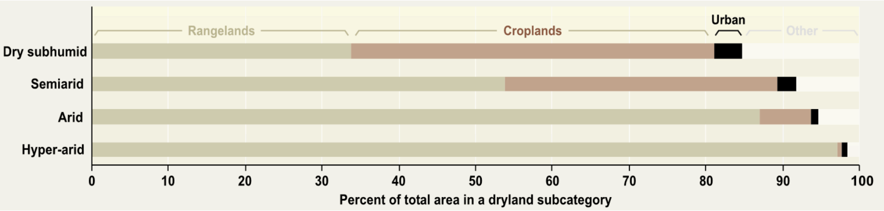


Figure 2.2 Land uses in drylands (Millennium Ecosystem Assessment, 2005)

2.4 Land degradation

Land degradation is the 'reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or a combination of processes, including processes from human activities and habitation patterns such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and economic properties of soil; and (iii) long-term loss of natural vegetation' (UNCCD, 1994).

According to the UN Convention to Combat Desertification, the term 'desertification' denotes a reduction of soils in arid, semi-arid and dry sub-humid areas resulting from a combination of human activities, a deterioration of the land to support core ecosystem functions, coupled with a long-term loss of natural vegetation (UNCCD, 1994). The status of desertification in Africa and Spain is given in Figure 2.3. The classification system used in the preparation of the desertification map is based on five levels of desertification: low, low-moderate, moderate, moderate-high, high. Approximately 26% of Africa is vulnerable to desertification with about 4.5 million km^2 or 55% of the considered land area at moderate or high risk (EC JRC, 2013).

Le Houérou (1968) focussed his attention on the northern edge of the Sahara in Tunisia and Algeria where the annual precipitation is from 100 to 150 mm. Desertification (he preferred the term 'desertization') meant, to him, the development of barren mobile sand dunes or a largely barren desert pavement in the steppe zone bordering the Sahara. He attributed desertification to population pressures: too many people and too many livestock overstressing the environment.

Climate change adds another layer of risk to this precarious situation. Its impacts threaten to exacerbate the existing land degradation problem and add to the vulnerability of drylands' inhabitants (IBRD/World Bank, 2010). There is considerable variability and uncertainty in current climate change projections. Nevertheless, there is now reasonable agreement from a number of different models, including IPCC's Fourth Assessment Report on Climate Change, that Africa is at the highest risk from climate change, given the magnitude of existing stresses in the continent (IPCC, 2007).

It is highly likely that in the coming years significant areas of the African drylands will see changing rainfall patterns with more frequent and more intense extreme events such as droughts and floods. Increased temperatures are expected to add to water problems by causing additional loss of moisture from the soil. For the sub-Saharan region, a decrease of 20-30% in sorghum yield and a median projected temperature increase and precipitation decrease of respectively 3.6 °C and 6% are expected from present to 2080-2099 (IPCC, 2007).

In the drylands, due to drought and desertification, 12 million of hectares of land are transformed into new man-made deserts each year (UNCCD, 2011). At the UN Conference on Sustainable Development (Rio+20), world leaders agreed to strive to achieve a Zero Net Land Degradation by 2030. Sustainable land use is not only a prerequisite for ensuring future water, food and energy security but also for biodiversity and many ecosystem services.

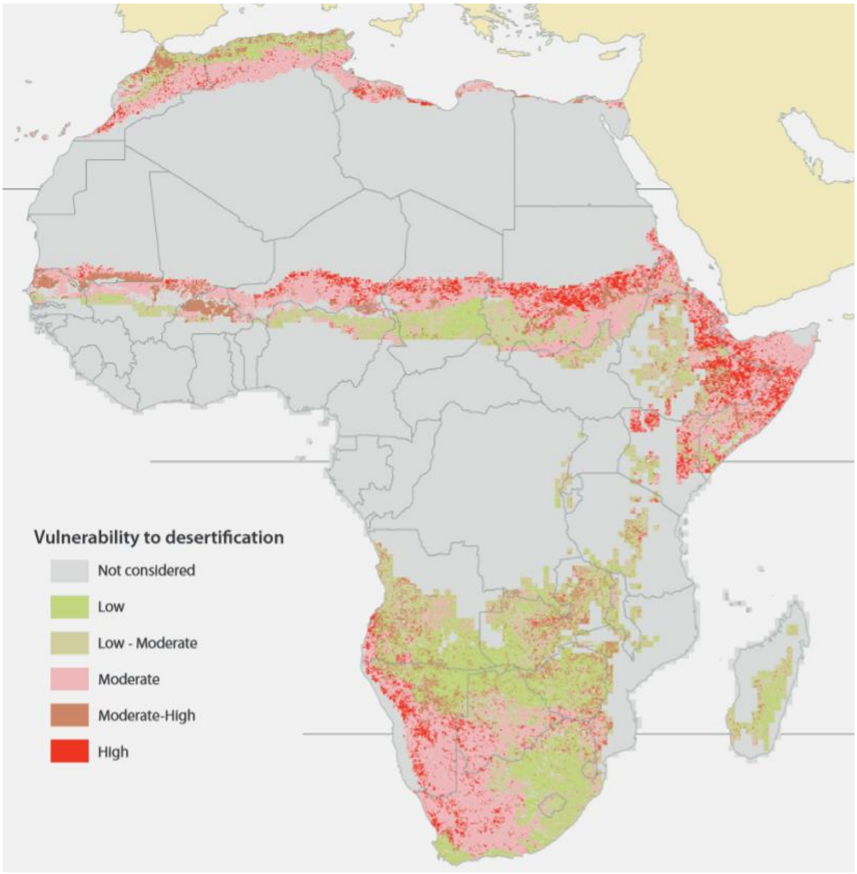


Figure 2.3 Map of Africa with estimated areas under risk of desertification (EC JRC, 2013)

2.5 Ecosystem services

One misconception is that drylands are barren places with little economic value. In truth, the value of ecosystems services provided by drylands is much higher than previously understood, even though their biological productivity is relatively low. Ecosystem services are defined as the benefits people obtain from ecosystems. It is therefore logical to measure productivity in terms of 'things that ecosystems provide that matter people' Hence, land degradation, i.e. reduction of biological and economic productivity, is made quantifiable in an operational way. The people living in the drylands are heavily dependent upon ecosystem services for their livelihoods in a direct and indirect way. From a functional point of view, key dryland ecosystem services are categorized in four groups following Millennium Ecosystem Assessment (2005): (i) provisioning (goods produced or provided by ecosystems such as food, fibre, forage, wood fuel and water), (ii) regulating (benefits obtained from the regulation of ecosystem processes such as water purification and regulation, soil protection and protection against desertification and climate regulation), (iii) supporting (services that maintain the conditions for life on earth such as soil development, primary production and nutrient cycling), and (iv) cultural services.

This dissertation investigates the facilitative role of scattered trees on the actual transpiration of the herbaceous ground vegetation underneath and outside their canopy. Therefore, the water-related ecosystem services provided by scattered trees, and more specific their impact on the water availability in the rootzone of the herbaceous layer, will be studied in detail.

Adaptation to climate variability in the African drylands should be 'ecosystem-based', i.e. integrating the use of biodiversity and ecosystem services into an overall strategy to help people adapt to the adverse impacts of climate change. There is growing recognition of the role healthy ecosystems can play in adaptation. These so-called natural solutions are based on sustainable land and water management as well as the restoration of degraded ecosystems. With the slogan *'Land Belongs to the Future - Let's Climate Proof It!'*, the World Day to Combat Desertification of 2014 was dedicated to ecosystem-based adaptation.

2.6 Climate

Drylands are characterised by excessive heat and inadequate, variable precipitation; however, contrasts in climate occur. In general, these climatic contrasts result from differences in temperature, the season in which rain falls, and in the degree of aridity. Following FAO (1989), three major types of climate are distinguished when describing drylands: the Mediterranean climate, the tropical climate and the continental climate.

For the Mediterranean climate, the rainy season is during autumn and winter. Summers are hot with no rains; winter temperatures are mild. The wet season starts in October and ends in April or May, followed by five months of dry season. According to the Köppen-Geiger climate classification (Peel *et al.*, 2007), this climate corresponds with dry-summer subtropical climate (Cs) (Figure 2.4).

For the continental climate, rainfall is distributed evenly throughout the year, although there is a tendency toward greater summer precipitation. According to the Köppen-Geiger climate classification (Peel *et al.*, 2007), this climate corresponds with semi-arid or steppe climate (BS). Semi-arid climate can be further divided in hot (BSh) and cold (BSk) semi-arid climate (Figure 2.4).

For the tropical climate, rainfall occurs during the summer. The greater the distance from the Equator, the shorter the rainy season. Winters are long and dry. According to the Köppen-Geiger climate classification (Peel *et al.*, 2007), this climate type corresponds with tropical wet-dry or savanna climate (Aw) and arid or desert climate (BW). Arid climate can be further divided in hot (BWh) and cold (BWk) arid climate (Figure 2.4).

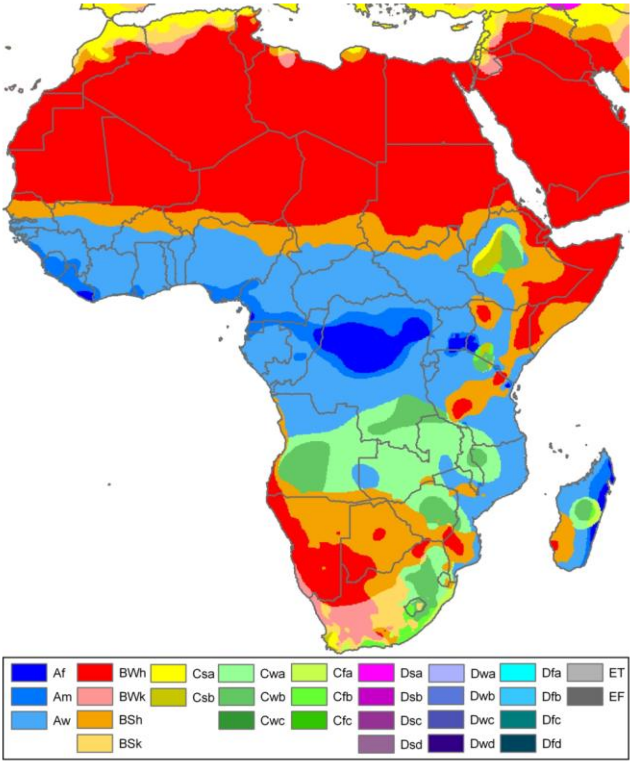


Figure 2.4 Köppen-Geiger climate classification of African continent (Peel *et al.*, 2007)

2.7 Vegetation forms

The vegetation cover in dryland zones is scarce. Nevertheless, three vegetation forms can be distinguished (FAO, 1989): ephemeral annuals, succulent perennials, non-succulent perennials. Ephemerals are drought-escaping species and, in general, are not considered true xerophytes. Succulent and non-succulent perennials are drought-enduring and drought-resisting species and are true xerophytes. Xerophytism refers to adaptive attributes of plants which can subsist with small amounts of moisture.

In general, *ephemeral annuals* are small in size, have shallow roots, and their physiological adaptation consists of their active growth. They appear after rains and complete their life cycle during a short season (± 8 weeks). Their growth is restricted to a short wet period.

Ephemerals live through the dry season, which may last a number of years, in the form of seeds. At times, ephemerals can form dense stands and provide some forage. Examples of ephemeral annuals from central Tunisia are given in Figure 2.5.

Stipa capensis (annual grass) (Photo source: Wikipedia)

Schismus barbatus (annual grass) (Photo source: Flickr)

Malva aegyptica (annual forb) (Photo source: OverBlog)

Paronychia arabica (annual forb) (Photo source: Mori Chen)

Figure 2.5 Ephemeral annuals in drylands: examples from Bou Hedma region (central Tunisia)

Succulent perennials are able to accumulate and store water (that may be consumed during periods of drought). This is because of the proliferation and enlargement of the parenchymal tissue of the stems and leaves and their physiological feature of low rates of transpiration. Cacti are typical succulent perennials.

Non-succulent perennials comprise the majority of plants in drylands. These are hardy plants, including grasses, woody herbs, shrubs and trees that withstand the stress of this harsh environment. Many non-succulent perennials have "hard" seeds that do not readily germinate; these seeds often must be treated (by soaking in water or acid) before they will germinate. Three growth forms of non-succulent perennials can be distinguished: evergreen (biologically active throughout the year), drought-deciduous (biologically dormant during the dry season), cold-deciduous (biologically dormant during the cold season). Examples of non-succulent perennial grasses and shrubs from central Tunisia are given in Figure 2.6. An example of a non-succulent perennial tree is given in Figure 3.8

Eragrostis papposa (perennial grass) (Photo source: Tim Harrison)

Cenchrus cilliaris (perennial grass) (Photo source:)

Hammada schmittiana (perennial shrub) (Photo source: Société Botanique de France)

Rhanterium suaveolens (perennial shrub) (Photo source: Daum Blog)

Figure 2.6 Non-succulent perennials in drylands: examples from Bou Hedma region (central Tunisia)

2.8 Dryland ecosystems

Although there are only four dryland subtypes (i.e., hyperarid, arid, semiarid and subhumid) there are a greater number of dryland ecosystems within the subtypes. These are aggregated into large, higher-order units known as biomes, which are characterised by distinctive life forms and principal plant species. The World Wide Fund for Nature biome classification (Olson *et al.*, 2001) was modified following Hassan *et al.* (2005) with four broad dryland biomes: desert, grassland, scrubland and savanna (Figure 2.7). They successively replace each other along the aridity gradient, with decreased aridity leading to an increase in plant cover, stature, and architectural complexity.

However there is no exact match between the four dryland subtypes and the four broad dryland biomes, such that savanna and grassland, for example may occur at different areas of the same dryland subtype. The number of broad biomes that may occur within a dryland subtype increases with reduced aridity, and the diversity of the biomes is greatest in the semiarid subtype, which also covers the largest area of various subtypes (Figure 2.1). The presence of different biomes within each dryland subtype demonstrates that biological species respond not only to overall moisture deficit but also to other environmental variables, such as soils and geomorphological and landscape features.

Desert (Sahara) (Photo source: Wikipedia)

Grassland (South Africa) (Photo source: Gerald Cubitt and Bruce Coleman)

Scrubland (Chihuahuan desert) (Photo source: Sandy Bryce)

Savanna (East Africa) (Photo source: Thure Cerling)

Figure 2.7 Four broad dryland biomes following Hassan *et al.* (2005)

Deserts are characterised by extremely sparse vegetation consisting of woody shrubs, succulents and ephemeral grasses and herbs which appear after infrequent rain showers. *Grassland* vegetation is characterised by a herbaceous layer with a mixture of annual and perennial grasses, forbs, and small, short trees and shrubs, interspersed with bare areas. *Scrubland* vegetation consists of a closed scrub of evergreen or semi-evergreen shrubs, small trees, climbers, and occasionally, some large trees, either with or without an interspersed herbaceous layer. Shrubs have glossy, leathery leaves or thorny, succulent leaves and are 2 to 3 meters high. The larger trees are widely scattered (FAO, 1989).

Savanna ecosystems contain a discontinuous tree canopy with a substantial grass understory (Eamus and Prior, 2001). Savanna vegetation includes a mixed type of grasses and herbs, with shrubs or trees (or both), in which the proportion of grass to shrubs or trees is determined by the frequency and intensity of fires. When grasses and herbs are dominant and shrubs and trees cover less than 50% of the ground, the savanna is classified as open and wooded grassland. This kind of savanna is typical for dry subhumid to semiarid zones (FAO, 1989). Mulga is an example of a savanna of semiarid to arid zones. It consists of a discontinuous tree layer (mainly *Acacia aneura* trees) over a grassy understory with highly seasonal rainfall (Eamus *et al.*, 2013). *Acacia anuera* is a low-to-medium high (2-8 m) tree possessing the ability to fix atmospheric nitrogen. It is distributed widely in central and western Australia between approximately 20 °S and 31 °S.

2.9 Soils

Dregne (1976) identified five major soil orders according to USDA Soil Taxonomy (Soil Survey Staff, 1999) in drylands: Entisols (41.5% of drylands), Aridisols (35.9%), Mollisols (11.9%), Alfisols (6.6%) and Vertisols (4.1%). In arid to semiarid regions, Aridisols with well developed profiles, and Entisols, with poorly developed profiles are most common. The major soil types in (semi)arid regions, classified according to IUSS Working Group WRB (2014), are Gypsisols, Calcisols, Solonchaks, Solonetz, Leptosols and Regosols (FAO, 1993). The former four soil types correspond to Aridisols and the latter two to Entisols. In semiarid to subhumid regions, the most common soils are Mollisols with a dark surface horizon rich in organic matter, typically under a grassland cover. Vertisols and Alfisols are mainly found in the more humid regions.

Soils of (semi)arid regions are quite diverse but have distinctive characteristics resulting from the common factors affecting the soil formation process (Nicholson, 2011). The nature of these soils is determined to a large extent by climatic factors, particularly low rainfall and relatively high temperatures. Low rainfall means that water and solutes penetrate only to a limited depth, where salts and silicates tend to be deposited when drying occurs and water movement is upwards. Leaching is insufficiently strong to transport bases downward to the water table. Soils in these regions tend to have high pH, high base saturation, low organic matter content and large accumulations of salt, calcium and silica close to the surface (Cooke *et al.*, 1993). The lack of water inhibits weathering, hence dryland soils tend to be coarse-textured (except in alluvial soils) and shallow, in contrast to more humid regions.

Gypsisols and Calcisols with both accumulation of calcium and Durisols with accumulation of silica are the typical soil types under arid and semiarid conditions (European Soil Bureau Network/European Commission, 2005). In the arid regions of North Africa and the Middle East, mud and debris floods formed the so-called '*wadis*' located in areas with low relief. Consecutive mudflow occurrences have been responsible for the development of Calcisols with variable contents of secondary carbonate (lime) accumulation. Gypsisols are characterised by substantial accumulation of secondary gypsum ($CaSO_4.nH_2O$). The largest concentration of Gypsisols in the Mediterranean occurs in the Libyan Desert, Jordan, Syria, parts of Central Anatolia and Cyprus. Durisols contain cemented secondary silica (SiO_2) in the upper one meter of the soil. Their typical feature is the presence of a hard-cemented layer identified as the '*duripan-phase*'. In the Mediterranean, they occur on terraces and slightly sloping alluvial and piedmont plains mainly in Jordan, Syria, Morocco, Tunisia, and Algeria.

Saline soils are common in (semi)arid regions. Major categories are Solonchak, a white alkali soil, and Solonetz, a dark or black alkali soil. Solonchaks have a horizon of soluble salts (chlorides and sulphates of sodium and magnesium), generally at the surface giving it the characteristic white colour. Solonetz contain alkali salts (carbonates and bicarbonates of sodium and magnesium) in the upper layers. The dark colour is a result of dissolved organic matter, which is soluble in alkaline solutions (Nicholson, 2011).

Soils with poorly developed profiles occurring in (semi)arid regions are Leptosols, with a shallow soil over hard rock or highly calcareous material, and Regosols, with a deeper stony soil layer (Nicholson, 2011).

Chapter 3. *Acacia raddiana*: ecology and geographical distribution

3.1 Taxonomy

Acacia is an important genus (member of the *Fabaceae*) with over 500 species in tropical and subtropical regions, especially in Africa and Australia. The leaves generally possess (especially for the Saharan species) spiny stipules at their base (Mihidjay, 1999; Caron, 2001). *A. raddiana* is an important species of (semi) arid regions in northern Africa. It is the only forest tree persisting on the edge of the desert and is therefore considered a keystone species (Abdallah *et al.*, 2008; Grouzis and Le Floc'h, 2003). In Arab, *A. raddiana* is known as '*Talah*', which explains the name of the region of Bou Hedma, i.e. '*Bled Talah*' (freely translated as *region of the gum tree*) in central Tunisia (Caron, 2001).

A. raddiana is often considered as one of four subspecies of *A. tortilis* (Brenan, 1983; Le Floc'h and Grouzis, 2003):

- *A. tortilis* (Forsk) Hayne subsp. *tortilis*
- *A. tortilis* subsp. *spirocarpa* (Rich)
- *A. tortilis* subsp. *heteracantha* (Burchell)
- *A. tortilis* subsp. *raddiana* (Savi) Brenan

3.2 General botanical properties

In general, *A. raddiana* is considered a tree, although bushy characteristics are not exceptional for young specimens. The bushy aspect is explained by the fact that young individuals are multi-stemmed from the base. At a certain age (starting from approximately 10 years), one of the axes becomes the trunk while the other axes are inhibited. The inhibited axes degenerate afterwards. Sometimes the bifurcation at the base remains (2 to 3 branches). The trees have a typical 'Y' profile in the form of a parasol. The crown is usually flat, although a more rounded shape is also observed (Brenan, 1983; Caron, 2001). The crown diameter is generally larger than the tree height (Mihidjay, 1999). A large variation in height is found in literature, from 1.5 to 18 m, with occasionally to 21 m (Brenan, 1983; Caron, 2001; Mihidjay, 1999; Le Floc'h and Grouzis, 2003). The bark is often roughly cracked with a grey to reddish brown colour (Figure 3.1).

A. raddiana trees are characterised by an apical growth, slowing down from July till September (Mihidjay, 1999). In the dry season, the apical tip dehydrates. In autumn, when growth restarts, an auxiliary bud retakes growth. The apical tip is also often eliminated by browsing, inducing growth of auxiliary buds. The described growth process can be generalized for all axes. When the conditions are not favourable, the axis only produces leafs without apical growth. This is particularly visible for aged trees (parasol form).

Two types of branches are found, both with paired spines, though with a different morphology. The first type has a strong apical growth with large, white spines (altered stipules, 1.2 to 10 cm long). The second type is short, with a limited apical growth (usually no longer than 2 cm) and short (5 mm), hooked spines. The short branches produce the inflorescences while the long branches are sterile. The inflorescences consist of a dense collection of white (to yellow) flowers in a spherical structure (comparable with other *Acacia* species), with a diameter of 1 to 2 cm. The pods are flattened and spirally twisted (Grouzis and Le Floc'h, 2003).

Figure 3.1 Bark, leafs and flowers of *Acacia raddiana (Photo source: Kevin Delaplace)*

The leaves are pinnately compound, glabrous to densely pubescent (Figure 3.1). They are 0.5 to 6 mm long and 0.2 to 1.5 mm wide (Brenan, 1983). *A. raddiana* is a semi-deciduous tree, as part of the leaves is shed at the end of August. It has to be stressed that this is highly dependent on the climatologic conditions each year. An important protection against herbivores is the browsing-induced formation of large spines (Gowda *et al.*, 2003).

A. raddiana has a tap root, which is probably more developed than the above biomass. Exact figures of the below-ground biomass are however not available. During the first years of growth, the tap root has very fine secondary roots, allowing the seedlings to extract water from the top 50 cm soil. A fully grown tree has a deep tap root and a large lateral root system in the superficial soil layer (between 0.5 and 3 m) (Dupuy *et al.*, 1991). The depth of the tap root can attain more than 30 m (Caron, 2001; Dupuy *et al.*, 1991;

Bensaid *et al.*, 1996). Even if they reach the ground water table, they still colonize the superficial soil layer (Lavauden, 1927; Lavauden, 1928; Dupuy *et al.*, 1991).

In the rainy season new roots are formed to increase water uptake from the superficial soil layer. This indicates the adaptation capacities of the species, although deeper water is considered unlimitedly available (Lavauden; 1928; Mihidjay, 1999). The transpiration of *A. raddiana* is high during the wet season (Nizinski *et al.*, 1992) especially when sufficient nutrients are available in the rhizosphere (Mihidjay, 1999). In the dry season, water in the superficial soil layer is scarce but water uptake from this layer remains high (Nizinski *et al.*, 1992).

As a member of the *Fabaceae*, nitrogen fixation through bacteria (*Rhizobia)* occurs (Le Floc'h and Grouzis, 2003; Ludwig *et al.*, 2004). Globular or ovoid nodules are formed, although nodulation is more irregular compared to other *Fabaceae* (Mihidjay, 1999). Their existence has been demonstrated for young trees, although they seem absent for adult trees (Dupuy *et al.*, 1991). A symbiotic association with mushrooms (mycorrhizae) is also observed (Mihidjay, 1999).

3.3 Phenology

Phenology is the study of periodic plant cycle events (e.g. flowering) and how these are influenced by variations in climate. Research concerning the phenology of (xerophilic) vegetation is important, as it allows to determine the determining factors and by consequence to predict their reaction to climatic fluctuations (Wahbi, 2006).

Flowering of *A. raddiana* depends on the bioclimatic zone in which the tree is located. In Tunisia, flowering is observed in two periods: from June to July and from August to November (Wahbi, 2006) (Figure 3.2). A study conducted in Bou Hedma National Park showed that the flower buds start to develop in the beginning of July and flowering continues up to September (Mihidjay, 1999). The pods grow from October till March and are ripe in April, which is also the beginning of the dry and warm season (Mihidjay, 1999) (Figure 3.2).

The phenology of the leaves is linked with climatic conditions, particularly temperature and rainfall, and therefore not consistent. In periods of drought, trees can be found without leaves, however not all individuals show this reaction. *A. raddiana* is therefore considered semi-deciduous (Mihidjay, 1999).

The development of the vegetative buds in Bou Hedma National Park starts in June and continues till the beginning of August (Figure 3.2). Afterwards, sprouts start to form and branches with leafs are formed by the end of September. Full leaf stage is reached shortly after and vegetative growth continues until the end of January (Mihidjay, 1999). Fall of leaves starts in February and maximum defoliation is obtained by the end of April (50 to 80% leave loss) (Grouzis and Le Floc'h, 2003), coinciding with the start of the dry and warm season.

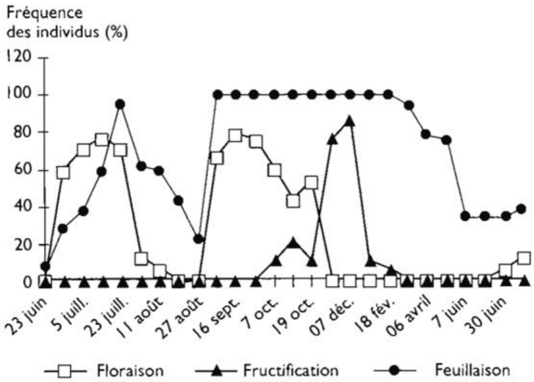


Figure 3.2 Phenology of flowering ('Floraison'), fruiting ('Fructification') and leaf forming ('Feuillaison') for *Acacia raddiana* trees in Bou Hedma National Park in terms of frequency ('Fréquence des individus') (Grouzis and Le Floc'h, 2003)

3.4 Water use

Do *et al.* (2008) found for *A. raddiana* trees growing in the northern Sahel a stable pattern with similar annual amounts of tree water use from year-to-year despite interannual and seasonal variations in soil-water availability in the upper soil layers. The daily water use was significantly related to the canopy fullness and varied between 10 and 50 l day^{-1}.

A. raddiana trees transpired readily throughout the year, except at the peak of the dry season. Throughout this season, there was only a modest decline in tree water use despite the exhaustion of soil water in the uppermost soil layers. The rapid depletion of water in the uppermost soil layers implies that there is extensive use of water from deep soil layers. Do *et al.* (2008) found living roots at 25 m depth, confirming that the trees have access to deep soil water.

A. raddiana trees can also decrease the hydraulic conductivity of sapwood by reducing leaf area, root density and sapwood area (Eamus and Prior, 2001). In addition, they can endure extended drought periods through regulation of the stomatal conductance (Xu and Baldocchi, 2003) and osmotic adjustment (Thomas *et al.*, 1999).

3.5 Hydraulic lift

Hydraulic lift is the process of water movement from relatively wet to dry soil layers through plant roots (Richards and Caldwell, 1987; Caldwell *et al.*, 1998). This transport takes place most commonly during the night when the leaf stomata are closed and the major water potential gradient is between the deep (wet) roots and the drier surface roots in the top soil. Trees can benefit from hydraulic lift as water lost to soils during the night through this process can be taken up by the tree the next day. In this way trees can increase their daily water uptake and more efficiently use deep soil water (Dawson, 1993; Emerman and Dawson, 1996). Ludwig *et al.* (2003) found hydraulic lift under *Acacia tortilis* trees in an East African savanna. Hydraulic lift may have important effects on plant communities and ecosystems in that hydraulically lifted water can also be taken up by the understory vegetation (Dawson, 1993; Caldwell and Richards, 1989).

3.6 Coexistence of trees and understory vegetation

The coexistence of trees and herbs in savannas has compelled many scientists to explain the relative dominance between the two plant functional types using hydrological and ecological explanations (Scholes and Archer, 1997; Higgins *et al.*, 2000; van Wijk and Rodriguez-Iturbe, 2002). It has been theorized that trees and grasses are able to co-exist in savannas by occupying different niches, which can be separated in space and time (Eagleson, 1982; Rodriguez-Iturbe *et al.*, 1999), or by keeping balanced competition with each other (Scholes and Archer, 1997; Higgins *et al.*, 2000). The niche separation theory is derived from the observation that grasses and trees tap different soil moisture reserves and they adopt different life strategies.

Grasses, for example have a relatively shallow root system (Jackson, 1996), so they are unable to tap deep sources of water in the soil profile. To survive across the hot dry summer in Mediterranean climates, many grass species adopt an annual life cycle and transmit their genetic information in the form of seed. Trees, growing adjacent to (or over) grasses, tap deeper sources of soil water (Lhote, 1961; Deans *et al.*, 2005). They also have the physiological capacity to withstand severe soil-water deficits (see section 3.4). Trees can remedy soil moisture deficits through hydraulic lift from which plant communities also benefit (see section 3.5).

3.7 Geographical distribution

A. raddiana shows a wide geographical distribution: from deserts up to regions with a subtropical humid climate (Mihidjay, 1999; Wahbi, 2006). In arid environments, *A. raddiana* is often the only tree species able to survive extreme conditions. *A. raddiana* is widespread in Africa and the Middle-East (from Palestine up to Saudi Arabia and Yemen). In Africa, the species covers two-thirds of the continent (Mihidjay, 1999) and are mainly found in the Northern half. Three distinct zones can be distinguished: North of the Sahara (Morocco, Algeria, Tunisia, Libya and Egypt), South of the Sahara (Sahel-Sudan zone, i.e. Mauritania, Senegal, Mali, Niger, Chad and Soudan) and a tropical humid zone (Nigeria and Cameroun up to Central African Republic) (Brenan, 1983; Mihidjay, 1999; Wahbi, 2006). The actual knowledge of the range and the density in the different countries remains limited (Le Floc'h and Grouzis, 2003) (Figure 3.3).

In Tunisia, the range is limited to central Tunisia including Djebel Bou Hedma (Mihidjay, 1999). In ancient times, the zone comprised between Gabès and Gafsa was covered with *A. raddiana*. Nowadays, the forest that covered about 30,000 ha in the past, is reduced to less than 10,000 ha (Wahbi, 2006). In Figure 3.4, the actual population distribution is presented. Distinction has been made between zones with (relative) high density, sparse density and individuals (or small group of individuals).

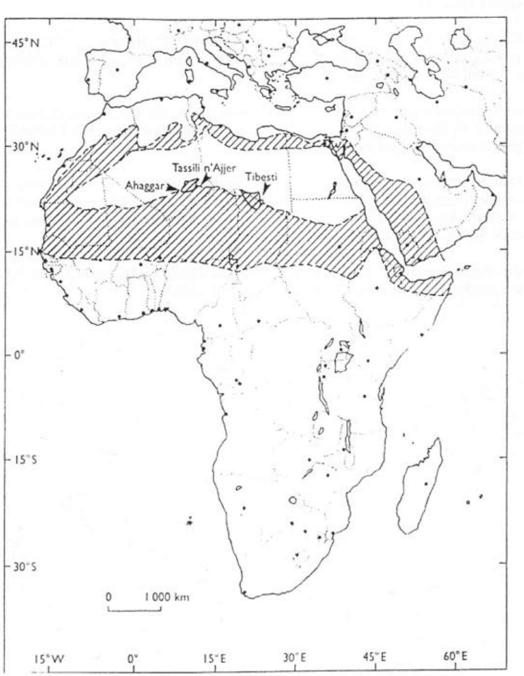


Figure 3.3 Distribution of *Acacia raddiana* in Africa mainly present in northern part (hatched zone) with some individuals or small groups spread around the continent (black dots) (Le Floc'h and Grouzis, 2003)

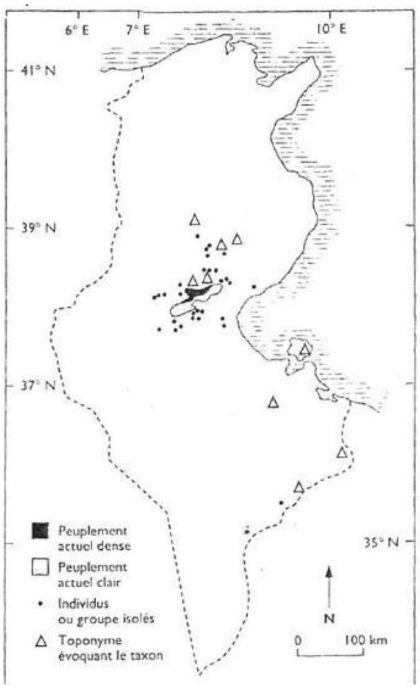


Figure 3.4 Distribution of *Acacia raddiana* in Tunisia with zones of high density ('Peuplement actuel dense'), low density ('Peuplement actuel clair'), and individuals or small groups of individuals ('Individus ou groupe isolés'). Places marked with a triangle are locations with names referring to the historical presence of *Acacia raddiana* ('Toponyme évoquant le taxon') (Le Floc'h and Grouzis, 2003)

The places marked with a triangle are locations with names referring to the historical presence of *A. raddiana* (Le Floc'h and Grouzis, 2003).

A. raddiana is one of the most xerophilic *Acacias* of the African continent (Vassal, 2003): the tree is able to tolerate extreme drought and can survive in zones with an annual rainfall limited to 100 mm (Mihidjay, 1999), with a range of 20 to 200 mm (Wahbi, 2006). It prefers limestone soils, with a sandy to sandy loam texture where water infiltration is high (Wahbi, 2006).

3.8 Bou Hedma National Park

Bou Hedma National Park (34° 39' N and 9° 48' E) is located in central Tunisia at the south side of Djebel Bou Hedma (see section 3.7) and covers an area of 16,488 ha (Figure 3.5). It was designated as a UNESCO Biosphere Reserve in 1977.

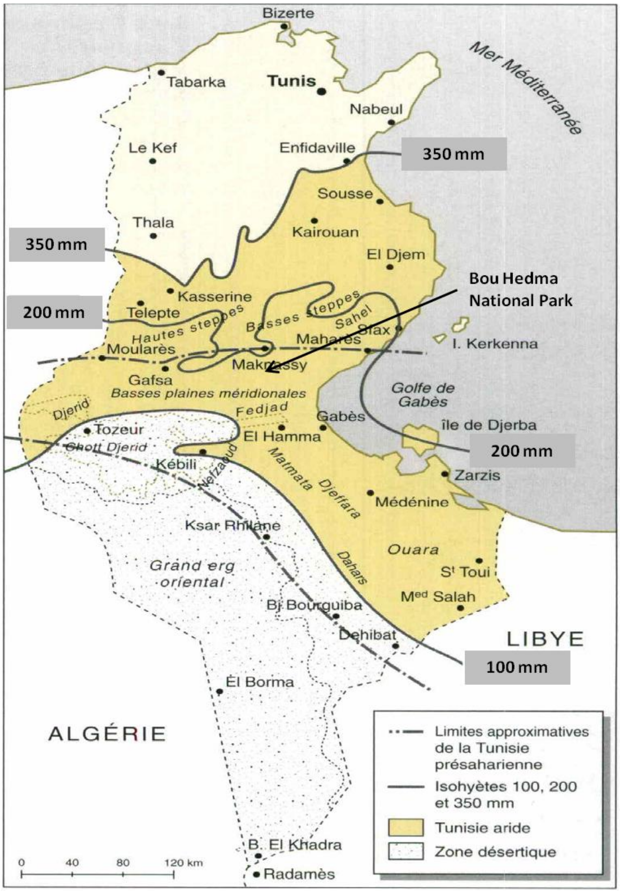


Figure 3.5 Geographical location of Bou Hedma National Park and rainfall distribution for Tunisia as indicated by isohyets of 100, 200 and 350 mm ('Isohyètes 100, 200 et 350 mm') together with the presaharan borders ('Limites approximatives de la Tunisie présaharienne'), arid Tunisia ('Tunisie aride') and the desert ('Zone désertique') (Floret and Pontanier, 1982)

The main climatic characteristics of the park are: an average annual rainfall of 180 mm, an average daily air temperature of 17.2 °C, and an average daily minimum and maximum air temperature of respectively 3.9 °C (December and January) and 38 °C (July and August). For the period 2009-2014, the average monthly rainfall and average daily air temperature ranges respectively between 1.3 mm (July) and 31.6 mm (September) and between 13.2 °C (January) and 30.8 °C (July) (Figure 3.6). The average daily potential evapotranspiration varies between 1.7 mm d^{-1} (December and January) and 6.8 mm d^{-1} (July) (Figure 3.6). The park has an arid Mediterranean climate with a moderate winter (Le Houérou, 1959).

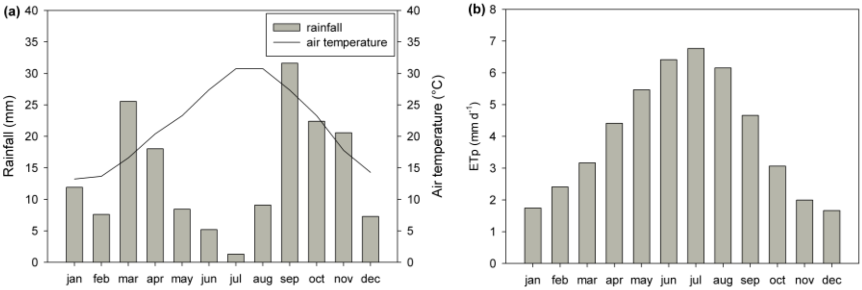


Figure 3.6 For the period 2009-2014 in Bou Hedma National Park (a) the average monthly rainfall and average daily air temperature and (b) the average daily potential evapotranspiration

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, sandy-loamy to loamy in low-lying flat area. Leptosol is the dominant soil type in the mountainous area and both Calcisols and Gypsisols are present in the flat area (Batjes, 2010). According to the USDA Salinity Laboratory (after Richards, 1954) the soils in Bou Hedma National Park are not saline nor alkaline (ECe<4.0 dS/m; Exchangeable Sodium Percentage <15; pH<8.5).

The park is divided in different zones: three Integral Protection Zones (IPZ1, IPZ2 and IPZ3) or core areas, two buffer zones and two agricultural zones or transition areas (Figure 3.7). 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 (antelopes, gazelles, ostriches) from escaping. *Acacia 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 terminology 'Acacia forest steppe' is used to describe the *Acacia raddiana* forest of central Tunisia (Figure 3.8). The origin of the forest remains doubtful: there are claims from the local population that the species was introduced in Tunisia through faeces of camels at the beginning of the 11th century (Zaafouri *et al.*, 1996). Lavauden (1927) consider the forest as a tropical relict, while others suggest *A. raddiana* was introduced from Radamès (Libya, close to border with South Tunisia, Figure 3.5) and planted in the Bou Hedma region (Zaafouri *et al.*, 1996). Some authors think that *A.*

raddiana is not native but originates from Southern Africa, with a centre of diversification in Northern Africa (Ouarda *et al.*, 2009).

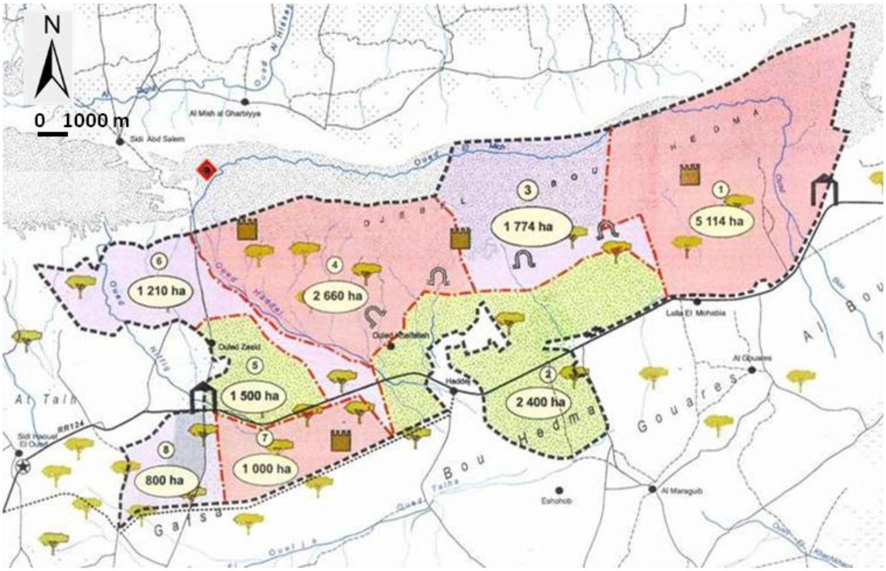


Figure 3.7 Map of Bou Hedma National Park with different management zones. The study site is located within Integral Protection Zone 1 (labelled with '1' on map) (Direction Générale des Forêts, 2005)

Figure 3.8 Forest steppe ecosystem of *Acacia raddiana* in Bou Hedma National Park in central Tunisia (Photo source: Maarten De Boever)

Several ecological studies were conducted in Bou Hedma National Park investigating the effect of scattered *Acacia raddiana* trees on the below-canopy herbaceous layer. The aspect of interaction between tree and understory layer was discussed in detail in the dissertations of Noumi (2010) and Abdallah (2010) with studies on species composition and richness, plant cover and productivity of the herbaceous layer. They both found that *A. raddiana* trees were associated with several herbaceous species such as *Paronychia arabica, Stipa capensis, Eragrostis papposa* and *Cenchrus ciliaris* and (dwarf)shrubs such as *Hammada schmittiana* and *Rhanterium suaveolens*. Perennial grass species such as *Eragrostis papposa, Cenchrus ciliaris* and *Cynodon dactylon* were mainly found below canopy whereas open areas were dominated by annual species (Abdallah *et al.*, 2012). Pictures of annual and perennial species for Bou Hedma National Park are given in Figure 2.5 and Figure 2.6.

Abdallah and Chaieb (2010) showed that herbaceous plant cover, plant biomass, plant density and diversity were higher below canopy and this positive interaction increased with increased drought stress. In addition, Abdallah and Chaieb (2013) concluded that tree age affects this interaction, and the positive effect of *A. raddian*a trees on the herbaceous layer tended to increase with increasing tree age. Noumi *et al.* (2012) concluded that *A. raddiana* acts as a foundation species promoting biodiversity of the herbaceous layer below canopy.

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.

The population of *A. raddiana* in Bou Hedma National Park also shows natural regeneration, although very limited. Many factors have been discussed to explain the low level of regeneration. Firstly, the semiparasitic mistletoe *Loranthus acacia* is considered to cause drying and mortality of *A. raddiana* trees (Noumi *et al.*, 2010). Secondly, *A. raddiana* trees suffer from extraordinarily high infestation of seed beetles (mostly Bruchidae, *Bruchidius raddianae* and *Caryedon palaestinicus*) (Grouzis and Le Floc'h, 2003). The low regeneration of *Acacia* seeds raises a real problem, not only in Tunisia but also in other regions of the world (Noumi *et al.*, 2010).

Delaplace (2010) conducted a monotemporal assessment of the amount and crown diameter distribution of *A. raddiana* trees in Bou Hedma National Park using Geographic Object-Based Image Analysis (GEOBIA). GEOBIA is a subdiscipline of Geographic Information Science (GIScience) devoted to developing automated methods to partition remote sensing imagery into meaningful image-objects, and assessing their characteristics through spatial, spectral and temporal scales, so as to generate new geographic information in GIS-ready format (Hay and Castilla, 2008). Based on two subsequent segmentation algorithms, i.e. multiresolution and contrast split segmentation, the object features were computed from a GeoEye-1 image of the area. Approximately 21,000 segments were classified as *A. raddiana* trees (Delaplace, 2010). The structure of the *A. raddiana* tree population in Bou Hedma National Park was determined based on the crown diameter using the modelled relation with the area feature (number of pixels).

Delaplace (2010) found an uneven-aged forest structure with a lack of small individuals, which was in accordance with the conducted field observations. The distribution of the crown diameters showed a clear presence of crown diameter classes 3 to 4 and 4 to 5 m (Figure 3.9). Small trees, with a crown diameter between 0 and 2 m were not detected by the segmentation algorithms. An exponential decrease in larger crown diameters was present. A mean density of 8.4 trees per ha was found, in line with the historical density of the forest (4 to 25 trees ha^{-1}) (Zaafouri *et al.*, 1996).

Noumi and Chaieb (2012) determined the age of 100 *A. raddiana* trees in Bou Hedma National Park based on the counting of rings (average of counts in three directions spaced 120° apart) from stemdiscs. A high correlation (R^2=0.85) was found between basal trunk circumference (measured at the base of the tree at 10 to 15 cm above ground level) and tree age using regression analysis within a range from 16 to 316 years. Delaplace (2010) found a significant and strong correlation of crown diameter with basal trunk circumference (p<0.001, R^2=0.89) for 456 *A. raddiana* trees in Bou Hedma National Park (Figure 3.10). Hence, a good and significant correlation was also found between crown diameter and tree age (Figure 3.11). The crown diameter is therefore used as a proxy for tree age in this dissertation.

For four *Acacia raddiana* trees, with a basal trunk diameter larger than 20 cm, roots were uncovered. All trees possessed a deep tap root and a large lateral root system located at least 10 cm below the soil surface. For the herbaceous vegetation, the roots were mainly concentrated within the top 10 cm soil and they were found up to 30 cm below the soil surface.

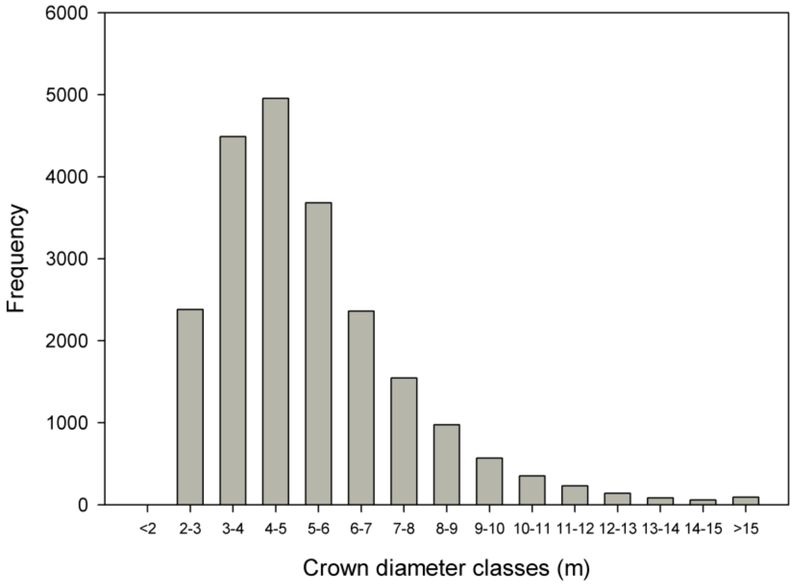


Figure 3.9 Crown diameter distribution in Bou Hedma National Park (Delaplace, 2010)

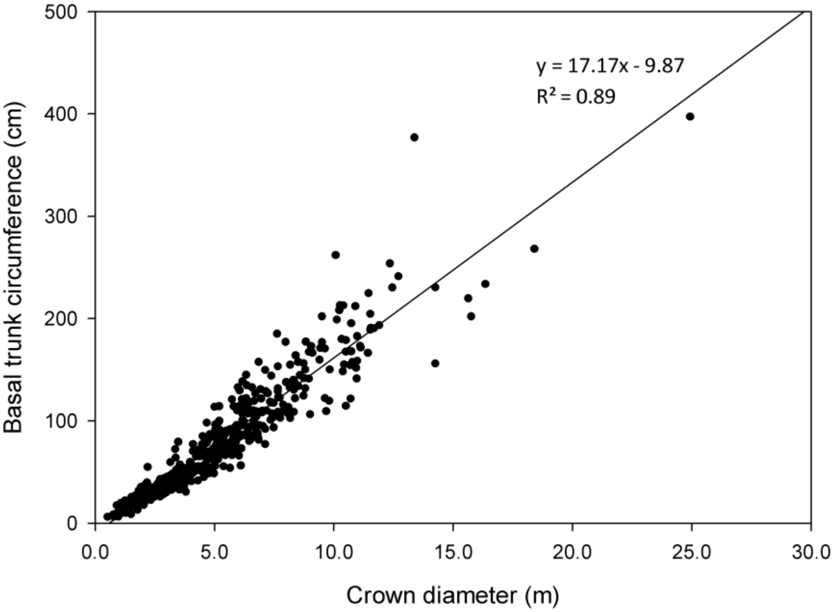


Figure 3.10 Regression between crown diameter and basal trunk circumference for 456 *Acacia raddiana* trees in Bou Hedma National Park (Delaplace, 2010)

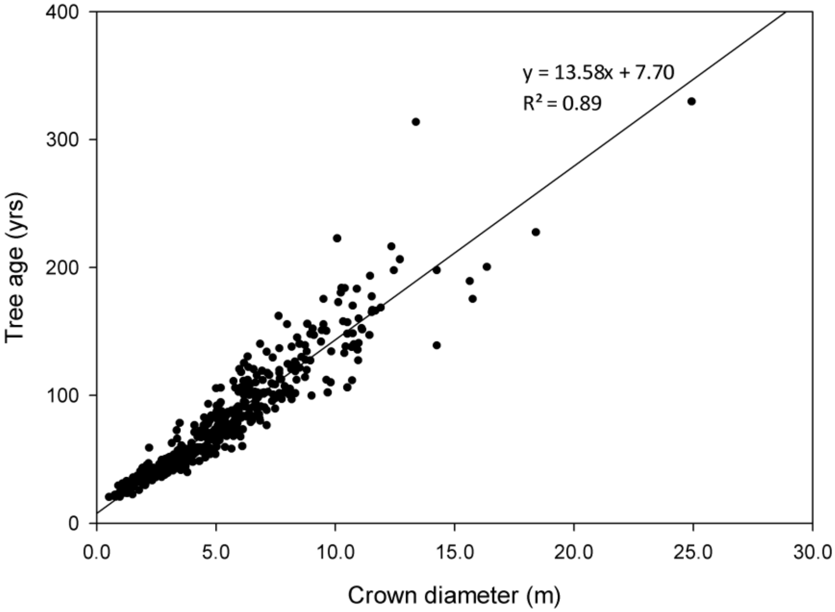


Figure 3.11 Regression between crown diameter and tree age for 456 *Acacia raddiana* trees in Bou Hedma National Park (valid within range from 15 to 316 years) (Delaplace, 2010)

Chapter 4. Influence of Acacia trees on near-surface soil physical and hydraulic properties in arid Tunisia[1]

4.1 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 microsite scale, scattered trees may strongly modify the physical environment underneath their canopies through their effects on biotic and abiotic processes (Shachak *et al.*, 2008). Typical changes in environmental conditions below canopy involve a cooler and often wetter microclimate due to 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 and Freudenberger, 2005). Scattered trees often function as 'nurse plants' or 'fertile islands', in that they facilitate the recruitment of other plants (San José *et al.*, 1991; Facelli and Brock, 2000). Positive effects are particularly pronounced in ecosystems where water stress limits plant growth.

In arid to semiarid 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 spatiotemporal 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 to interpatch areas. For trees, studies on ecohydrological interactions were mainly executed in semiarid Eucalypt savannas of northeast Australia (Roth *et al.*, 2003), Mulga woodlands of central Australia (Dunkerley, 2002) and semiarid Piñon-Juniper woodlands of northern New Mexico (e.g. Wilcox *et al.*, 2003; Madsen *et al.*, 2008), and agroforestry parklands in semiarid Burkina Faso (Tobella *et al.*, 2014). However, little is known about the effects of Acacia trees on soil hydraulic properties in arid and semiarid regions of Africa. *Acacia tortilis* (Forssk.) Hayne subsp. *raddiana* (Savi) Brenan for example is an important woody species in pre-Saharan Tunisia, as it can 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). Hence, understanding the

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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 retention curve and saturated and unsaturated hydraulic conductivities on a microsite scale, i.e. underneath and outside their canopy. Where most other studies only focus on the infiltration properties, our study investigates the soil-water retention curve and the hydraulic conductivity. Therefore, the effects of *A. raddiana* trees on soil physical quality indicators are considered. 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 with increasing tree age.

4.2 Materials and methods

4.2.1 Study site

A description of the study site is given in section 3.8.

4.2.2 Experimental design

A total of 30 *A. raddiana* trees was randomly selected in the plain of IPZ1 covering an area of approximately 10 ha. With a mean density of 8.4 trees per hectare in Bou Hedma National Park, more than one third of the tree population in the study area is sampled. Many other studies (Ludwig *et al.*, 2001, 2004; Eldridge and Wong, 2005) apply a sampling strategy in savanna ecosystems where five trees for each tree type are selected within a study area of 300 to 400 ha.

To characterize the *A. raddiana* population present in the park, three crown diameter classes based on the crown diameter distribution of Bou Hedma National Park (Figure 3.9) were distinguished each containing 10 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, i.e. the below-canopy microsite. In addition, the crown diameter is used as a proxy for tree age. For each canopy size class, crown diameter, basal trunk diameter (basal trunk circumference/π) and tree age are listed in Table 4.1.

Table 4.1 Mean ± SD of *Acacia raddiana* tree attributes with small (SCD, N=10), medium (MCD, N=10) and large crown diameter (LCD, 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] (yrs)	64 ± 7	88 ± 10	140 ± 37

[a]Calculation of *Acacia raddiana* tree age based on basal trunk diameter following Noumi and Chaieb (2012).

For those 30 trees, 10 per crown diameter class, two locations were distinguished: underneath (canopy) and outside canopy (open), respectively at 25% of the canopy radius (in which 100% is the distance from the tree stem to the canopy edge) in the northern direction and 10 m away from the canopy edge. This study only focuses on the top 10 cm soil as roots of the herbaceous cover are mainly concentrated in the upper layer.

Soil texture on air-dried fine earth (<2 mm) samples was determined for all 30 trees underneath and outside the canopy with the pipette method (Gee and Or, 2002), and classified according to the USDA textural triangle (Soil Survey Staff, 1999). $CaCO_3$ was not removed in the pre-treatment process as it originates from the parent material and forms as such a substantial part of the soil texture. Organic matter (OM) was determined according to the Walkley and Black (1934) method.

Infiltration measurements underneath and outside the canopy of all 30 trees were performed at the soil surface with a tension disk infiltrometer (Soil Measurement Systems, Tucson AZ, USA) with the infiltration disk (20 cm in 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 disk and the soil. Three successive matric potentials (ψ) were applied, -0.29, -0.59, and -1.18 kPa, for at least 10 minutes or until the infiltration rate of three consecutive time intervals was constant.

To obtain the soil-water retention curve (SWRC), undisturbed soil samples of the top 10 cm soil 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 -1500 kPa) as described by Cornelis *et al.* (2005). The soil bulk density (BD) was determined at -10 kPa following the procedure of Grossman and Reinsch (2002). The total porosity is calculated by:

$$TP = 1 - \frac{\rho_b}{\rho_s} \tag{1}$$

where ρ_b is the bulk density (Mg m^{-3}), 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 and Horton (2004).

The model of van Genuchten (1980) was used to describe the soil-water retention curve:

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

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 (kPa^{-1}) and n were estimated using the Retention Curve model (RETC) of van Genuchten *et al.* (1991) and $m = 1 - 1/n$.

Matrix porosity (*MatPor*), macroporosity (*MacPor*), air capacity (*AC*), plant-available water capacity (*PAWC*) and relative water capacity (*RWC*) were derived from the SWRC using the equations below (Reynolds *et al.*, 2007):

$$MatPor = \theta_m \tag{3}$$

$$MacPor = \theta_s - MatPor \tag{4}$$

$$AC = \theta_s - \theta_{FC} \tag{5}$$

$$PAWC = \theta_{FC} - \theta_{PWP} \tag{6}$$

$$RWC = \frac{\theta_{FC}}{\theta_s} \tag{7}$$

where θ_m (m^3 m^{-3}) is the volumetric water content of the matrix porosity (ψ = -5 kPa), θ_{FC} (m^3 m^{-3}) and θ_{PWP} (m^3 m^{-3}) are the volumetric water content at field capacity (ψ = -10 kPa) and permanent wilting point (ψ = -1500 kPa), respectively.

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:

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

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 the macroscopic capillary length. The two unknowns $K(\psi)$ and κ were derived from tension infiltrometer measurements using the steady-state approach of Logsdon and 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 saturated hydraulic conductivity (m s^{-1}).

4.2.3 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 ANOVA was performed. In case of a significant main effect of canopy size, a Tukey post-hoc test was executed to indicate significant differences amongst the levels of this factor. The organic matter contents were lognormally transformed prior to statistical analyses.

As is common for *in situ* measurements of hydraulic conductivities (Warrick and 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. After calculating the mean (μ) and variance (σ^2) of the lognormally transformed values, the data were retransformed to the original units using equations 9 and 10:

$$G = e^{\mu} \times \Psi\left(\frac{\sigma^2}{2}\right) \tag{9}$$

$$SD^2 = e^{2\mu} \times \left[\Psi(2\sigma^2) - \Psi\left(\frac{N-2}{N-1}\,\sigma^2\right)\right] \tag{10}$$

where *G* is the retransformed geometric mean value for K_s or $K(\psi)$, *SD* the retransformed standard deviation, *N* is the number of observations, and *Ψ(x)* (with *x* substituted by the corresponding terms in equations 9 and 10) the power series defined by equation 11:

$$\Psi(x) = 1 + \frac{x(N-1)}{N} + \frac{x^2(N-1)^3}{n^2(N+1)\,2!} + \frac{x^3(N-1)^5}{n^3(N+1)(N+3)\,3!} + \frac{x^4(N-1)^7}{n^4(N+1)(N+3)(N+5)\,4!} + \cdots \tag{11}$$

which is evaluated until the final term accounts for less than 1% of the sum of the preceding terms.

Trend analysis using linear regression was performed on all parameters to study the effect of distance from the stem and canopy size. The standard error of the mean (s.e.m.) was calculated across all canopy sizes and microsites for all parameters. In order to evaluate associations between parameters, the Pearson correlation coefficient and corresponding level of significance was calculated.

4.3 Results and discussion

4.3.1 Soil physical properties

There were no significant differences in sand and silt fractions between the soils of the three canopy size classes and between the two microsites (Table 4.2). For clay, a significantly higher fraction was found underneath compared to outside the canopy (8.9 vs. 8.0%). The difference is mainly due to the lower clay content outside the canopy of LCD trees and as such not related to preferential deposition of clay particles from wind erosion. 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 to MCD (1.1 vs. 1.5%) and LCD (1.1 vs. 1.8%). A significantly higher OM content was found for microsite canopy compared to open (2.1 vs. 0.8%), irrespective of the canopy size. The higher OM content can be related to greater litter production from leaves and understory vegetation, and improved cycling of organic matter. Even if litter fall inputs are relatively low in drylands due to constraints in plant productivity (Breckle, 2002), they may be substantially higher underneath the canopy (Cortina and Maestre, 2005). Higher soil moisture content and greater litter production beneath woody canopies lead to improved microbial activity and accumulation of organic matter (Gutiérrez and Jones, 2006).

Table 4.2 Mean and standard error of the mean (s.e.m.) of soil physical properties in the top 10 cm soil on microsite locations canopy and open for *Acacia raddiana* trees with small (SCD, N=10), medium (MCD, N=10) and large crown diameter (LCD, N=10)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
Sand (2000-50 µm) (%)	canopy	70.1	66.2	68.8	68.3	1.6	ns	ns	ns
	open	66.5	68.9	70.6	68.7				
	mean	68.2	67.5	69.7					
Silt (50-2 µm) (%)	canopy	21.7	24.1	22.7	22.9	1.3	ns	ns	ns
	open	25.0	22.5	22.6	23.4				
	mean	23.4	23.3	22.7					
Clay (<2 µm) (%)	canopy	8.3	9.7	8.5	8.9	0.3	ns	<0.05	ns
	open	8.5	8.6	6.8	8.0				
	mean	8.4	9.2	7.6					
BD (Mg m^{-3})	canopy	1.38	1.37	1.33	1.36	0.15	ns	<0.01	ns
	open	1.54	1.51	1.48	1.51				
	mean	1.46	1.44	1.41					
TP (m^{3} m^{-3})	canopy	0.48	0.48	0.49	0.48	0.06	ns	<0.01	ns
	open	0.42	0.43	0.44	0.43				
	mean	0.45	0.45	0.46					
OM (%)	canopy	1.4	2.1	2.7	2.1	1.0	<0.01	<0.01	ns
	open	0.7	0.9	0.9	0.8				
	mean	1.1^{a}	1.5^{b}	1.8^{b}					

BD: bulk density; TP: total porosity, OM: organic matter, CS: canopy size, M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant.

Furthermore, it was shown from regression analysis that OM content increased with increasing canopy size (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 and Pugnaire (2003). BD was significantly higher for the open microsite location compared to below-canopy (1.51 vs. 1.36 Mg m^{-3}). Accordingly, TP was significantly lower for open compared to canopy (0.43 vs. 0.48 m^{3} m^{-3}).

The increase of OM in the soil under trees with increasing canopy size was reflected in a decreasing bulk density (R^2-adj = 0.543, $p<0.001$), and hence in an increasing total porosity (R^2-adj = 0.511, $p<0.001$). In accordance, Greenwood and Buttle (2014) found increased soil organic matter content and porosity with increasing forest plantation age in southern Ontario, Canada. Positive effects of OM content on the physical quality of the soil were also reported by Shukla *et al.* (2006).

4.3.2 Soil hydraulic conductivity

The geometric mean saturated ($K_{S,G}$) and unsaturated ($K_{\psi,G}$) hydraulic conductivities were significantly higher underneath compared to outside the canopy (Table 4.3). Numerically higher values for $K_{S,G}$ and $K_{\psi,G}$ were found for LCD compared to SCD, with MCD having intermediate values. Following regression analysis, values in saturated (R^2-adj = 0.129,

$p<0.05$) and unsaturated hydraulic conductivities at -0.29 kPa (R^2-adj = 0.143, $p<0.05$), -0.59 kPa (R^2-adj = 0.184, $p<0.05$) and -1.19 kPa (R^2-adj = 0.206, $p<0.01$) significantly increased with increasing canopy size. The saturated values in our study were within the range of sandy to loamy soils (Carsel and Parrish, 1988).

Several studies mention higher hydraulic conductivities underneath canopies, particularly under positive head (Lyford and Qashu, 1969; Daryanto *et al.*, 2013), following natural rainfall (Reid *et al.*, 1999; Bhark and 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 (Wang *et al.*, 2009), protection of the soil by leaf-litter creating aggregation, and a more developed network of macropores (Dunkerley, 2000).

Table 4.3 Geometric mean and standard error of the mean (s.e.m.) of the saturated ($K_{S,G}$ x 10^{-6} m s^{-1}) and unsaturated ($K_{\psi,G}$ x 10^{-6} m s^{-1}) hydraulic conductivities at the soil surface on microsite locations canopy and open for *Acacia raddiana* trees with small (SCD, N=10), medium (MCD, N=10) and large crown diameter (LCD, N=10)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
$K_{S,G}$	canopy	4.39	7.63	7.39	6.42	0.52	ns	<0.01	ns
	open	3.73	4.07	4.37	4.07				
	mean	4.12	5.79	6.05					
$K_{\psi,G}$ (-0.29 kPa)	canopy	3.46	5.87	5.72	4.99	0.39	ns	<0.01	ns
	open	3.06	3.40	3.59	3.36				
	mean	3.29	4.61	4.77					
$K_{\psi,G}$ (-0.59 kPa)	canopy	2.73	4.53	4.43	3.89	0.29	ns	<0.01	ns
	open	2.52	2.84	2.96	2.78				
	mean	2.64	3.68	3.77					
$K_{\psi,G}$ (-1.18 kPa)	canopy	1.72	2.73	2.69	2.38	0.17	ns	<0.05	ns
	open	1.72	1.99	2.02	1.91				
	mean	1.72	2.37	2.39					

CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant.

4.3.3 Soil-water retention

Soil-water content was significantly higher underneath compared to outside the canopy at all matric potentials except -10 and -1500 kPa (Table 4.4). Following regression analysis, values of soil-water content significantly increased with increasing canopy size at low suctions, i.e., 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 significantly 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 -1500 kPa (R^2-adj = 0.244, $p<0.01$). This is in accordance with Garba *et al.* (2011), who stated that organic matter can play an important role in water retention capacity of sandy soils, such as those in the Sahel.

Table 4.4 Mean and standard error of the mean (s.e.m.) of soil-water content at eight matric potentials in the 0-10 cm soil layer on microsite locations canopy and open for *Acacia raddiana* trees with small (SCD, N=7), medium (MCD, N=7) and large crown diameter (LCD, N=7)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
θ (-1 kPa) ($m^3\ m^{-3}$)	canopy	0.39	0.41	0.44	0.41	0.04	ns	<0.01	ns
	open	0.38	0.37	0.37	0.37				
	mean	0.38	0.39	0.40					
θ (-3 kPa) ($m^3\ m^{-3}$)	canopy	0.35	0.36	0.40	0.37	0.04	ns	<0.01	ns
	open	0.35	0.35	0.34	0.34				
	mean	0.35	0.36	0.37					
θ (-5 kPa) ($m^3\ m^{-3}$)	canopy	0.31	0.32	0.36	0.33	0.04	ns	<0.05	ns
	open	0.31	0.31	0.31	0.31				
	mean	0.31	0.32	0.34					
θ (-7 kPa) ($m^3\ m^{-3}$)	canopy	0.28	0.29	0.32	0.30	0.04	ns	<0.05	ns
	open	0.27	0.27	0.28	0.28				
	mean	0.28	0.28	0.30					
θ (-10 kPa) ($m^3\ m^{-3}$)	canopy	0.23	0.24	0.25	0.24	0.04	ns	ns	ns
	open	0.22	0.22	0.23	0.23				
	mean	0.23	0.23	0.24					
θ (-33 kPa) ($m^3\ m^{-3}$)	canopy	0.12	0.14	0.12	0.13	0.03	ns	<0.05	ns
	open	0.12	0.11	0.11	0.11				
	mean	0.12	0.13	0.11					
θ (-100 kPa) ($m^3\ m^{-3}$)	canopy	0.12	0.12	0.10	0.11	0.03	ns	<0.01	ns
	open	0.10	0.10	0.09	0.10				
	mean	0.11	0.11	0.09					
θ (-1500 kPa) ($m^3\ m^{-3}$)	canopy	0.07	0.07	0.06	0.07	0.02	ns	ns	ns
	open	0.06	0.06	0.06	0.06				
	mean	0.06	0.07	0.06					

θ: water content at a given matric potential; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant.

The soil-water retention parameters derived according to the van Genuchten model are listed in Table 4.5. 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 soil-water content 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.

Table 4.5 van Genuchten parameters θ_r, θ_s, α and *n* obtained by fitting to water retention data in the 0-10 cm soil layer on microsite locations canopy and open for *Acacia raddiana* trees with small (SCD, N=7), medium (MCD, N=7) and large crown diameter (LCD, N=7)

		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

θ_r: residual water content; θ_S: saturated water content; α and *n*: parameters of the van Genuchten model.

Parameters *α* and *n* showed similar values, indicating a similar shape of the water retention curve, irrespective of the canopy size or microsite (Figure 4.1).

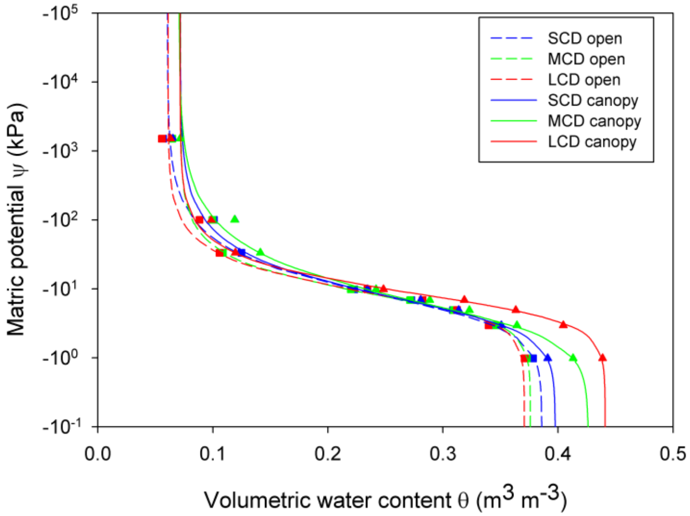

Figure 4.1 Soil-water retention curves for microsite locations canopy (solid line) and open (dashed line) with observations of mean soil-water content at eight matric potentials (canopy: triangles; open: squares) in the top 10 cm soil for *Acacia raddiana* trees with canopy sizes small (SCD) (N=7), medium (MCD) (N=7) and large crown diameter (LCD) (N=7)

4.3.4 Soil physical quality

Matrix porosity (MatPor), macroporosity (MacPor) and air capacity (AC) showed significantly higher values underneath compared to outside the canopy (Table 4.6). Furthermore, a significant interaction effect between canopy size and microsite was found for AC. No significant differences in plant-available water capacity (PAWC) and relative water capacity (RWC) were found between the three canopy size classes or between the two microsites. Values of PAWC were comparable due to similar values of soil-water content at both field capacity and permanent wilting point (Table 4.4).

The air capacity of the soils in our study area was higher than 0.10 $m^3\ m^{-3}$, which has traditionally been recommended to achieve minimum susceptibility to damaging aeration deficits in the root zone (de Witt and McQueen, 1992). The optimal balance between root-zone soil water and soil air capacity appears to be effectuated when RWC has a value between 0.6 and 0.7 (Olness *et al.*, 1998). RWC values of the soils in the study area were below 0.6 and hence sub-optimal conditions were obtained. The plant-available water capacity varies between 0.16 and 0.19 for the soils in the study area. Cockroft and Olsson (1997) suggest that a PAWC value greater than 0.20 $m^3\ m^{-3}$ is required for maximum root growth and minimum susceptibility to 'droughtiness'. For coarse-textured soils, the optimum value should be set far lower this value because they have a lower PAWC owing to the homogenous nature of their pores (Arthur *et al.*, 2011). The soil in the study area showed good conditions for root growth and a limited susceptibility to drought.

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 4.3). 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. In accordance, Greenwood and Buttle (2014) suggested that increases in saturated hydraulic conductivities of reforested soils in southern Ontario, were related to greater macroporosity. As both macropores and large matrix pores are responsible for soil-water flow under saturated and near-saturated conditions, i.e. for example during an intensive rainfall event, more infiltration into the soil profile will occur underneath the canopy compared to interspaces between trees.

Table 4.6 Mean and standard error of the mean (s.e.m.) of soil physical quality indicators in the 0-10 cm soil layer on microsite locations canopy and open for *Acacia raddiana* trees with small (SCD, N=7), medium (MCD, N=7) and large crown diameter (LCD, N=7)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
MatPor (m^3 m^{-3})	canopy	0.31	0.32	0.36	0.33	0.04	ns	<0.05	ns
	open	0.31	0.31	0.31	0.31				
	mean	0.31	0.31	0.34					
MacPor (m^3 m^{-3})	canopy	0.09	0.11	0.08	0.09	0.03	ns	<0.01	ns
	open	0.08	0.07	0.06	0.07				
	mean	0.08	0.09	0.07					
AC (m^3 m^{-3})	canopy	$0.16^{a,b}$	0.18^{b}	0.19^{b}	0.18	0.03	ns	<0.01	<0.05
	open	$0.16^{a,b}$	$0.16^{a,b}$	0.14^{a}	0.15				
	mean	0.16	0.17	0.16					
PAWC (m^3 m^{-3})	canopy	0.17	0.17	0.19	0.17	0.03	ns	ns	ns
	open	0.17	0.16	0.18	0.17				
	mean	0.17	0.16	0.18					
RWC (-)	canopy	0.59	0.57	0.56	0.57	0.07	ns	ns	ns
	open	0.57	0.58	0.63	0.59				
	mean	0.58	0.57	0.59					

MatPor: soil matrix porosity; MacPor: soil macroporosity; AC: soil air capacity; PAWC: plant-available water capacity; RWC: relative water capacity; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a row (a,b) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

Higher hydraulic conductivities and higher water retention in the below-canopy soil can positively affect the water availability for the herbaceous vegetation. Abdallah *et al.* (2008) found a significantly higher plant cover and biomass production of the below-canopy herbaceous vegetation in Bou Hedma National Park. In accordance, Noumi *et al.*

(2012) found significantly higher species densities underneath scattered *A. raddiana* trees in Bou Hedma National Park. Hence, an interplay between the hydrological and ecological processes was found when comparing these binary studies. However, to address the findings of Noumi *et al.* (2012) with regard to the higher water availability and species density at the north compared to the south side below canopy, spatial patterns in soil hydraulic properties need to be considered.

4.4 Conclusions

Compared to open areas between trees, below-canopy soils have a higher organic matter content causing a lower bulk density and a higher total porosity. The improved soil structure below canopy resulted in higher saturated and unsaturated hydraulic conductivities and their rates increased with increasing tree age. This could be related to the ratio of water content at field capacity to saturation, confirming 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. This is in accordance with recent ecological studies, showing higher species density and biomass production of the herbaceous layer below canopy. However, to understand the impact of scattered *A. raddiana* trees on the soil hydraulic properties on a field scale and their interaction with the herbaceous vegetation, spatial patterns in those properties need to be considered.

Chapter 5. Spatial gradients in near-surface soil physical and hydraulic properties as affected by Acacia trees in arid Tunisia[2]

5.1 Introduction

Ecosystems with scattered trees occur throughout the world. In arid and semiarid regions, trees and shrubs become increasingly abundant (cf. woody encroachment, see section 2.3) through changes in land use and environmental conditions (Van Auken, 2009; Goodale and Davidson, 2002). Scattered trees often function as 'nurse plants' in that they facilitate the recruitment of other plants (San José *et al.*, 1991; Facelli and Brock, 2000).

Positive effects of scattered trees are particularly pronounced in harsh environments, such as arid and semiarid environments, where water availability in the soil is the most critical factor controlling productivity and reproduction of vegetation (Noy-Meir, 1973; Rodriguez-Iturbe, 2000). Facilitation may occur through a more favourable microclimate (Moro *et al.*, 1997; Breshears *et al.*, 1998), improved nutrient availability (Belsky, 1994; Ludwig *et al.*, 2004) and enhanced infiltration of rainwater.

Many studies investigated the effect of vegetation on infiltration properties (see Chapter 4). In the arid regions north and south of the Saharan desert, *Acacia raddiana* is considered being a keystone species for its tolerance to extreme droughts and persistence on the edge of the desert (Le Floc'h and Grouzis, 2003). In Chapter 4 the impact of scattered *A. raddiana* trees from three canopy size classes was investigated on the near-surface soil physical and soil hydraulic properties both underneath and outside the canopy. It was concluded that the improved soil structure below-canopy resulted in higher saturated and unsaturated hydraulic conductivities and the rates increased with increasing canopy size.

In Chapter 4, an interplay between the hydrological and ecological processes was found when comparing our binary study on soil hydraulic properties with the ecological studies of Abdallah *et al.* (2008) and Noumi *et al.* (2012). However, to understand the impact of scattered *A. raddiana* trees on the herbaceous layer at field scale, spatial patterns in soil physical and hydraulic properties need to be investigated, accounting for the effect of distance from the stem and the effect of compass direction. Regarding the influence of compass direction, Noumi *et al.* (2012) found a higher water content at the northern side underneath the canopy of *A. raddiana* trees compared with the southern side for a short period after a rainfall event. Improved water availability at the northern side was related to a more favourable microclimate, i.e. reduced air and soil temperature, resulting in higher species density and richness. As a consequence, a higher input of organic matter

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[2] Part of this chapter is under revision for *Ecohydrology* and was submitted as De Boever M, Gabriels D, Ouessar M, Cornelis W. 2014. Spatial gradients in near-surface hydrophysical properties as affected by Acacia trees in arid Tunisia.

from the herbaceous layer is expected at the northern side affecting soil physical quality and hydraulic conductivity.

Therefore, we quantify in this chapter the influence of scattered *A. raddiana* trees of three canopy sizes on physical and hydraulic properties of the top 10 cm soil along gradients from underneath to outside the canopy in the four compass directions on a study site in arid Tunisia. We hypothesized that (i) scattered *A. raddiana* trees improve soil hydraulic properties not only underneath but also outside their canopy and these effects (ii) will be more pronounced in the longer term, i.e. with increasing tree age and (iii) will depend on the compass direction.

5.2 Materials and methods

5.2.1 Study site

A description of the study site is given in section 3.8.

5.2.2 Experimental design

A total of 15 *A. raddiana* trees was randomly selected (different from the trees in Chapter 4) in the plain of IPZ1. To characterise the *A. raddiana* population present in the park, three crown diameter classes based on the crown diameter distribution of Bou Hedma National Park (Figure 3.9) were distinguished each containing five 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, i.e. the below-canopy microsite. In addition, the crown diameter is used as a proxy for tree age. For each canopy size class, crown diameter, basal trunk diameter (basal trunk circumference/π) and tree age are listed in Table 5.1.

Table 5.1 Mean ± SD of *Acacia raddiana* tree attributes with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

	Canopy size		
	SCD	MCD	LCD
Crown diameter (m)	3.8 ± 0.5	5.6 ± 0.4	8.6 ± 1.0
Basal trunk diameter (cm)	19.6 ± 2.9	29.3 ± 4.6	37.7 ± 7.6
Tree age[a] (yrs)	64 ± 7	88 ± 11	109 ± 19

[a] Calculation of *Acacia raddiana* tree age based on basal trunk diameter following Noumi and Chaieb (2012).

For those 15 trees, five microsites were distinguished for the top 10 cm soil: M1, M2, M3 and M4 respectively at 25%, 75%, 125% and 175% of the canopy radius (in which 100% is the distance from the tree stem to the canopy edge) in the four compass directions (i.e. north, east, south and west) and M5 (interspace) at least 10 m away from the canopy.

5.2.3 Soil analysis

Soil texture on air-dried fine earth (<2 mm) samples of the top 10 cm soil was determined with the pipette method (Gee and Or, 2002), and classified according to the USDA textural triangle (Soil Survey Staff, 1999). $CaCO_3$ was not removed in the pre-treatment process as it originates from the parent material and forms as such a substantial part of the soil texture. Organic matter (OM) was determined according to Walkley and Black (1934). The soil bulk density (BD) was determined following the procedure of Grossman and Reinsch (2002). The total porosity (TP) is calculated using equation 1 in Chapter 4.

Infiltration measurements were performed at the soil surface for each tree at microsites M1 to M4 in the four compass directions and at microsite M5. A tension disk infiltrometer (Soil Measurement Systems, Tucson AZ, USA) with the infiltration disk (20 cm in diameter) separated from the water reservoir was used following the procedure as described in chapter 4.2.2. The saturated Ks and unsaturated $K(\psi)$ hydraulic conductivities were obtained from tension infiltrometer measurements based on the equation of Wooding (1968) in combination with the steady-state approach of Logsdon and Jaynes (1993).

5.2.4 Data analysis

To evaluate and compare both saturated and unsaturated hydraulic conductivities as influenced by crossed factors compass direction, canopy size, microsite and factor tree nested in canopy size, a four-way ANOVA was performed. In case of a significant main effect of compass direction, canopy size or microsite, Tukey's Honest Significant Difference post-hoc test was executed between all levels of that factor.

Statistical analyses on the hydraulic conductivities were performed on lognormally transformed values. Geometric mean values (G) and standard deviation (SD) were calculated using the uniformly minimum variance estimator method developed by Finney (1941).

To evaluate and to compare the soil physical properties as influenced by crossed factors canopy size and microsite and factor tree nested in canopy size, a three-way ANOVA was performed. In case of a significant main effect of canopy size or microsite, Tukey's Honest Significant Difference post-hoc test was executed between all levels of that factor. Prior to statistical analysis, the organic matter contents were lognormally transformed to achieve normality.

Trend analysis using linear regression was performed on all parameters to study the effect of distance from the stem and canopy size. The standard error of the mean (s.e.m.) was calculated across all canopy sizes and microsites for all parameters except saturated hydraulic conductivity. For the latter, s.e.m. was calculated across compass directions and microsites for each canopy size separately. In order to evaluate associations between parameters, the Pearson correlation coefficient and corresponding level of significance was calculated.

5.3 Results

5.3.1 Soil texture

There were no significant differences in sand, silt and clay fractions between the soils of the three canopy size classes and between the microsites M1 and M5 in the northern direction (Table 5.2). The textural classes were varying between loamy sand, sandy loam and loam (Soil Survey Staff, 1999).

Table 5.2 Mean and standard error of the mean (s.e.m.) of sand, silt and clay fractions in the top 10 cm soil on microsites canopy (M1) and interspace (M5) in the northern direction for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
Sand	M1	61.0	61.1	57.6	59.9	1.9	ns	ns	ns
(2000-50 μm) (%)	M5	57.4	59.5	59.3	58.7				
	mean	59.2	60.3	58.5					
Silt	M1	29.0	28.6	31.2	29.6	1.5	ns	ns	ns
(50-2 μm) (%)	M5	32.9	30.2	32.0	31.7				
	mean	31.0	29.4	31.6					
Clay	M1	10.0	10.3	11.2	10.5	0.5	ns	ns	ns
(<2 μm) (%)	M5	9.6	10.2	8.7	9.5				
	mean	9.8	10.3	10.0					

M1: microsite at 25% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant.

5.3.2 Soil physical properties

As no interaction occurred between factors microsite and canopy size, averages across the three canopy sizes and averages across the five microsites were considered when looking respectively at the effect of microsite and canopy size on the soil physical properties. The distance from the tree stem affected the soil physical properties of the top 10 cm soil (Table 5.3).

Microsite M1 (closest to the tree stem) showed greatest differences among microsites, containing significantly more organic matter (OM), and showing higher total porosity (TP) and lower bulk density (BD). OM showed a significant negative and positive correlation with BD (R^2-adj = 0.415, p<0.001) and TP (R^2-adj = 0.379, p<0.001) respectively.

Table 5.3 Mean and standard error of the mean (s.e.m.) of soil physical properties for the top 10 cm soil along a gradient from underneath to outside the canopy in the northern direction for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=4) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
OM (%)	M1	1.7	2.2	3.4	2.4^{a}	0.1	ns	<0.01	ns
	M2	1.0	1.7	1.7	1.5^{b}				
	M3	0.9	1.3	0.9	$1.0^{b,c}$				
	M4	0.9	1.0	1.3	1.0^{c}				
	M5	0.9	1.1	1.1	$1.0^{b,c}$				
	mean	1.1	1.5	1.7					
BD (Mg m^{-3})	M1	1.36	1.29	1.29	1.31^{a}	0.02	ns	<0.01	ns
	M2	1.43	1.36	1.40	$1.40^{a,b}$				
	M3	1.47	1.43	1.42	1.44^{b}				
	M4	1.48	1.46	1.33	1.43^{b}				
	M5	1.47	1.34	1.42	1.41^{b}				
	mean	1.44	1.38	1.37					
TP (m^3 m^{-3})	M1	0.48	0.51	0.50	0.50^{a}	0.01	ns	<0.01	ns
	M2	0.46	0.48	0.47	$0.47^{a,b}$				
	M3	0.44	0.46	0.46	0.45^{b}				
	M4	0.44	0.44	0.50	0.46^{b}				
	M5	0.44	0.49	0.46	0.46^{b}				
	mean	0.45	0.48	0.48					

OM: organic matter; BD: bulk density; TP: total porosity. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a column (a,b,c) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

There were some clear trends in soil physical properties along gradient from canopy to interspace. A significant decrease in OM (R^2-adj = 0.256, $p<0.001$) and TP (R^2-adj = 0.041, $p<0.05$), and a significant increase in BD (R^2-adj = 0.050, $p<0.05$) was found with increasing distance from the stem. Both MCD and LCD showed numerically higher values for OM and TP and a lower value for BD than SCD. The OM content significantly increased with increasing canopy size (R^2-adj = 0.052, $p<0.05$).

5.3.3 Soil-water retention

The distance from the tree stem significantly affected soil-water content at two matric potentials for the top 10 cm soil at low suctions (at -1 and -3 kPa), while no effect was found on soil-water content at the other matric potentials (Table 5.4). Microsite M1 (closest to the tree stem) showed greatest differences among microsites, with significantly higher values for the soil-water content at the aforementioned matric potentials at low suctions. With increasing distance from the stem, water content decreased significantly at matric potentials -1 kPa (R^2-adj = 0.064, $p<0.05$) and -3 kPa (R^2-adj = 0.062, $p<0.05$). Canopy size did not affect water content at all matric potentials.

Table 5.4 Mean and standard error of the mean (s.e.m.) soil-water content at eight matric potentials in the top 10 cm soil along a gradient from underneath to outside the canopy in the northern direction for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=4) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
θ (-1 kPa) (m^{3} m^{-3})	M1	0.43	0.46	0.46	0.45^{a}	0.004	ns	<0.01	ns
	M2	0.43	0.40	0.44	$0.43^{a,b}$				
	M3	0.40	0.43	0.42	$0.42^{a,b}$				
	M4	0.39	0.41	0.41	0.40^{b}				
	M5	0.42	0.42	0.43	$0.42^{a,b}$				
	mean	0.41	0.43	0.43					
θ (-3 kPa) (m^{3} m^{-3})	M1	0.39	0.42	0.42	0.41^{a}	0.004	ns	<0.05	ns
	M2	0.39	0.37	0.41	$0.39^{a,b}$				
	M3	0.36	0.39	0.39	$0.38^{a,b}$				
	M4	0.36	0.38	0.37	0.37^{b}				
	M5	0.38	0.38	0.39	$0.39^{a,b}$				
	mean	0.38	0.39	0.40					
θ (-5 kPa) (m^{3} m^{-3})	M1	0.35	0.38	0.38	0.37	0.005	ns	ns	ns
	M2	0.36	0.34	0.38	0.36				
	M3	0.32	0.36	0.36	0.35				
	M4	0.32	0.35	0.34	0.34				
	M5	0.35	0.35	0.36	0.36				
	mean	0.34	0.36	0.36					
θ (-7 kPa) (m^{3} m^{-3})	M1	0.32	0.35	0.34	0.33	0.005	ns	ns	ns
	M2	0.32	0.31	0.34	0.33				
	M3	0.29	0.33	0.33	0.32				
	M4	0.28	0.32	0.32	0.31				
	M5	0.32	0.32	0.33	0.33				
	mean	0.31	0.33	0.33					
θ (-10 kPa) (m^{3} m^{-3})	M1	0.27	0.29	0.28	0.28	0.005	ns	ns	ns
	M2	0.28	0.27	0.30	0.28				
	M3	0.24	0.29	0.28	0.27				
	M4	0.24	0.28	0.27	0.26				
	M5	0.28	0.28	0.30	0.28				
	mean	0.26	0.28	0.29					
θ (-33 kPa) (m^{3} m^{-3})	M1	0.16	0.15	0.16	0.16	0.004	ns	ns	ns
	M2	0.15	0.14	0.16	0.15				
	M3	0.13	0.17	0.13	0.14				
	M4	0.12	0.15	0.16	0.14				
	M5	0.12	0.15	0.16	0.14				
	mean	0.14	0.15	0.15					
θ (-100 kPa) (m^{3} m^{-3})	M1	0.12	0.12	0.13	0.13	0.004	ns	ns	ns
	M2	0.12	0.11	0.12	0.12				
	M3	0.11	0.13	0.11	0.11				
	M4	0.12	0.12	0.13	0.12				
	M5	0.11	0.11	0.13	0.12				
	mean	0.11	0.12	0.12					

θ: water content at a given matric potential. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a column (a,b) are significantly different (p<0.05) following Tukey's Honest Significant Difference test.

Table 5.4 (continued)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
θ (-1500 kPa) (m^3 m^{-3})	M1	0.07	0.08	0.07	0.07	0.002	ns	ns	ns
	M2	0.07	0.08	0.08	0.08				
	M3	0.06	0.08	0.07	0.07				
	M4	0.07	0.07	0.06	0.07				
	M5	0.06	0.07	0.07	0.07				
	mean	0.07	0.08	0.07					

θ: water content at a given matric potential. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant.

The soil-water retention parameters derived according to the van Genuchten model are listed in Table 5.5. Neither canopy size nor microsite affected the residual water content (θ_r) and the parameters α and n. As the latter two parameters showed similar values, the shape of the water retention curves was also similar irrespective of the canopy size or microsite (Figure 5.1).

Table 5.5 Mean and standard error of the mean (s.e.m.) of the van Genuchten parameters in the top 10 cm soil along a gradient from underneath to outside the canopy in the northern direction for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=4) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
θ_r (m^3 m^{-3})	M1	0.07	0.08	0.08	0.07	0.002	ns	ns	ns
	M2	0.06	0.08	0.08	0.07				
	M3	0.05	0.06	0.07	0.06				
	M4	0.07	0.07	0.07	0.07				
	M5	0.07	0.07	0.07	0.07				
	mean	0.06	0.07	0.07					
θ_S (m^3 m^{-3})	M1	0.44	0.46	0.47	0.46^{a}	0.004	ns	<0.01	ns
	M2	0.44	0.41	0.44	$0.43^{a,b}$				
	M3	0.41	0.44	0.42	0.42^{b}				
	M4	0.40	0.41	0.41	0.41^{b}				
	M5	0.42	0.42	0.43	$0.43^{a,b}$				
	mean	0.42	0.43	0.44					
α (kPa^{-1})	M1	2.01	1.64	2.01	1.89	0.10	ns	ns	ns
	M2	2.67	1.71	1.47	1.95				
	M3	2.15	2.04	1.32	1.83				
	M4	1.73	1.48	1.72	1.64				
	M5	1.57	1.64	1.70	1.64				
	mean	2.03	1.71	1.64					
n (-)	M1	1.82	1.95	1.84	1.87	0.05	ns	ns	ns
	M2	1.91	2.18	1.96	2.02				
	M3	1.82	1.70	2.24	1.92				
	M4	2.00	1.96	1.90	1.95				
	M5	2.16	1.91	1.82	1.97				
	mean	1.94	1.94	1.95					

θ_r: residual water content; θ_S: saturated water content; α and n: parameters of the van Genuchten model. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a column (a,b) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

The distance from the tree stem significantly affected the soil water content at saturation (θ_S) in the top 10 cm soil, whereas no effect of canopy size was found. Microsite M1 (closest to the tree stem) showed greatest differences among microsites, with a significantly higher value compared with the other microsites except with microsite M2. Water content at saturation significantly decreased with increasing distance from the stem (R^2-adj = 0.097, p<0.01).

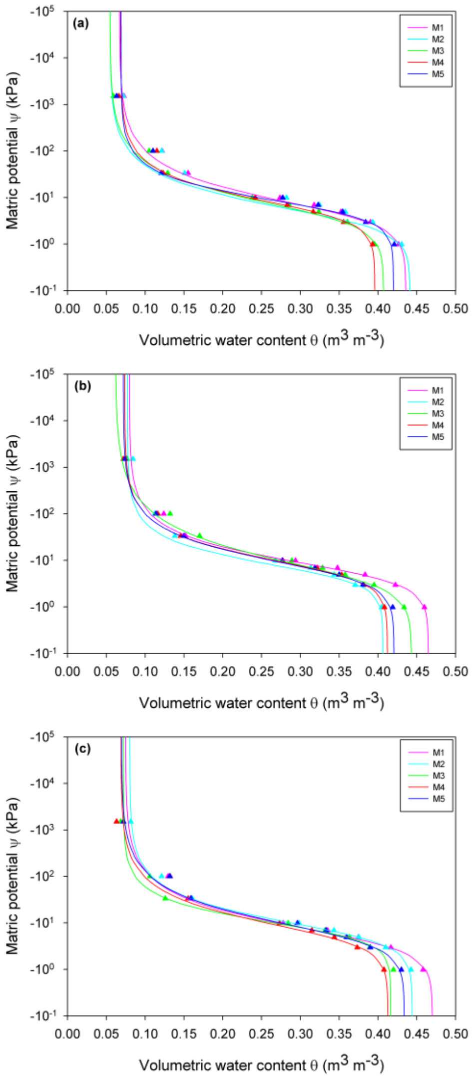

Figure 5.1 Soil-water retention curves for microsite locations M1, M2, M3, M4 and M5 with observations of mean soil-water content at eight matric potentials in the top 10 cm soil in the northern direction for *Acacia raddiana* trees with canopy sizes (a) small (N=5), (b) medium (N=4) and (c) large crown diameter (N=5)

5.3.4 Soil physical quality

No significant effect of canopy size or microsite was found for all parameters except for soil air capacity (AC), which was higher at microsite M1 than at microsites M4 and M5 (Table 5.6). Microsite M1 showed greatest numerical differences among microsites, with higher values for matrix porosity (MatPor) and macroporosity (MacPor) and a lower value for relative water capacity (RWC). Values of plant-available water capacity (PAWC) were comparable between canopy sizes or microsites due to similar values of soil-water content at both field capacity (-10 kPa) and permanent wilting point (-1500 kPa) (Table 5.4). Although not significant, MatPor and AC markedly increased with decreasing distance from the tree stem and MatPor also showed an increase with increasing canopy size.

Table 5.6 Mean and standard error of the mean (s.e.m.) of soil physical quality indicators in the top 10 cm soil along a gradient from underneath to outside the canopy in the northern direction for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=4) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
MatPor ($m^3 m^{-3}$)	M1	0.35	0.38	0.37	0.37	0.005	ns	ns	ns
	M2	0.36	0.34	0.38	0.36				
	M3	0.32	0.36	0.37	0.35				
	M4	0.32	0.35	0.34	0.34				
	M5	0.36	0.35	0.36	0.36				
	mean	0.34	0.36	0.36					
MacPor ($m^3 m^{-3}$)	M1	0.08	0.08	0.10	0.09	0.003	ns	ns	ns
	M2	0.08	0.06	0.07	0.07				
	M3	0.09	0.08	0.05	0.07				
	M4	0.08	0.06	0.07	0.07				
	M5	0.06	0.07	0.07	0.07				
	mean	0.08	0.07	0.07					
AC ($m^3 m^{-3}$)	M1	0.16	0.17	0.19	0.18^{a}	0.004	ns	<0.05	ns
	M2	0.16	0.14	0.15	$0.15^{a,b}$				
	M3	0.17	0.15	0.13	$0.15^{a,b}$				
	M4	0.15	0.13	0.14	0.14^{b}				
	M5	0.14	0.14	0.14	0.14^{b}				
	mean	0.16	0.15	0.15					
PAWC ($m^3 m^{-3}$)	M1	0.20	0.22	0.21	0.21	0.005	ns	ns	ns
	M2	0.21	0.18	0.22	0.20				
	M3	0.18	0.21	0.22	0.20				
	M4	0.18	0.21	0.21	0.20				
	M5	0.21	0.20	0.22	0.21				
	mean	0.20	0.20	0.21					
RWC (-)	M1	0.63	0.63	0.59	0.62	0.01	ns	ns	ns
	M2	0.63	0.66	0.67	0.66				
	M3	0.58	0.65	0.68	0.64				
	M4	0.60	0.67	0.66	0.65				
	M5	0.65	0.66	0.69	0.67				
	mean	0.62	0.66	0.66					

MatPor: soil matrix porosity; MacPor: soil macroporosity; AC: soil air capacity; PAWC: plant-available water capacity; RWC: relative water capacity. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a column (a,b) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

5.3.5 Soil hydraulic conductivity

The geometric mean values of saturated hydraulic conductivity ($K_{S,G}$) showed a significant interaction between canopy size and compass direction (Table 5.7). Therefore, the effect of compass direction and microsite was evaluated for the three canopy sizes separately.

No differences between the four compass directions were found for canopy sizes SCD and LCD, whereas for MCD significantly higher values were found for the western and southern direction compared with the eastern direction. The distance from the tree stem affected the saturated hydraulic conductivities. Microsite M1 (closest to the tree stem) showed greatest differences among microsites, having significantly higher hydraulic conductivities compared with microsite M4 (for SCD), microsites M3 and M4 (for LCD), and microsites M2, M3 and M4 (for MCD). $K_{S,G}$ significantly decreased with increasing distance from the stem for SCD (R^2-adj = 0.038, $p<0.05$), MCD (R^2-adj = 0.078, $p<0.01$) and LCD (R^2-adj = 0.123, $p<0.01$). No significant increasing trend for $K_{S,G}$-values with larger canopy size was found.

Table 5.7 Geometric mean and standard error of the mean (s.e.m.) of the saturated hydraulic conductivities ($K_{S,G}$ x 10^{-6} m s^{-1}) at the soil surface for the four compass directions along a gradient from underneath to outside the canopy for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		north	east	south	west	mean	s.e.m.	CD	M	CD*M
SCD	M1	4.04	4.83	6.23	3.98	4.74^{a}	0.38	ns	<0.05	ns
	M2	2.94	3.72	4.77	6.42	$4.40^{a,b}$				
	M3	2.61	5.73	4.64	6.47	$4.82^{a,b}$				
	M4	2.51	4.59	2.59	3.31	3.22^{b}				
	mean	3.05	4.76	4.61	4.94					
MCD	M1	8.85	5.16	11.3	16.7	10.2^{a}	0.70	<0.01	<0.01	ns
	M2	4.93	3.59	7.40	6.61	5.64^{b}				
	M3	3.44	3.86	5.78	6.64	4.93^{b}				
	M4	3.36	3.65	4.15	4.54	3.95^{b}				
	mean	$5.03^{A,B}$	4.14^{A}	7.01^{B}	8.32^{B}					
LCD	M1	6.66	7.82	6.14	6.04	6.72^{a}	0.47	ns	<0.01	ns
	M2	3.81	5.84	5.58	3.64	$4.75^{a,b}$				
	M3	3.23	5.30	6.48	3.29	4.53^{b}				
	M4	3.46	3.39	4.39	3.55	3.79^{b}				
	mean	4.36	5.67	5.99	4.18					

M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius; CD: compass direction; M: microsite. CD, M, CD*M: level of significance of the effect of compass direction, microsite and compass direction x microsite respectively; ns: not significant. Means bearing different superscripts within a row (A,B) or column (a,b) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

For the geometric mean values of unsaturated hydraulic conductivities ($K_{\psi,G}$) no effect of compass direction or interaction with other factors was found. Therefore, $K_{\psi,G}$-values were averaged across the four compass directions when investigating the effect of canopy size or microsite. The distance from the tree stem affected the unsaturated hydraulic conductivities (Table 5.8). Microsite M1 (closest to the tree stem) showed greatest differences among microsites, having significantly higher values at the matric potentials -0.29, -0.59 and -1.18 kPa.

The unsaturated hydraulic conductivities significantly decreased with increasing distance from the stem: at -0.29 kPa (R^2-adj = 0.068, $p<0.001$), at -0.59 kPa (R^2-adj = 0.061, $p<0.001$) and at -1.18 kPa (R^2-adj = 0.041, $p<0.01$). In addition, canopy size MCD showed numerically higher values than SCD for all three matric potentials. However, there was no significant increasing trend with larger canopy size for all unsaturated hydraulic conductivities.

Between TP and the hydraulic conductivities a positive correlation was found at saturation (R^2-adj = 0.030, $0.05<p<0.1$), as well as for the unsaturated hydraulic conductivities at -0.29 kPa (R^2-adj = 0.039, $0.05<p<0.1$), -0.59 kPa (R^2-adj = 0.049, $p<0.05$) and -1.18 kPa (R^2-adj = 0.070, $p<0.05$).

Table 5.8 Geometric mean and standard error of the mean (s.e.m.) of the unsaturated hydraulic conductivities ($K_{\psi,G}$ x 10^{-6} m s^{-1}) averaged across the four compass directions at the soil surface going from underneath to outside the canopy for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
$K_{\psi,G}$ (-0.29 kPa)	M1	3.64	7.00	5.25	5.19^{a}	0.20	ns	<0.01	ns
	M2	3.55	4.31	3.77	3.89^{b}				
	M3	3.69	3.80	3.59	3.70^{b}				
	M4	2.60	3.20	3.01	2.94^{b}				
	M5	4.01	3.26	2.98	3.43^{b}				
	Mean	3.42	4.45	3.91					
$K_{\psi,G}$ (-0.59 kPa)	M1	2.81	4.90	4.11	3.89^{a}	0.15	ns	<0.01	ns
	M2	2.87	3.31	3.00	3.07^{b}				
	M3	2.84	2.94	2.86	2.89^{b}				
	M4	2.10	2.60	2.40	2.37^{b}				
	M5	3.18	2.75	2.50	2.82^{b}				
	Mean	2.69	3.38	3.10					
$K_{\psi,G}$ (-1.18 kPa)	M1	1.71	2.53	2.54	2.25^{a}	0.08	ns	<0.01	ns
	M2	1.88	1.99	1.93	$1.94^{a,b}$				
	M3	1.72	1.80	1.84	1.79^{b}				
	M4	1.39	1.74	1.54	1.56^{b}				
	M5	2.02	1.96	1.76	$1.92^{a,b}$				
	Mean	1.69	2.02	1.97					

M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a column (a,b) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

5.3.6 Effect of organic matter on soil hydraulic properties

An increased OM content resulted in significantly higher water retention values at low suctions -1 kPa (R^2-adj = 0.166, $p<0.001$), -3 kPa (R^2-adj = 0.138, $p<0.01$), -5 kPa (R^2-adj = 0.078, $p<0.01$), -7 kPa (R^2-adj = 0.056, $p<0.05$) and -10 kPa (R^2-adj = 0.041, $p<0.05$) and at high suctions -33 kPa (R^2-adj = 0.104, $p<0.01$), -330 kPa (R^2-adj = 0.083, $p<0.01$) and -1500 kPa (R^2-adj = 0.102, $p<0.01$).

A higher OM content also leads to significantly higher values of both residual (R^2-adj = 0.077, $p<0.01$) and saturated (R^2-adj = 0.224, $p<0.001$) water content. The OM content was significantly and positively related with MatPor (R^2-adj = 0.064, $p<0.05$), MacPor (R^2-adj = 0.042, $p<0.05$) and AC (R^2-adj = 0.042, $p<0.05$).

5.4 Discussion

Irrespective of canopy size the top 10 cm soil closest to the tree stem contained most OM which significantly decreased with longer distance from the stem. Numerous studies have reported higher OM in the topsoil under trees than in open areas (e.g., Belsky *et al.*, 1993; Eldridge and Wong, 2005). The higher below-canopy OM content can be related to the larger tree litter inputs from roots and leafs, and improved cycling of OM through greater soil faunal (Dunn, 2000) and soil microbial activity (Gutiérrez and Jones, 2006).

McElhinny *et al.* (2010) reported a heterogeneous spatial arrangement of litter under tree crowns for scattered tree ecosystems, following a declining gradient with distance from the stem as was found in our study. These patterns are also in accordance with the architecture of tree crowns in which the depth of crown contributing to litter fall is at a maximum directly above the main stem. Litter inputs below canopy may also originate from the decomposition of the herbaceous layer as was found by Morris *et al.* (1982).

For *A. raddiana* trees with canopy sizes MCD and LCD higher levels of OM were found up to 175% of the canopy radius. Barnes *et al.* (2011) found a substantial quantity of tree litter outside the canopy edge up to 2.5 times the canopy radius. Not only tree litter but also herbaceous litter might explain these elevated OM levels as scattered trees can facilitate the growth of the herbaceous layer outside their canopy (e.g., Warnock *et al.*, 2007).

Furthermore, the OM content significantly increased with increasing crown diameter (see section 4.3.1). Tree crowns are hereby considered as simple hemispherical shapes with crown volume proportional to crown diameter. McElhinny *et al.* (2010) found that large trees (comparable to LCD in our study) produced substantially higher loads of litter fall than small trees (SCD in our study). Therefore, greater inputs of litter are generated with increasing canopy size resulting in elevated levels of OM.

Increasing trends in OM content closer to the tree stem and with increasing crown diameter were only partly reflected in decreasing bulk density or increasing total porosity values. Across the three canopy sizes, lower bulk density (and higher total porosity) values were restricted to the microsite closest to the tree stem. However, lower values of bulk density (and higher total porosity) were also found outside the canopy for MCD and LCD as compared to SCD.

According to the classification of soil quality in section 4.3.4, the soils in the study area showed good aeration (AC>0.10 $m^3\ m^{-3}$), a good ration between root-zone soil water and soil air capacity ($0.6 \leq RWC \leq 0.7$), good conditions for root growth and a limited susceptibility to 'droughtiness' (PAWC values between 0.18 and 0.22).

Irrespective of canopy size a significant decrease in soil-water content at saturation and at low suctions (-1 and -3 kPa) was observed with increasing distance from the stem. No effect of canopy size on the soil-water content was found for all pressure heads from -1 to -1500 kPa. A significant positive correlation between OM content and the soil-water content at saturation and all negative pressure heads was found.

In accordance, Facelli and Brock (2000) found that changes in water retention curves under canopies of *Acacia papyrocarpa* are most likely related to the increased organic matter content in the soil. These changes are important because they are likely to affect water availability for plants at most ranges of soil-water contents. Mapa (1995) studied the effect of reforestation using *Tectona grandis* on soil hydraulic properties and found that the increase in water retention in the wet and dry range was attributed to respectively soil structure development and the hydrophilic nature of organic matter. Hence, organic matter can play an important role in water retention capacity of sandy soils, such as those in the Sahel as stated by Garba *et al.* (2011).

An increasing but not significant trend in air capacity and matrix porosity was observed closer to the tree stem, and for the latter this trend was also present with increasing canopy size. This can be attributed to their positive correlation with the OM content. The soil below canopy typically has improved physical structure and stability, and greater porosity than the surrounding soil matrix (Greene, 1992; Dunkerley, 2000). No significant effect of *A. raddiana* was found on the soil physical quality indicators outside the canopy.

The saturated hydraulic conductivities at our study site were within the range of sandy to loamy soils (Carsel and Parrish, 1988). Significant differences between the four compass directions only occurred for canopy size MCD, with highest values in south and west. However, higher hydraulic conductivities were expected at the north side, where higher abundance of understory vegetation (cf. Noumi *et al.*, 2012) might result in a better soil structure through plant roots and OM input. Because these differences were not observed for canopy sizes SCD and LCD, they may result from site-specific variations and not from variations caused by scattered trees. In addition, determination of saturated hydraulic conductivities can result in very high variability due to soil heterogeneity and other aspects such as the measurement method, the number of replications and the calculation method used (e.g., Verbist *et al.*, 2012; Reynolds *et al.*, 2000). For the unsaturated hydraulic conductivities, no significant differences between the four compass directions were observed. Hence, no influence of the herbaceous layer on the soil physical and hydraulic properties was present.

Saturated and unsaturated hydraulic conductivities gradually decreased with longer distance from the stem with highest values closest to the tree stem. For all three canopy sizes, higher values of saturated hydraulic conductivities were not only found underneath but also outside the canopy. For canopy sizes MCD and LCD, higher values of unsaturated hydraulic conductivities were found outside the canopy up to 125% of the canopy radius. These trends are in accordance with the improved soil physical properties occurring both underneath and outside the canopy of scattered *A. raddiana* trees. There was no significant trend in increasing saturated and unsaturated hydraulic conductivities with increasing canopy size.

Bedford and Small (2008) demonstrated that enhanced infiltrability can extend well beyond the edge of plant canopies for shrublands in central New Mexico, USA. The boundary distinguishing altered soils from their surroundings is therefore not sharp but rather a broad transitional zone of influence is existing. Caldwell *et al.* (2008) for example, found for *Larrea tridentata* (creosotebush) and *Lycium pallidum* (desert thorn) in the Mojave desert that spatial correlations to hydraulic conductivities (both saturated and unsaturated) were observed to approximately 1.4 times the canopy diameter, beyond which random processes dominated.

The greater volumetric moisture contents closer to the tree stem in the matric potential range 0 to -3 kPa suggest that macropores are mainly responsible for water flow under saturated and near-saturated conditions. This is in accordance with our findings in Chapter 4. When comparing saturated and unsaturated hydraulic conductivities, the importance of large (with pore diameter > 1 mm) and smaller (with pore diameter between 0.25 and 1 mm) macropores was shown. Furthermore, no significant correlations between hydraulic conductivities and soil physical quality parameters except total porosity were found. In accordance with trends in TP, larger amounts of water are conducted in the soil at microsites closer to the stem.

5.5 Conclusions

We documented here for a forest steppe in arid Tunisia, the effect of *A. raddiana* trees on the near-surface physical and hydraulic properties underneath and outside their canopy. Along gradients from underneath to outside the canopy, greatest differences in soil physical properties were mainly found between the microsite closest to the tree stem and the other microsites irrespective of tree age. Enhanced soil physical properties may be mainly due to elevated OM levels, as reflected in strong correlations with total porosity and bulk density. With increasing distance from the tree stem, significant changes in OM, total porosity and bulk density were found.

Saturated and unsaturated hydraulic conductivities were highest closest to the tree stem and significantly decreased with longer distance from the stem. This could be related to the decreasing values in saturated and near-saturated soil-water content, confirming hydraulic conductivities are mainly driven by macropores. The effect of compass direction was not consistent across canopy sizes for the saturated hydraulic conductivities and absent for the unsaturated hydraulic conductivities. Even though a higher density of herbaceous vegetation was observed at the northern side underneath the canopy, this was not reflected in the near-surface hydraulic properties.

Although enhanced soil physical and hydraulic properties were found up to 175% and 125% of the canopy radius respectively, especially for the trees older than 75 years with a medium or large crown diameter, the differences were not significant outside the canopy.

There was no significant increasing trend in soil physical or hydraulic properties with increasing tree age except for OM. By improving the near-surface soil hydraulic properties and soil-water retention, *A. raddiana* trees can positively affect the water availability below canopy which is of crucial importance for the productivity and reproduction of the herbaceous vegetation in water-limited environments.

A spatial structure in soil physical and hydraulic properties exists between canopy and open microsites. Hence, developing hydrological models to look at the impact of scattered *A. raddiana* trees on the soil-water balance on a field scale could exploit this spatial structure.

Chapter 6. Influence of scattered Acacia trees on soil nutrient levels in arid Tunisia[3]

6.1 Introduction

Scattered trees in savanna ecosystems may suppress growth of below-canopy vegetation cover through direct competition for water, light, and nutrients resulting from overlapping root profiles and canopy shading (Scholes and Archer, 1997; Ludwig *et al.*, 2004). Conversely, they may facilitate growth of the herbaceous layer by improving the biophysical and biogeochemical conditions. Such facilitation may occur through improved soil hydraulic properties (see Chapter 4 and Chapter 5), a more favourable microclimate (Moro *et al.*, 1997; Breshears *et al.*, 1998) and nutrient availability.

Dohn *et al.* (2013) reported a shift from net competitive to net facilitative effects of trees on herbaceous productivity in transition between mesic and arid savannas in sub-Saharan Africa, consistent with the stress-gradient hypothesis (SGH). The SGH postulates that beneficial environmental modification by neighbouring organisms outweighs competition for resources under conditions of high environmental stress, such as high disturbance frequency or low resource availability (Bertness and Callaway, 1994; Brooker and Callaghan, 1998).

Nutrient levels under scattered trees are typically enhanced by litter accumulation (Barnes *et al.*, 2011) and decomposition from microbial activity (Fterich *et al.*, 2012), nutrient inputs from animal dung (Dean *et al.*, 1999; Allington and Valone, 2014), mining of nutrients by tree roots (Belsky, 1994; Wilson *et al.*, 2007) and the interception of nutrients by trees from aeolian processes (Li *et al.*, 2008), and from hydrologic processes such as surface runoff (Parsons *et al.*, 1992; Schlesinger *et al.*, 1999) and rainfall through stemflow (Whitford *et al.*, 1997; Dunkerley, 2013).

Local increase of nutrients by scattered trees was demonstrated in paddocks of south-eastern Australia (Wilson, 2002), the Brazilian Caatinga (Tiessen *et al.*, 2003), and African savannas (Belsky, 1994; Scholes, 1990; Deans *et al.*, 1999). This so called 'fertile island' effect further enhances the ability of scattered trees 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). Hence, those trees often function as 'nurse plants', in that they facilitate the recruitment of other plants (San José *et al.*, 1991; Facelli and Brock, 2000).

Restoration of degraded lands should aim at reversing the effects of degradation by improving soil conditions, increasing plant cover, and introducing keystone woody species (Cortina *et al.*, 2011). *Acacia raddiana* is such an important keystone species, for its

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tolerance to extreme droughts and persistence on the edge of the desert (Le Floc'h and Grouzis, 2003). Spatial heterogeneity in resource availability is one of the key factors that shape communities and impact ecosystem functioning (Kneitel and Chase, 2004; Jones and Callaway, 2007). In order to obtain a complete understanding of the 'fertile island' effect of scattered *A. raddiana* trees and the extent of their influence on soil conditions, one should look at the changes in nutrient levels along a gradient from underneath to outside the canopy.

Most studies in wooded and savanna ecosystems focus on the nutrient levels in a binary way on microsite-scale, i.e. underneath and outside the canopy (e.g., Abdallah *et al.*, 2008, 2012; Bernhard-Reversat, 1982; Kellman, 1979; Weltzin and Coughenour, 1990), and only few include the distance gradient (e.g., Belsky, 1994; Belsky and Canham, 1994; Belsky *et al.*, 1989). Studies investigating the effects of trees on soil properties in a binary way indicated higher levels of mineralizable nitrogen (N), and extractable phosphorus (P), potassium (K^+) and calcium (Ca^{2+}) underneath compared to outside the canopy. Studies including the distance gradient observed highest concentrations of organic matter, total and available N, Ca^{2+}, K^+, P, sodium (Na^+) and sulphur (S) adjacent to the tree stem and declining with increasing distance from the tree stem.

In order to investigate the impact of scattered *A. raddiana* trees on the herbaceous layer on a field scale, spatial patterns in soil chemical properties should be considered in both horizontal and vertical direction. By taking into account the horizontal distance gradient, the extent of the 'fertile island' effect outside the canopy of scattered trees can be examined. To understand in an accurate way the influence of scattered *A. raddiana* trees on the vertical distribution of soil nutrients in the topsoil layer, a vertical distance gradient with small depth intervals is needed. Moreover, in-depth studies investigating the field-scale impact of scattered trees on the soil nutrient status are mainly available for eucalypt trees (McElhinny *et al.*, 2010; Barnes *et al.*, 2011) and for mature Acacia trees (Ludwig *et al.*, 2004; Belsky *et al.*, 1989). By incorporating tree age, one can investigate how long it would take before reforestation affects the soil nutrient status

Therefore, we quantify in this paper the influence of scattered *A. raddiana* trees of three canopy sizes (representing different tree growth stages) on the nutrient levels along gradients from underneath to outside the canopy for the 0-10 cm soil layer on a study site in arid Tunisia. In addition, changes in nutrient levels with depth for the 0-30 cm soil layer were investigated in a binary way at microsites underneath and outside the canopy. We hypothesized that the nutrient levels in the presence of scattered *A. raddiana* trees would (i) decrease with increasing distance from the stem, (ii) decrease with increasing soil depth at the microsite closest to the stem, and (iii) increase with increasing tree age.

6.2 Materials and methods

6.2.1 Study site

A description of the study site is given in section 3.8.

6.2.2 Experimental design

A total of 15 *A. raddiana* trees was randomly selected (same trees as in Chapter 5) in the plain of IPZ1 and assigned to three crown diameter classes (small, SCD, i.e. 3-5 m; medium, MCD, i.e. 5-7m, large, LCD, >7 m; see section 0). Tree attributes for five trees of each class (crown diameter, basal trunk diameter and tree age) are listed in Table 5.1.

For those 15 trees, five per crown diameter class, five microsites were distinguished for the top 10 cm soil (depth D1): M1, M2, M3 and M4 respectively at 25%, 75%, 125% and 175% of the canopy radius (in which 100% is the distance from the stem to the canopy edge) in the northern direction and M5 at least 10 m away from the canopy. In addition, two more soil depths for microsites M1 and M5 were distinguished: D2 and D3 respectively at 10-20 cm and 20-30 cm.

6.2.3 Soil analysis

Soil texture on air-dried fine earth (<2 mm) samples was determined with the pipette method (Gee and Or, 2002), and classified according to the USDA textural triangle (Soil Survey Staff, 1999). $CaCO_3$ was not removed in the pre-treatment process as it originates from the parent material and forms as such a substantial part of the soil texture. Organic matter (OM) was determined according to Walkley and Black (1934). The $CaCO_3$ content was measured by back-titrating the excess of H_2SO_4 with 0.5 M NaOH (Cottenie *et al.*, 1982). The pH-KCl was measured potentiometrically in a 1:5 soil:KCl extract. The electrical conductivity (EC) was measured in a 1:5 soil-water extract.

Exchangeable cation concentrations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}) and extractable phosphorus (P) were determined following an ammoniumlactate extraction using ICP-AES (ICAP 6300 series, Thermo scientific). Total C and N contents were measured with a CNS elemental analyzer (Variomax Elementar Analysesysteme, Germany), according to the principle of catalytic tube combustion under excess oxygen supply and high temperature (850-1150 °C).

6.2.4 Data analysis

To evaluate and compare the different chemical parameters for the top 10 cm soil as influenced by crossed factors canopy size and microsite and factor tree nested in canopy size, a three-way ANOVA was performed. Prior to statistical analyses, OM, total N, Mg^{2+} and P were lognormally, whereas $CaCO_3$ was inversely transformed to achieve normality. In case of a significant main effect of canopy size or microsite, Tukey's Honest Significant Difference post-hoc test was executed between all levels of that factor.

To evaluate and compare the different chemical parameters for the top 30 cm soil as influenced by crossed factors canopy size and depth and factor tree nested in canopy size, a three-way ANOVA was performed both underneath and outside the canopy respectively at microsites M1 and M5. All chemical parameters except total C and pH-KCl were lognormally transformed prior to statistical analyses to achieve normality. In case of a significant main effect of canopy size or depth, Tukey's Honest Significant Different post-hoc test was executed between all levels of that factor.

Trend analysis using linear regression was performed on all parameters to study the effect of distance from the stem, depth and canopy size. The standard error of the mean (s.e.m) for each parameter was calculated across all canopy sizes and microsites for the top 10 cm soil and across all canopy sizes and depths for microsites M1 and M5 for the top 30 cm soil. In order to evaluate associations between parameters, the Pearson correlation coefficient and corresponding level of significance was calculated.

6.3 Results

There were no significant differences in sand, silt and clay fractions for the top 10 cm soil between the three canopy size classes and between the microsites M1 and M5 as was reported in Table 5.2 (Chapter 5). The textural classes varied between loamy sand, sandy loam and loam (Soil Survey Staff, 1999).

6.3.1 Gradients in soil chemical properties from canopy to interspace

The distance from the tree stem affected most properties of the top 10 cm soil (Table 6.1, Table 6.2 and Table 6.3). As no interaction occurred between factors microsite and canopy size for all soil properties except total C, averages across the three canopy size classes were considered. For total C, the interaction was taken into account by looking at differences between microsites for the canopy sizes separately.

Microsite M1 (closest to the tree stem) showed greatest differences among microsites, containing significantly ($p<0.05$) more OM, total N, K^+, P, and less Mg^{2+}, a higher EC and a lower pH-KCl. The total C-content and Na^+ for M1 were numerically higher as compared to the other microsites. For total C-content, the difference between M1 and the other sites was significant for all three canopy sizes.

There were some clear trends in soil chemistry going from underneath to outside the canopy. With increasing distance from the stem, a significant decrease in nutrient levels was found for OM (R^2-adj = 0.256, $p<0.001$), total N (R^2-adj = 0.318, $p<0.001$), EC (R^2-adj = 0.236, $p<0.001$), K^+ (R^2-adj = 0.196, $p<0.001$) and P (R^2-adj = 0.043, $p<0.05$), whereas a significant increase was observed for pH-KCl (R^2-adj = 0.164, $p<0.001$) and Mg^{2+} (R^2-adj = 0.115, $p<0.05$). For total C, a significant decrease with larger distance from the stem was found for canopy size LCD only (R^2-adj = 0.368, $p<0.05$).

Table 6.1 Mean and standard error of the mean (s.e.m.) of pH and electrical conductivity (EC) for the top 10 cm soil along a gradient from underneath to outside the canopy for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
pH-KCl	M1	8.1	8.0	7.9	8.0^{a}	0.02	ns	<0.01	ns
	M2	8.2	8.1	8.1	8.2^{b}				
	M3	8.3	8.2	8.2	8.2^{b}				
	M4	8.2	8.2	8.2	8.2^{b}				
	M5	8.3	8.2	8.3	8.3^{b}				
	mean	8.2^{A}	8.1^{B}	8.1^{B}					
EC (µS cm^{-1})	M1	270	278	372	307^{a}	9	ns	<0.01	ns
	M2	241	258	234	244^{b}				
	M3	223	237	242	234^{b,c}				
	M4	203	231	224	220^{b,c}				
	M5	184	194	193	191^{c}				
	mean	224	240	253					

M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a row (A,B) or column (a,b,c) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

Table 6.2 Mean and standard error of the mean (s.e.m.) of nutrient levels for the top 10 cm soil along a gradient from underneath to outside the canopy for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
OM (%)	M1	1.7	2.2	3.4	2.4^{a}	0.1	ns	<0.01	ns
	M2	1.0	1.7	1.7	1.5^{b}				
	M3	0.9	1.3	0.9	1.0^{b,c}				
	M4	0.9	1.0	1.3	1.0^{c}				
	M5	0.9	1.1	1.1	1.0^{b,c}				
	Mean	1.1	1.5	1.7					
CaCO$_3$ (%)	M1	32.1	31.9	30.8	31.6^{a}	0.4	ns	<0.01	ns
	M2	34.3	33.3	33.1	33.5^{b}				
	M3	33.5	33.7	33.1	33.4^{b}				
	M4	33.4	34.8	33.2	33.8^{b}				
	M5	33.1	32.7	30.5	32.1^{a}				
	Mean	33.3	33.3	32.1					
total C (g kg^{-1})	M1	51.1^{a}	54.0^{a}	62.1^{a}	55.7	0.8	ns	<0.01	<0.01
	M2	46.9^{a,b}	48.4^{b}	46.7^{b}	47.3				
	M3	45.9^{b}	47.7^{b}	45.3^{b}	46.3				
	M4	45.5^{b}	48.1^{b}	47.5^{b}	47.0				
	M5	48.6^{a,b}	48.5^{b}	43.1^{b}	46.7				
	mean	47.6	49.3	48.9					
total N (g kg^{-1})	M1	0.69	1.00	1.95	1.22^{a}	0.06	ns	<0.01	ns
	M2	0.44	0.68	0.58	0.57^{b}				
	M3	0.39	0.51	0.45	0.45^{b,c}				
	M4	0.36	0.44	0.62	0.47^{b,c}				
	M5	0.27	0.42	0.34	0.34^{c}				
	mean	0.43	0.61	0.79					

OM: organic matter; M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a column (a,b,c) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

Table 6.3 Mean and standard error of the mean (s.e.m.) of soil cations for the top 10 cm soil along a gradient from underneath to outside the canopy for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		SCD	MCD	LCD	mean	s.e.m.	CS	M	CS*M
Ca^{2+} (g kg^{-1})	M1	89.5	92.4	88.6	90.2	1.2	ns	ns	ns
	M2	92.1	93.1	92.1	92.4				
	M3	90.8	93.6	90.4	91.6				
	M4	89.8	95.0	92.2	92.3				
	M5	99.4	97.9	89.1	95.5				
	mean	92.3	94.4	90.5					
Mg^{2+} (g kg^{-1})	M1	5.2	4.8	4.7	4.9^{a}	0.1	ns	<0.01	ns
	M2	5.2	5.1	5.2	5.2^{a,b}				
	M3	5.2	5.1	5.5	5.3^{b}				
	M4	5.3	5.4	5.4	5.4^{b}				
	M5	5.6	5.3	5.4	5.4^{b}				
	mean	5.3	5.1	5.2					
K^{+} (g kg^{-1})	M1	0.36	0.40	0.45	0.41^{a}	0.01	ns	<0.01	ns
	M2	0.38	0.45	0.39	0.41^{a}				
	M3	0.32	0.36	0.36	0.35^{a,b}				
	M4	0.32	0.35	0.40	0.36^{a}				
	M5	0.25	0.31	0.26	0.27^{b}				
	mean	0.33	0.38	0.37					
Na^{+} (g kg^{-1})	M1	0.14	0.07	0.09	0.10	0.005	ns	ns	ns
	M2	0.08	0.08	0.08	0.08				
	M3	0.08	0.08	0.09	0.08				
	M4	0.07	0.08	0.07	0.07				
	M5	0.07	0.07	0.09	0.08				
	mean	0.09	0.08	0.09					
P (g kg^{-1})	M1	0.11	0.11	0.17	0.13^{a}	0.004	ns	<0.05	ns
	M2	0.10	0.11	0.12	0.11^{a,b}				
	M3	0.10	0.11	0.09	0.10^{a,b}				
	M4	0.11	0.11	0.12	0.12^{a,b}				
	M5	0.09	0.09	0.10	0.09^{b}				
	mean	0.10	0.11	0.12					

M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; M: microsite. CS, M, CS*M: level of significance of the effect of canopy size, microsite and canopy size x microsite respectively; ns: not significant. Means bearing different superscripts within a column (a,b) are significantly different (p<0.05) following Tukey's Honest Significant Difference test.

6.3.2 Changes in soil chemical properties with depth underneath and outside the tree canopy

As no interaction occurred between factors depth and canopy size for all soil properties except total C at microsite M1, averages across the three canopy size classes were considered. For total C, the interaction was taken into account by looking at differences between depths for the canopy sizes separately. Significantly higher values for OM and P at both microsites and for EC, total N, exchangeable K^+ and Na^+ at microsite M1 only were present at depth D1 compared with D3 (Table 6.4, Table 6.5 and Table 6.6).

The opposite was found for $CaCO_3$ at both microsites and for pH-KCl, Ca^{2+} and Mg^{2+} at microsite M1 only. In addition, intermediate but significantly different concentrations at depth D2 compared with depths D1 and D3 were found for OM, total N and P at microsite M1. For total C-content, microsite M1 showed significantly higher values at depth D1 compared with D3 for canopy sizes MCD and LCD. Nutrient concentrations were typically highest at the surface, and declined with depth.

A significant decrease with increasing depth was found for OM (R^2-adj = 0.526, $p<0.001$), total N (R^2-adj = 0.460, $p<0.001$), EC (R^2-adj = 0.288, $p<0.001$) and K^+ (R^2-adj = 0.152, $p<0.05$) at microsite M1 and for P at both microsites M1 (R^2-adj = 0.381, $p<0.001$) and M5 (R^2-adj = 0.097, $p<0.05$). A significant increasing trend with increasing depth was found for pH-KCl (R^2-adj = 0.297, $p<0.001$) and Ca^{2+} (R^2-adj = 0.096, $p<0.05$) at microsite M1. A significant decrease in levels of total C with increasing depth was found for canopy sizes MCD (R^2-adj = 0.249, $p<0.05$) and LCD (R^2-adj = 0.446, $p<0.05$) at microsite M1.

Table 6.4 Mean and standard error of the mean (s.e.m.) of pH and electrical conductivity (EC) in the top 30 cm soil on microsite locations canopy (M1) and interspace (M5) for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		depth	SCD	MCD	LCD	mean	s.e.m.	CS	D	CS*D
pH-KCl	M1	0-10 cm	8.1	8.0	7.9	8.0^a	0.03	ns	<0.01	ns
		10-20 cm	8.3	8.2	8.1	8.2^b				
		20-30 cm	8.3	8.3	8.2	8.3^b				
		mean	8.2	8.2	8.1					
	M5	0-10 cm	8.3	8.2	8.3	8.3	0.02	ns	ns	ns
		10-20 cm	8.3	8.3	8.3	8.3				
		20-30 cm	8.3	8.3	8.3	8.3				
		mean	8.3	8.3	8.3					
EC (µS cm^{-1})	M1	0-10 cm	270	278	372	307^a	10	ns	<0.01	ns
		10-20 cm	252	240	241	245^b				
		20-30 cm	231	220	207	219^b				
		mean	251	246	273					
	M5	0-10 cm	184	194	193	191	9	ns	ns	ns
		10-20 cm	171	212	171	185				
		20-30 cm	194	205	205	201				
		mean	183	204	190					

M1: microsite at 25% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; D: depth. CS, D, CS*D: level of significance of the effect of canopy size, depth and canopy size x depth respectively; ns: not significant. Means bearing different superscripts within a column (a,b) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

Table 6.5 Mean and standard error of the mean (s.e.m.) of nutrient levels in the top 30 cm soil on microsite locations canopy (M1) and interspace (M5) for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		depth	SCD	MCD	LCD	mean	s.e.m.	CS	D	CS*D
OM (%)	M1	0-10 cm	1.7	2.2	3.4	2.4^{a}	0.1	<0.05	<0.01	ns
		10-20 cm	1.1	1.3	1.6	1.3^{b}				
		20-30 cm	0.8	0.9	1.0	0.9^{c}				
		mean	1.2^{A}	1.5^{A}	2.0^{B}					
	M5	0-10 cm	0.9	1.1	1.1	1.0^{a}	0.1	ns	ns	ns
		10-20 cm	0.8	0.9	1.0	$0.9^{a,b}$				
		20-30 cm	0.8	0.8	0.8	0.8^{b}				
		mean	0.8	0.9	0.1					
$CaCO_3$ (%)	M1	0-10 cm	32.1	31.9	30.8	31.6^{a}	0.6	ns	<0.01	ns
		10-20 cm	34.5	33.8	33.5	33.9^{b}				
		20-30 cm	35.0	34.0	32.6	33.9^{b}				
		mean	33.9	33.2	32.3					
	M5	0-10 cm	33.1	32.7	30.5	32.1^{a}	0.6	ns	<0.01	ns
		10-20 cm	35.2	34.1	31.8	33.7^{b}				
		20-30 cm	35.4	34.9	31.9	34.1^{b}				
		mean	34.5	33.9	31.4					
total C ($g\ kg^{-1}$)	M1	0-10 cm	51.1^{a}	54.0^{a}	62.1^{a}	55.7	1.1	ns	<0.01	<0.01
		10-20 cm	48.6^{b}	49.9^{b}	49.4^{b}	49.3				
		20-30 cm	$49.3^{a,b}$	47.1^{b}	45.9^{b}	47.4				
		mean	49.7	50.3	52.5					
	M5	0-10 cm	48.6	48.5	43.1	46.7	0.7	ns	ns	ns
		10-20 cm	47.6	47.7	43.5	46.3				
		20-30 cm	48.0	49.1	43.1	46.7				
		mean	48.1	48.4	43.2					
total N ($g\ kg^{-1}$)	M1	0-10 cm	0.69	1.00	1.95	1.22^{a}	0.09	<0.05	<0.01	ns
		10-20 cm	0.46	0.45	0.79	0.56^{b}				
		20-30 cm	0.30	0.39	0.45	0.38^{c}				
		mean	0.48^{A}	0.61^{A}	1.06^{B}					
	M5	0-10 cm	0.27	0.42	0.35	0.34	0.02	ns	ns	ns
		10-20 cm	0.25	0.34	0.34	0.31				
		20-30 cm	0.25	0.37	0.33	0.32				
		mean	0.25	0.38	0.34					

OM: organic matter; M1: microsite at 25% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; D: depth. CS, D, CS*D: level of significance of the effect of canopy size, depth and canopy size x depth respectively; ns: not significant. Means bearing different superscripts within a row (A,B) or column (a,b,c) are significantly different (*p*<0.05) following Tukey's Honest Significant Difference test.

Table 6.6 Mean and standard error of the mean (s.e.m.) of soil cations in the top 30 cm soil on microsite locations canopy (M1) and interspace (M5) for *Acacia raddiana* trees with small (SCD, N=5), medium (MCD, N=5) and large crown diameter (LCD, N=5)

		depth	SCD	MCD	LCD	mean	s.e.m.	CS	D	CS*D
Ca^{2+} (g kg^{-1})	M1	0-10 cm	89.5	92.4	88.6	90.2^{a}	1.7	ns	<0.01	ns
		10-20 cm	95.9	93.0	92.6	$93.8^{a,b}$				
		20-30 cm	101.4	97.4	101.1	100.0^{b}				
		mean	95.6	94.2	94.1					
	M5	0-10 cm	99.4	97.9	89.1	95.5	2.1	ns	ns	ns
		10-20 cm	95.7	95.2	98.0	96.3				
		20-30 cm	100.4	99.2	97.7	99.1				
		mean	98.5	97.4	94.9					
Mg^{2+} (g kg^{-1})	M1	0-10 cm	5.2	4.8	4.7	4.9^{a}	0.1	ns	<0.05	ns
		10-20 cm	5.3	5.1	5.3	5.2^{b}				
		20-30 cm	5.2	5.1	5.3	$5.2^{a,b}$				
		mean	5.2	5.0	5.1					
	M5	0-10 cm	5.6	5.3	5.4	5.4	0.1	ns	ns	ns
		10-20 cm	5.2	5.4	5.1	5.3				
		20-30 cm	5.2	5.4	5.3	5.3				
		mean	5.3	5.3	5.3					
K^{+} (g kg^{-1})	M1	0-10 cm	0.36	0.40	0.45	0.41^{a}	0.02	ns	<0.01	ns
		10-20 cm	0.32	0.42	0.60	0.44^{a}				
		20-30 cm	0.26	0.27	0.32	0.28^{b}				
		mean	0.31	0.36	0.46					
	M5	0-10 cm	0.25	0.31	0.26	0.27	0.02	ns	ns	ns
		10-20 cm	0.24	0.21	0.41	0.29				
		20-30 cm	0.27	0.20	0.30	0.25				
		mean	0.25	0.24	0.32					
Na^{+} (g kg^{-1})	M1	0-10 cm	0.14	0.07	0.09	0.10^{a}	0.007	ns	<0.01	ns
		10-20 cm	0.07	0.07	0.08	0.07^{b}				
		20-30 cm	0.08	0.07	0.08	0.07^{b}				
		mean	0.10	0.07	0.08					
	M5	0-10 cm	0.07	0.07	0.09	0.08^{a}	0.004	ns	<0.01	ns
		10-20 cm	0.05	0.05	0.07	0.05^{b}				
		20-30 cm	0.06	0.06	0.08	$0.07^{a,b}$				
		mean	0.06	0.06	0.08					
P (g kg^{-1})	M1	0-10 cm	0.11	0.11	0.17	0.13^{a}	0.006	ns	<0.01	ns
		10-20 cm	0.09	0.08	0.10	0.09^{b}				
		20-30 cm	0.06	0.08	0.08	0.07^{c}				
		mean	0.08	0.09	0.12					
	M5	0-10 cm	0.09	0.09	0.10	0.09^{a}	0.004	<0.05	<0.01	ns
		10-20 cm	0.07	0.06	0.09	0.07^{b}				
		20-30 cm	0.07	0.06	0.10	0.08^{b}				
		mean	0.07^{A}	0.07^{A}	0.10^{B}					

M1: microsite at 25% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy; CS: canopy size; D: depth. CS, D, CS*D: level of significance of the effect of canopy size, depth and canopy size x depth respectively; ns: not significant. Means bearing different superscripts within a row (A,B) or column (a,b,c) are significantly different ($p<0.05$) following Tukey's Honest Significant Difference test.

6.3.3 Effects of canopy size on soil chemical properties

As no interaction occurred between canopy size and depth for all soil properties except total C at microsite M1, averages across all depths were considered. For total C, the interaction was taken into account by looking at differences between canopy sizes for the depths separately. Significantly higher values for OM and total N at microsite M1 and for P at microsite M5 were found for canopy size class LCD compared with both SCD and MCD (Table 6.4, Table 6.5 and Table 6.6). At microsite M1, numerically higher values for K^+ and P were found for canopy size LCD compared with MCD and SCD. With increasing canopy size, values of OM (R^2-adj = 0.107, $p<0.05$), total N (R^2-adj = 0.136, $p<0.05$), K^+ (R^2-adj = 0.121, $p<0.05$) and P (R^2-adj = 0.109, $p<0.05$) increased, while pH-KCl (R^2-adj = 0.096, $p<0.05$) decreased.

6.3.4 Effects of organic matter on soil chemical properties

With increasing OM content, total N (R^2-adj = 0.849, $p<0.001$), total C (R^2-adj = 0.426, $p<0.001$), EC (R^2-adj = 0.316, $p<0.001$) and contents of K^+ (R^2-adj = 0.134, $p<0.001$) and P (R^2-adj = 0.333, $p<0.001$) increased, while pH-KCl (R^2-adj = 0.603, $p<0.001$) and Mg^{2+}-content (R^2-adj = 0.044, $p<0.05$) decreased.

6.3.5 Effects of soil nutrient levels on EC and pH-KCl

A significant positive correlation was found between EC and nutrient levels of exchangeable Na^+ (R^2-adj = 0.235, $p<0.001$), K^+ (R^2-adj = 0.093, $p<0.001$) and Ca^{2+} (R^2-adj = 0.025, $p<0.05$), extractable P (R^2-adj = 0.150, $p<0.001$) and total N (R^2-adj = 0.283, $p<0.001$). A significant positive correlation between pH-KCl and exchangeable K^+ (R^2-adj = 0.119, $p<0.001$), Na^+ (R^2-adj = 0.038, $p<0.05$) and Ca^{2+} (R^2-adj = 0.032, $p<0.05$) and extractable P (R^2-adj = 0.393, $p<0.001$) and total N (R^2-adj = 0.584, $p<0.001$) was also found.

6.4 Discussion

In general, highest levels of nutrients within the upper soil layer were found closest to the tree stem. Levels of OM significantly decreased with increasing distance from the tree stem and a significant correlation with most nutrients was found. Concentrations of total C (only for LCD), total N, exchangeable K^+ and extractable P significantly decreased with increasing distance from the tree stem in accordance with other studies (e.g., Ludwig *et al.*, 2004; Belsky, 1994). For exchangeable Ca^{2+} and Mg^{2+} the opposite trend with longer distance from the tree stem was found. Numerically higher levels of total N, exchangeable K^+ and extractable P were found up to 175% of the canopy radius. No clearly defined patterns were present with distance from the tree stem for $CaCO_3$ and exchangeable Na^+. High contents of $CaCO_3$ were found both underneath and outside the canopy resulting in elevated total C-content (inorganic C input).

Alkaline pH-KCl values were found and, based on the positive association between increases in exchangeable cations and soil pH, higher pH-KCl values closer to the stem were expected as reflected by higher contents of exchangeable cations (Barnard and Fölscher, 1972). However, increasing values of pH-KCl with longer distance from the stem were found in our study which could be mainly attributed to increasing Ca^{2+}-levels. Increasing values of electrical conductivity closer to the tree stem can be related to higher levels of both exchangeable cations and anions.

Higher nutrient concentrations closer to the tree stem can be related to the greater litter input from leaves and understory vegetation, and improved OM cycling. In addition, symbiotic N_2 fixation associated with Acacia trees can contribute to elevated N-inputs below canopy (Vetaas, 1992). Several studies on forest nutrient cycling recognise a link between soil nutrient status and litter production (e.g., Eldridge and Wong, 2005). McElhinny *et al.* (2010) reported a heterogeneous spatial arrangement of litter under tree crowns for scattered tree ecosystems, following a declining gradient with distance from the stem as was reflected in the decreasing levels of most nutrients in our study. These patterns are also in accordance with the architecture of tree crowns in which the depth of crown contributing to litter fall is at a maximum directly above the main stem.

Abdallah *et al.* (2008) studied the impact of scattered *A. raddiana* trees on the soil nutrient status and the grass species composition and yield in Bou Hedma National Park. For the top 20 cm soil, they found higher pH, EC, OM, total N, exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+ and extractable P underneath compared to outside the canopy. This was in accordance with our observations except for pH, Ca^{2+} and Mg^{2+}, where the opposite trend was found. In addition, they found a higher plant cover and dry matter yield below canopy which could be attributed to the improved soil fertility.

As soils outside the canopy of *A. raddiana* trees were found to be more fertile up to 175% of the canopy radius, especially for trees with medium and large crown diameter, these trees increase nutrients available for the herbaceous layer on a landscape scale. Hence, the fertile island effect of *A. raddiana* trees is not only limited to the canopy radius. As indicated by an increased OM content found outside the canopy edge, a valid explanation for the elevated nutrient levels outside the canopy of *A. raddiana* trees is provided.

In dryland ecosystems, low soil-water content and high soil alkalinity decrease both soil N and P availability (Noy-Meir, 1973). The occurrence and degree of nutrient limitation for the herbaceous layer is difficult to determine, because it depends on the process (e.g. plant growth) and time scale considered (Güsewell, 2004). Overall, low soil N availability decreases primary productivity and seed production in desert plants. However, how ubiquitous P limitations are in arid systems is not known (Drenovsky and Richards, 2004). High pH-KCl values (>8.0) were found in our study area leading to decreased N availability. Nevertheless, *A. raddiana* trees may enhance N availability through N fixation.

Reduced levels of most nutrients were found with increasing depth underneath the tree canopy. Levels of OM, total C (both for MCD and LCD), total N, exchangeable K^+ and extractable P significantly decreased whereas levels of pH-KCl and exchangeable Ca^{2+} significantly increased with increasing depth. For OM, total N, exchangeable K^+ and extractable P significantly higher levels were found up to 20 cm soil depth, whereas for exchangeable Na^+ this was limited up to 10 cm soil depth. Several studies in woodlands and grasslands worldwide have demonstrated that nutrient levels are highest at the surface and decline rapidly with depth (Ryan and McGarity, 1983; Schlesinger and Pilmanis, 1998; Eldridge and Wong, 2005).

Abdallah *et al.* (2008) found decreasing pH, EC, OM, total N, exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+ and extractable P with increasing depth in accordance with our observations except for pH, Ca^{2+} and Mg^{2+}, where the opposite trend was found. Differences in nutrient levels among different depths within the top 30 cm soil were largely driven by OM content, as shown by the significant correlations with most nutrients. Similar to the gradient from canopy to interspace for the upper soil layer, increase in pH-KCl with depth at the microsite closest to the tree stem can be related to the increase in Ca^{2+}-content. The greater litter input and improved cycling resulted in higher nutrient concentrations available for the herbaceous layer below-canopy compared with interspace up to a depth of 20 cm.

With increasing canopy size, increased levels of OM, total N, exchangeable K^+ and extractable P and decreased pH-KCl were found within the below-canopy soil layer. Similarly, Facelli and Brock (2000) observed a clear accumulation of nutrients below canopy of *Acacia papyrocarpa* trees in older stages (MCD and LCD in our study) compared with the youngest age class (SCD in our study) in arid lands of south Australia. McElhinny *et al.* (2010) found that large trees (comparable to LCD in our study) produced substantially higher loads of litter fall than small trees (SCD in our study). Hence, greater inputs of organic matter are generated with increasing canopy size resulting in elevated nutrient concentrations available for the herbaceous layer below-canopy.

6.5 Conclusions

We documented here for a forest steppe in arid Tunisia, that *A. raddiana* trees improved the nutrient distribution in soils both horizontally and vertically. Along gradients from underneath to outside the canopy, greatest differences in soil nutrient levels were mainly found between the microsite closest to the tree stem and the other microsites irrespective of tree age.

Although higher levels of OM, total N, exchangeable K^+ and extractable P were found up to 175% of the canopy radius, especially for trees older than 75 years with a medium or large crown diameter, the differences were not significant outside the canopy. Significantly higher levels of OM, total N, K^+ and P were found up to a soil depth of 20 cm.

Levels of OM, total N, exchangeable K^+ and extractable P significantly decreased with increasing distance and with increasing depth whereas the opposite was found with increasing tree age. Due to the close link between OM content and total N, exchangeable K^+ and extractable P, changes in nutrient levels were largely driven by greater litter inputs from leaves and vegetation cover.

Through their amelioration of the soil nutrient status both horizontally and vertically, *A. raddiana* trees may create favourable conditions for the regeneration of the herbaceous layer and play as such a key role in the rehabilitation of degraded areas. A spatial structure in soil chemical properties exists between canopy and open microsites. When combined with information on spatial patterns in soil hydraulic properties as found in Chapter 5, the interaction between scattered *A. raddiana* trees and the herbaceous vegetation can be investigated more profoundly.

Chapter 7. Influence of Acacia trees on near-surface soil-water balance in arid Tunisia[4]

7.1 Introduction

In savannas scattered trees may suppress or facilitate growth of below-canopy vegetation (Scholes and Archer, 1997; Ludwig *et al.*, 2004). A shift from net competitive to net facilitative effects of trees on the productivity of the herbaceous layer was reported by Dohn *et al.* (2013) in transition between mesic and arid savannas in sub-Saharan Africa. Facilitation by scattered trees may occur through a more favourable microclimate (Moro *et al.*, 1997; Breshears *et al.*, 1998), improved nutrient availability (Belsky, 1994; Chapter 6) and enhanced soil physical and soil hydraulic properties as suggested in Chapter 5.

In accordance with the stress-gradient hypothesis (Bertness and Callaway, 1994), positive effects of scattered trees are particularly pronounced in harsh environments, such as arid and semiarid environments, where water availability in the soil is the most critical factor controlling productivity and reproduction of vegetation (Noy-Meir, 1973; Rodriguez-Iturbe, 2000).

Terrestrial ecosystems depend almost entirely on the green-water flow for their productivity and functioning (Rockström and Gordon, 2001). Green-water flow represents the vapour flow in terms of evapotranspiration, whereas blue-water flow concerns the liquid water fluxes, such as groundwater flow, base flow in rivers, and surface runoff. The green-water flow has two components: a productive part, or transpiration, involved in biomass production in terrestrial ecosystems, and a non-productive part, or evaporation (Falkenmark, 1995). Little research has been conducted to evaluate the regulation of green- and blue-water flows by terrestrial ecosystems. Maes *et al.* (2009) for example developed an impact assessment method to evaluate the effect of land use occupation and transformation focusing on both flows.

In the arid regions north and south of the Saharan desert *Acacia raddiana* is considered as a keystone species for its tolerance to extreme droughts and persistence on the edge of the desert (Le Floc'h and Grouzis, 2003). In order to evaluate how scattered *A. raddiana* trees provide water-related ecosystem services and more specifically how they affect the actual transpiration of the herbaceous cover both underneath and outside their canopy, a near-surface soil-water balance was examined.

To understand the impact of scattered trees on a field scale, near-surface soil-water content should be investigated in function of a distance gradient from underneath to outside the canopy. In Chapter 5, a spatial structure in soil physical and soil hydraulic properties was found between canopy and open microsites. This information, along with

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[4] This chapter is under revision for *Vadose Zone Journal* and was submitted as De Boever M, Gabriels D, Ouessar M, Cornelis W. 2014. Influence of Acacia trees on near-surface soil-water balance in arid Tunisia.

measured soil-water contents near an *A. raddiana* tree of a forest steppe in central Tunisia, was used to establish the near-surface soil-water balance of 40 cm rootzone of the herbaceous layer with Hydrus-1D.

We hypothesized that scattered *A. raddiana* trees (i) improve the soil-water availability within the herbaceous root zone both underneath and outside their canopy, (ii) have a positive impact on the productivity of the herbaceous layer as indicated by a higher value for the actual transpiration, and (iii) improve water use efficiency, i.e. the biomass production per unit of water used, by the herbaceous layer.

7.2 Materials and methods

7.2.1 Study site

A description of the study site is given in section 3.8.

7.2.2 Experimental design

A single *A. raddiana* tree was selected (one tree from the selection of Chapter 5) in the study area with crown diameter 7.2 m, basal trunk diameter 25.5 cm and tree age 79 years with the latter calculated following Noumi and Chaieb (2012). According to the three crown diameter classes distinguished in Bou Hedma National Park (small, SCD, i.e. 3-5 m; medium, MCD, 5-7 m; large, LCD, >7 m), the selected tree belongs to class LCD. The superficial root system of LCD trees in Bou Hedma National Park was found to be located at least 40 cm below the soil surface.

Five microsites at which water balance components were evaluated were distinguished: M1, M2, M3 and M4 respectively at 25%, 75%, 125% and 175% of the canopy radius (in which 100% is the distance from the tree stem to the canopy edge) in the northern direction and M5 at least 10 m away from the canopy. The selected tree was well representative for the study area.

7.2.3 Field measurements

At each microsite an infiltration measurement was performed with a tension disk infiltrometer (Soil Measurement Systems, Tucson AZ, USA) following the procedure as described by in Chapter 5. Three successive matric potentials (ψ) were applied, -0.29, -0.59, and -1.18 kPa, for at least 10 minutes or until the infiltration rate of three consecutive time intervals was constant. The saturated hydraulic conductivities (Ks) were obtained from the tension infiltrometer measurements based on the equation of Wooding (1968) in combination with the steady-state approach of Logsdon and Jaynes (1993).

To obtain the soil-water retention curve (SWRC), 15 undisturbed soil samples of the top 30 cm soil were taken at each microsite at depths of 5, 15 and 25 cm using 100 cm³

Kopecky rings at the five microsites. On those samples the soil-water content (SWC) was determined at eight matric potentials (-1, -3, -5, -7, -10, -33, -100 and -1500 kPa) as described by Cornelis *et al.* (2005). The model of van Genuchten (1980) was used to describe the soil-water retention curve. The soil bulk density (BD) was determined at -10 kPa following the procedure of Grossman and Reinsch (2002).

7.2.4 Field monitoring system

Bou Hedma National Park is equipped with a weather station (type BWS-200, Campbell Scientific Inc., Utah, USA) since July 2009 (Figure 7.1). In a radius of at least 50 m around this weather station there is no influence of vegetation. The station is connected to a CR200 data logger (Campbell Scientific Inc., Utah, USA).

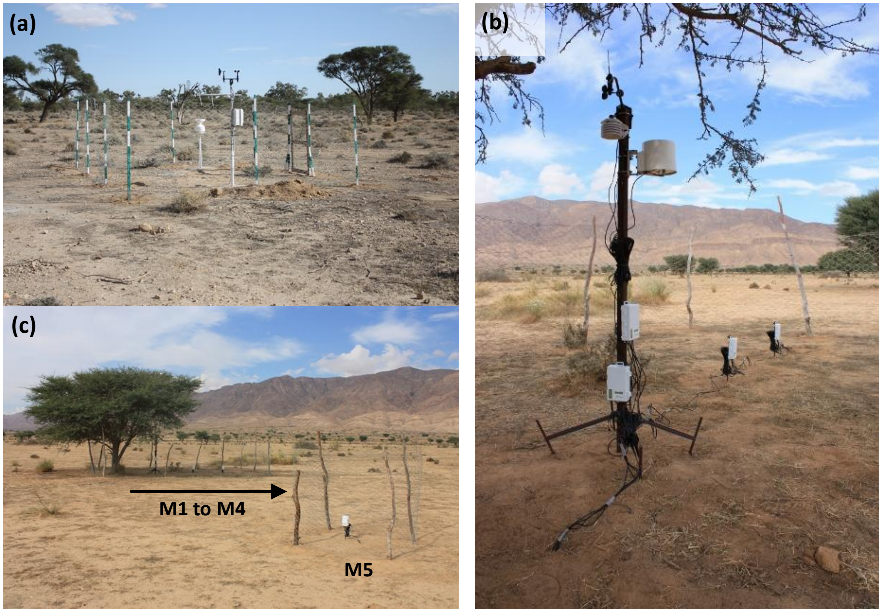

Figure 7.1 Weather station (a) outside and (b) underneath a single *Acacia raddiana* tree and (c) configuration of soil moisture sensors along a gradient from underneath to outside the canopy (microsites M1 to M5) in National Park Bou Hedma (Photo source: Maarten De Boever)

A second weather station (Decagon Devices, Pullman, WA, USA) was installed at 1.5 km distance in December 2012 underneath a single *A. raddiana* tree in the northern direction between microsites M1 and M2. Technical equipment information of both weather stations is listed in Table 7.1.

In addition, soil-water content was recorded at the five microsites of the selected *A. raddiana* tree using 5 cm long capitance sensors 5TE and EC-5 (ECH_2O Series, Decagon Devices, Pullman, WA, USA) (Figure 7.1). Sensor 5TE differs from EC-5 as it not only measures soil-water content but also soil temperature. At each microsite, one 5TE sensor was placed vertically at 5 cm depth and three EC-5 sensors were placed vertically at 15, 25 and 35 cm depth. The weather station and the capitance sensors were connected to EM50 data loggers (Decagon Devices, Pullman, WA, USA). Meteorological data (solar radiation, air temperature and humidity, wind speed and precipitation) at both weather stations and soil-moisture data were recorded on an hourly basis from 16 December 2012 until 31 May 2014. Rainfall data were presented as daily total values whereas the other meteorological data and soil-moisture data as daily mean values.

Table 7.1 Technical equipment information of the weather stations outside and underneath a single *Acacia raddiana* tree

	outside canopy	underneath canopy
pyranometer	CS300 (height: 185 cm)	40006 PYR (height: 165 cm)
relative humidity and temperature sensor	CS215 (height: 115 cm)	PASS-RHT (height: 160 cm)
cup anemometer	R M Young Wind Sentry (height: 210 cm)	40030 (height: 195 cm)
rain gauge	ARG100 (funnel diameter: 25.4 cm) (height: 125 cm)	ECRN-100 (funnel diameter: 17.5 cm) (height: 125 cm)

The growing season for the herbaceous cover in a Mediterranean climate lasts eight months and is defined from October till May (Merou and Papanastasis, 2009; Paço *et al.*, 2009). Hence, the monitoring period in our study contains two growing seasons, i.e. an incomplete growing season *gs2013* (from 16 December 2012 until 31 May 2013) and a complete growing season *gs2014* (from 1 October 2013 until 31 May 2014). To compare these two growing seasons, two equal periods were determined and referred to as *spring2013* (from 15 February 2013 till 15 May 2013) and *spring2014* (from 15 February 2014 till 15 May 2014).

Monthly rainfall and average daily air temperature from September until August for two successive periods 2012/2013 and 2013/2014, recorded at the weather station outside the canopy, are given in Figure 7.2. The rainy season lasts four months from September until December. Rainfall during this period amounted to 38.2 and 117 mm respectively for 2012/2013 and 2013/2014. Monthly temperature was lowest just after the rainy season (January and February) and highest in the dry season (July and August) for both 2012/2013 and 2013/2014.

To classify *gs2013* and *gs2014* in wet, normal or dry growing seasons, the total rainfall during eight months (October-May) in Bou Hedma National Park was analyzed from 1995 to 2014, containing nineteen growing seasons, with the RAINBOW software (Raes *et al.*, 1996, 2006). The rainfall data from the weather station outside the canopy were used. The statistical tests in RAINBOW revealed that the square roots of total rainfall during the growing season are normally distributed. By means of a frequency analysis the total rainfall that can be expected with various probabilities of exceedance in this eight-month period was estimated. When compared with the long term rainfall of the October-May period, *gs2013* can be considered as dry (probability of exceedance of more than 80%), and *gs2014* as normal (probability of exceedance between 40 and 60%).

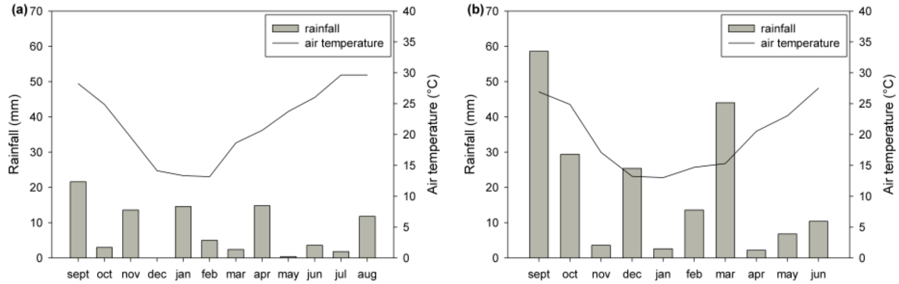

Figure 7.2 Monthly rainfall and average daily air temperature in Bou Hedma National Park for period (a) 2012/2013 and (b) 2013/2014

As ECH_2O sensors of the same type perform very similarly (Cobos and Chambers, 2010), the soil-specific calibration was only performed using one sensor and applied to the other sensors. Based on an evaporation experiment in which a saturated soil column containing soil from the study site at observed BD was saturated and allowed to evaporate, during which its weight was continuously monitored on an automatic balance (with 0.1 g precision) and water content recorded simultaneously with a probe, a calibration curve was established. A high correlation was found ($R^2 = 0.99$) and a zero intercept correction was made by subtracting 0.04 $cm^3\ cm^{-3}$ from the sensor measured soil-water data.

7.2.5 Numerical modelling

Hydrus-1D software (Šimůnek *et al.*, 2008) was used to examine the effect of a single *A. raddiana* tree on the near-surface soil-water balance of the top 40 cm along a gradient from underneath to outside the canopy. We assumed no lateral flow between the microsites. Hydrus-1D numerically solves Richards' equation for variable saturated porous media in one-dimension:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial h}{\partial z} - K(\theta)\right] - S(z,t) \qquad (12)$$

where θ is the volumetric water content ($cm^3\ cm^{-3}$), t is time (d), z is the radial and vertical space coordinate taken positive upward (cm), K is the hydraulic conductivity ($cm\ d^{-1}$), h is the pressure head (cm), and S represents a sink term related to plant water uptake ($cm^3\ cm^{-3}\ d^{-1}$).

Since it was observed that LCD trees did not had superficial roots above 40 cm, no water uptake by the tree from the top 40 cm soil was assumed. The model of Feddes *et al.* (1978) was used for root water uptake by the herbaceous layer assuming no occurrence of solute stress. The rooting depth was assumed to linearly increase from 0 cm in October to a maximum of 30 cm in February for all five microsites. For the root water uptake parameters, values for grass as suggested by Taylor and Ashcroft (1972) were used.

With Hydrus-1D change in soil-water storage in the rootzone is taken into account by the soil-water balance approach:

$$\Delta SWC = P - ET_a - R - D_d \qquad (13)$$

where ΔSWC is the change in total soil-water storage in the top 40 cm, P is rainfall, ET_a is the actual evapotranspiration, R is runoff, and D_d is deep drainage out of the soil profile. All units are in length (i.e., mm of water).

Hydrus-1D uses the parametric models of van Genuchten (1980) for the $\theta(\psi)$ relation and of Mualem (1976) for the $K(\psi)$ relation, called the Mualem-van Genuchten (MVG) model. No air entry value and hysteresis were assumed and the pore-connectivity parameter of MVG model was set at 0.5. The soil to a depth of 40 cm was simulated by means of a single layer soil profile consisting of hydraulic properties derived from the soil-water retention curve and infiltration measurements.

The lower boundary was specified as a free-drainage condition, which is appropriate as the soil-water table at the study site is far below the investigated soil layer. The upper boundary is controlled by prescribed atmospheric conditions. The upper boundary was generated using meteorological data averaged on a daily basis. For microsites M1 and M2 meteorological data (solar radiation, air temperature and humidity and wind speed) were taken from the weather station underneath the canopy, whereas for microsites M3, M4 and M5 the weather station outside the canopy was used.

The potential evapotranspiration (ET_p) for the reference crop was calculated using the FAO Penman-Monteith equation (Allen *et al.*, 1998). To obtain the potential evapotranspiration of the herbaceous layer (ET_c), a mid-season stage crop factor of 0.9 for pasture with rotated grazing (Allen *et al.*, 1998) was considered and multiplied by ET_p.

Tree canopies intercept a substantial proportion of the rainfall which is either evaporated (interception loss) or reaches the ground as stemflow (concentrating water at the stem basis) or throughfall (Ward and Robinson, 2000). Many studies reported rainfall interception loss totals in wooded ecosystems between 10 and 40% of the annual gross rainfall (Cui and Jia, 2014). The rainfall gauge underneath the canopy of the single *A. raddiana* tree was used for all five microsites considering a rainfall interception loss of 10% under the canopy to calculate the corresponding rainfall amount at microsites M3 to M5.

Actual evapotranspiration was simulated using Hydrus-1D based on precipitation and potential evapotranspiration of the herbaceous layer (ET_c). The latter was partitioned in potential evaporation and potential transpiration based on data of the plant cover fraction following AquaCrop (Raes *et al.*, 2009). Plant cover fraction data on the herbaceous layer for the different growth stages, both underneath and outside the canopy of *A. raddiana* trees in Bou Hedma National Park, are given in Table 7.2 for a dry and normal year based on observations of Abdallah *et al.* (2012).

Table 7.2 Plant cover fraction (%) of the herbaceous layer underneath (UC) and outside (OC) the canopy of *A. raddiana* trees in Bou Hedma National Park based on observations of Abdallah *et al.* (2012)

	Initial stage	Development stage			Mid-season stage	Late season stage
	October	November	December	January	February-April	May
Dry year						
UC	0.10	0.15	0.20	0.25	0.30	0.25
OC	0.01	0.03	0.05	0.07	0.10	0.07
Normal year						
UC	0.10	0.25	0.40	0.55	0.60	0.55
OC	0.10	0.20	0.30	0.40	0.50	0.40

For the application of Hydrus-1D, the soil profile was discretizised into 80 layers, each with a thickness of 0.5 cm. Four observation nodes were added to the soil profile at 5, 15, 25 and 35 cm depth to follow the simulated soil-water content. The initial soil-water content of the soil profile was set equal to the initial soil-water content measured by the capitance sensors. The observed soil moisture data for *gs2013* and *gs2014* were used to respectively calibrate, using the inverse modeling tool of Hydrus-1D, and validate the model.

7.2.6 Analysis of model performance

To compare simulated daily values of soil-water content with those observed by the soil moisture sensors for both growing seasons *gs2013* and *gs2014*, the following indices were used:

Nash-Sutcliffe index (Nash and Sutcliffe, 1970), NS:

$$NS = 1 - \frac{\sum_{i=1}^{N}(\theta_{sim} - \theta_{obs})^2}{\sum_{i=1}^{N}(\theta_{obs} - \theta_{obs-mean})^2} \tag{14}$$

coefficient of determination, R^2:

$$R^2 = \left(\frac{\sum_{i=1}^{N}(\theta_{obs} - \theta_{obs-mean})(\theta_{sim} - \theta_{sim-mean})}{\sqrt{\sum_{i=1}^{N}(\theta_{obs} - \theta_{obs-mean})^2 \sum_{i=1}^{N}(\theta_{sim} - \theta_{sim-mean})^2}}\right)^2 \tag{15}$$

and root mean square error, RMSE:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(\theta_{sim} - \theta_{obs})^2}{N}} \tag{16}$$

where θ_{sim} and θ_{obs} are simulated and observed water content, respectively; N is the number of data pairs for the investigated time period; and $\theta_{obs-mean}$ and $\theta_{sim-mean}$ represent the corresponding mean values. The NS index ranges between $-\infty$ and 1 and is considered satisfying when close to one. The coefficient of determination ranges from 0 to 1 and a value of 1 indicates a perfect fit between observed and simulated values. The absolute error measure RMSE should be close to zero for good model performance.

7.3 Results

7.3.1 Meteorological parameters

The rainfall underneath the canopy amounted to 42.2 and 66.4 mm for *spring2013* and *spring2014* respectively (Figure 7.3). The average daily soil temperature increased from 18.9 to 21.1 °C and from 17.8 to 21.0 °C respectively for *spring2013* and *spring2014* when going from microsite M1 to M5 and reached minimum and maximum values in January and August respectively (Figure 7.3).

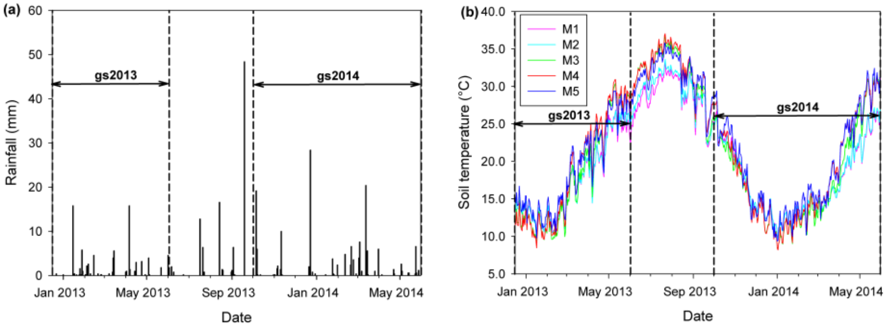

Figure 7.3 For a single *A. raddiana* tree (a) rainfall underneath the canopy and (b) soil temperature at microsite locations M1, M2, M3, M4 and M5 for the top 10 cm soil

The average daily potential evapotranspiration underneath and outside the canopy was 1.8 and 2.8 mm d^{-1} respectively for *spring2013* and 2.3 and 3.5 mm d^{-1} respectively for *spring2014* and reached minimum and maximum values in January and June respectively (Figure 7.4).

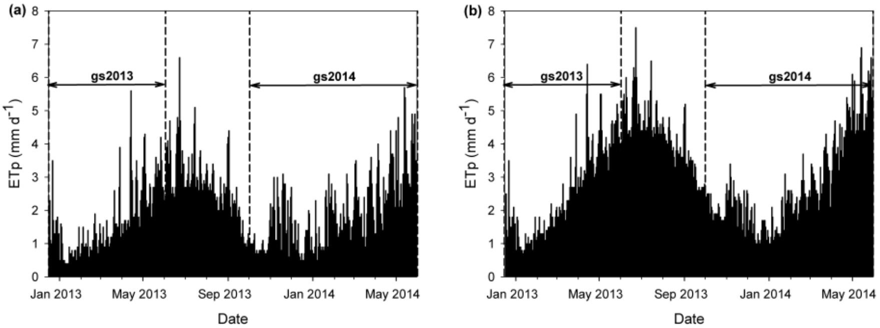

Figure 7.4 Potential evapotranspiration (ET_p) (a) underneath and (b) outside the canopy of a single *Acacia raddiana* tree

The average daily air temperature underneath and outside the canopy amounted to 18.7 and 19.5 °C respectively for *spring2013* and to 17.7 and 18.3 °C respectively for *spring2014*. The average daily relative humidity underneath and outside the canopy was 47.7 and 47.3% respectively for *spring2013* and 54.7 and 53.3 % respectively for *spring2014*. For solar radiation, average daily values underneath and outside the canopy were 57.7 and 171.3 W m^{-2} respectively for *spring2013* and 47.2 and 165.9 W m^{-2} respectively for *spring2014*.

7.3.2 Near-surface soil-water content

The Hydrus-1D model was used to simulate the near-surface soil-water content for microsites M1 to M5 along a gradient from underneath to outside the canopy for a single *A. raddiana* tree. Observed saturated hydraulic conductivities (K_S) at the soil surface and average values of the van Genuchten parameters θ_r, θ_S, α and n at 5, 15 and 25 cm depths were used as initial estimates for the MVG model of the top 40 cm soil (Table 7.3). Higher hydraulic conductivities and saturated water content at 5 and 15 cm depths were observed closer to the tree stem.

Table 7.3 Saturated hydraulic conductivities (K_S) at the soil surface and the van Genuchten parameters θ_r, θ_s, α and n for the top 40 cm soil along a gradient from underneath to outside the canopy for a single *Acacia raddiana* tree

		M1	M2	M3	M4	M5
K_S (cm d^{-1})		92.5	39.5	16.9	19.8	49.8
θ_r (cm^3 cm^{-3})	5 cm	0.10	0.07	0.08	0.06	0.08
	15 cm	0.06	0.09	0.07	0.08	0.08
	25 cm	0.09	0.08	0.09	0.08	0.08
	mean	0.08	0.08	0.08	0.07	0.08
θ_S (cm^3 cm^{-3})	5 cm	0.48	0.42	0.38	0.36	0.40
	15 cm	0.43	0.43	0.41	0.40	0.42
	25 cm	0.38	0.41	0.42	0.36	0.39
	mean	0.43	0.42	0.40	0.38	0.40
α (kPa^{-1})	5 cm	0.012	0.016	0.015	0.016	0.015
	15 cm	0.014	0.016	0.016	0.016	0.017
	25 cm	0.022	0.020	0.016	0.021	0.026
	Mean	0.016	0.017	0.016	0.018	0.019
n (-)	5 cm	2.14	1.83	1.93	1.74	1.98
	15 cm	2.15	1.97	2.40	1.91	1.91
	25 cm	1.70	1.74	1.85	1.70	1.64
	mean	2.00	1.85	2.06	1.79	1.84

θ_r: residual water content; θ_S: saturated water content; α and n: parameters of the van Genuchten model. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy.

The observed soil moisture data for *gs2013* were used to calibrate the model. Most sensitive MVG parameters, i.e. K_S and θ_S, were optimized during the inverse modeling procedure in Hydrus-1D whereas θ_r, α and n were kept fixed at their initial values. The initial values of the model input parameters were kept unchanged as no additional minimization of the error was found. Only the configuration of the root distribution was adjusted based on trial and error to calibrate the model. During calibration, model performance was evaluated and values of NS, R^2 and RMSE of the optimized model are given in Table 7.4. For the optimized model, the maximum rooting depth of the herbaceous layer was set at 30 cm for microsites M1 and M2, and at 25 cm for microsites M3, M4 and M5. In general, the model performed well for the top 20 cm soil. For microsites M2 and M5 at 15 cm depth, the observed values were consistently lower than the simulated values resulting in negative values for NS but still acceptable values for R^2 and RMSE. To validate the model the observed soil moisture data for *gs2014* were used and the corresponding model performance indices are given in Table 7.5.

Table 7.4 Performance criteria of calibrated model at depths of 5, 15, 25 and 35 cm along a gradient from underneath to outside the canopy for a single *Acacia raddiana* tree using soil moisture data from *gs2013*

		M1	M2	M3	M4	M5
NS	5 cm	0.58	-0.06	-0.08	0.24	-0.10
	15 cm	0.61	-1.56	0.28	0.53	(-)
	25 cm	0.08	-0.01	-4.10	-0.31	-21.89
	35 cm	-0.61	-0.21	-0.96	-7.81	(-)
R^2	5 cm	0.60	0.48	0.49	0.58	0.48
	15 cm	0.75	0.66	0.74	0.59	(-)
	25 cm	0.59	0.51	0.20	0.08	0.08
	35 cm	0.32	0.53	0.63	0.01	(-)
RMSE (cm^3 cm^{-3})	5 cm	0.021	0.023	0.022	0.020	0.019
	15 cm	0.023	0.024	0.015	0.017	0.036
	25 cm	0.031	0.011	0.014	0.016	0.024
	35 cm	0.029	0.005	0.007	0.014	0.014

NS: Nash-Sutcliff index; R^2: coefficient of determination; RMSE: root mean square error. (-): no value as dividing by zero. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy.

Table 7.5 Performance criteria of validated model at depths of 5, 15, 25 and 35 cm along a gradient from underneath to outside the canopy for a single *Acacia raddiana* tree using soil moisture data from *gs2014*

		M1	M2	M3	M4	M5
NS	5 cm	0.51	0.25	0.15	0.01	0.14
	15 cm	0.39	-2.48	-0.46	-1.28	-4.18
	25 cm	0.06	-1.00	0.51	-5.05	-18.08
	35 cm	-0.08	-6.16	-0.11	-0.75	(-)
R^2	5 cm	0.61	0.66	0.63	0.68	0.54
	15 cm	0.47	0.53	0.49	0.58	0.45
	25 cm	0.42	0.50	0.56	0.36	0.16
	35 cm	0.30	0.48	0.27	0.44	(-)
RMSE (cm^3 cm^{-3})	5 cm	0.028	0.025	0.029	0.026	0.026
	15 cm	0.034	0.050	0.034	0.038	0.045
	25 cm	0.048	0.026	0.023	0.046	0.049
	35 cm	0.041	0.039	0.039	0.023	0.074

NS: Nash-Sutcliff index; R^2: coefficient of determination; RMSE: root mean square error. (-): no value as dividing by zero. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy.

The model performed well for the top 20 cm soil. For microsites M2 and M5 at 15 cm, the observed values were consistently lower than the simulated values resulting in negative values for NS but still acceptable values for R^2 and RMSE. As observations of soil-water content were available at 5, 15, 25 and 35 cm soil depth for each microsite, the simulated values were displayed at the same depths for microsites M1 to M5 (Figure 7.5 to Figure 7.9). Both observed and simulated soil-water content are given as daily values.

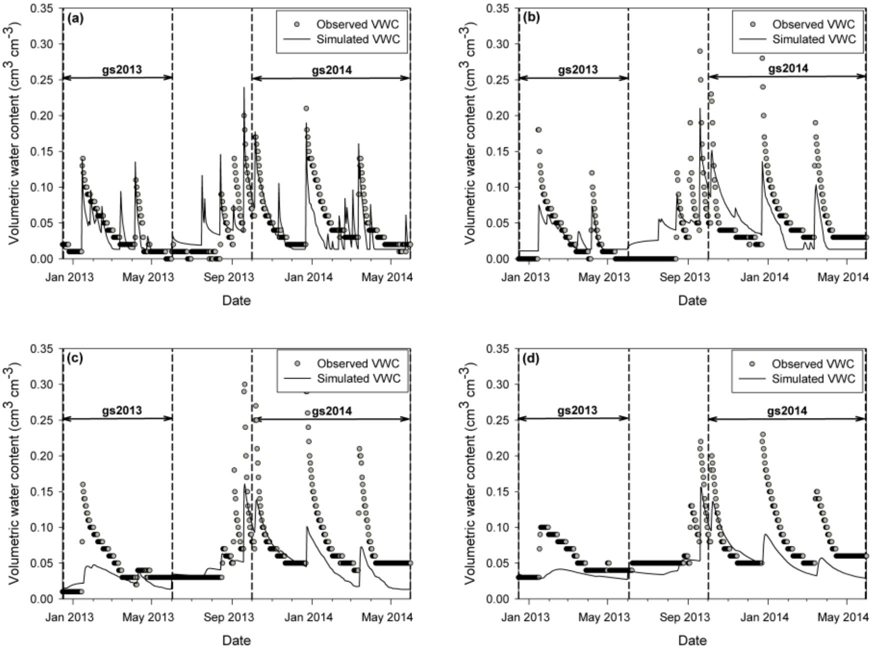

Figure 7.5 Observed and simulated volumetric water content (VWC) for microsite M1 at (a) 5 cm, (b) 15 cm, (c) 25 cm and (d) 35 cm depth for a single *Acacia raddiana* tree

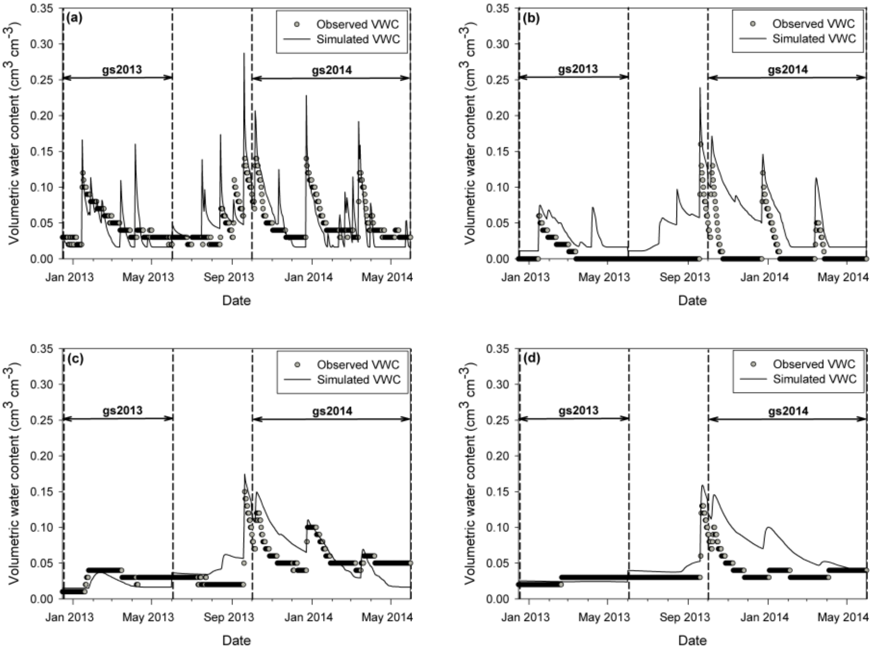

Figure 7.6 Observed and simulated volumetric water content (VWC) for microsite M2 at (a) 5 cm, (b) 15 cm, (c) 25 cm and (d) 35 cm depth for a single *Acacia raddiana* tree

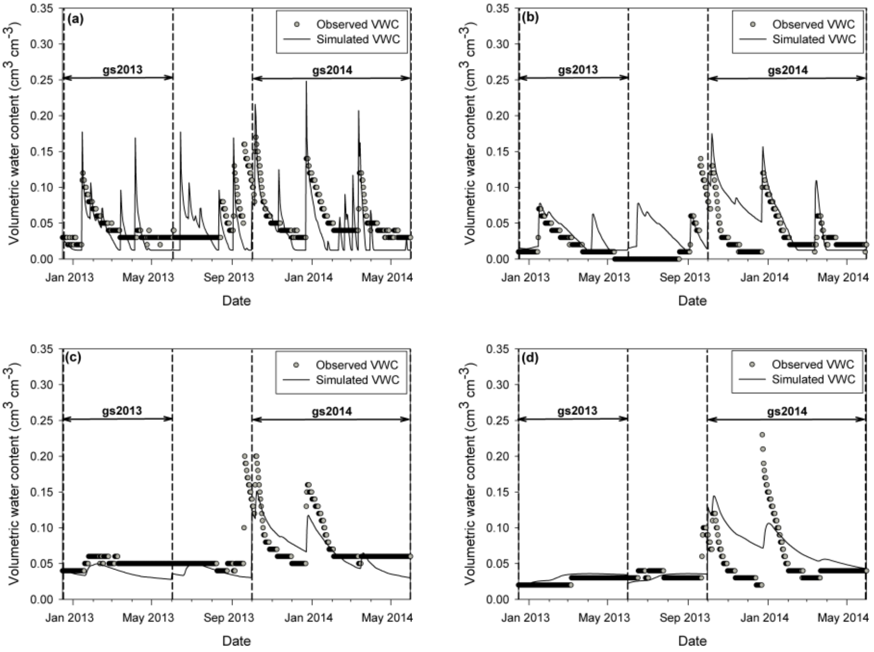

Figure 7.7 Observed and simulated volumetric water content (VWC) for microsite M3 at (a) 5 cm, (b) 15 cm, (c) 25 cm and (d) 35 cm depth for a single *Acacia raddiana* tree

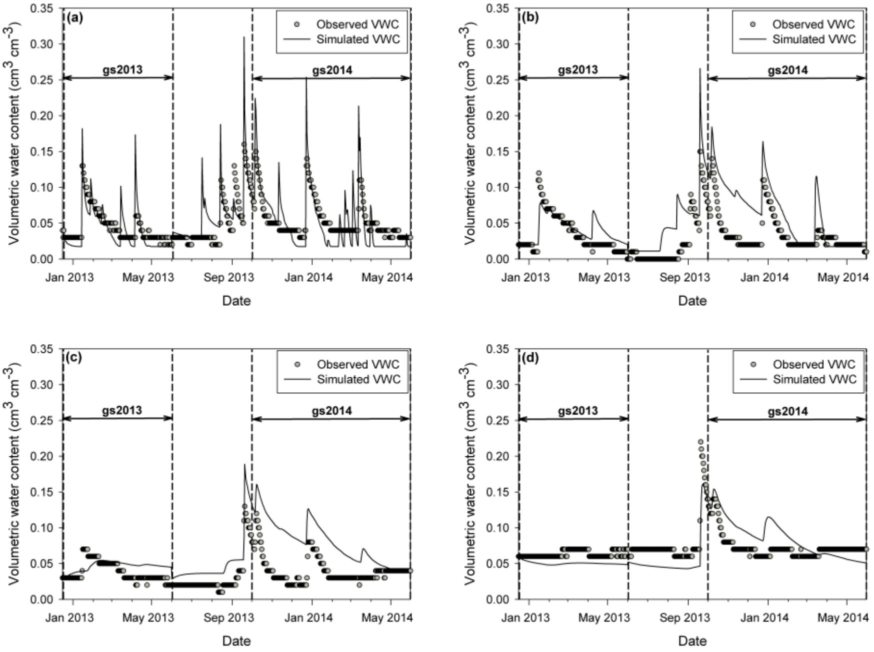

Figure 7.8 Observed and simulated volumetric water content (VWC) for microsite M4 at (a) 5 cm, (b) 15 cm, (c) 25 cm and (d) 35 cm depth for a single *Acacia raddiana* tree

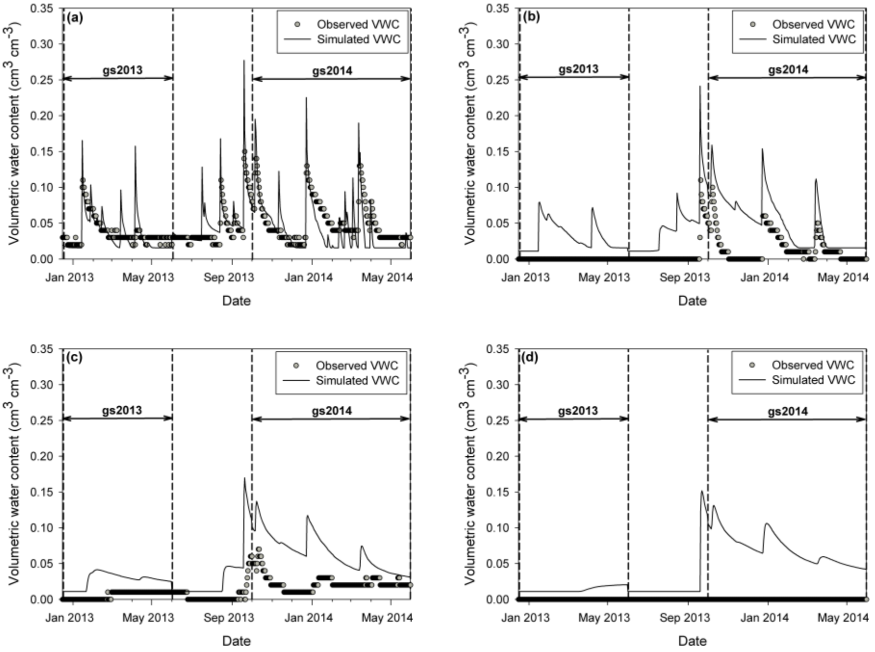

Figure 7.9 Observed and simulated volumetric water content (VWC) for microsite M5 at (a) 5 cm, (b) 15 cm, (c) 25 cm and (d) 35 cm depth for a single *Acacia raddiana* tree

The rainfall pattern in Figure 7.3 corresponded with the observed soil-water content at the five microsites. Some recorded rainfall events were not detected by the soil moisture sensors but were reflected in the simulated soil-water content (e.g. in March and November 2013 and March 2014). This might explain the negative values of NS for both *gs2013* and *gs2014*.

After a rainfall event, a higher soil-water content for a longer period available was found for microsites M1 to M4 compared to M5. After 15 January 2013 with a 18-mm rain for example, a higher soil-water content at 5 cm depth was observed for a period 1.5 to 2 times longer at microsites M4 to M1 compared to microsite M5 (58 to 74 vs. 39 days). The soil-water content decreased with increasing depth and a similar pattern was observed across the different soil layers. However, fluctuations in soil-water content were less pronounced with increasing depth.

In both the drier *gs2013* and the normal *gs2014*, observed soil-water content started to increase from August and reached a maximum by the end of October coinciding with the start of the growing season. Afterwards, the soil-water content decreased and reached a minimum by the end of December. From January, the soil-water content increased again with fluctuations depending on the rainfall pattern and reached a minimum by the end of May which is also the end of the growing season. Between May and August, the soil-water content stayed unchanged corresponding with the dry season.

Time series for cumulative precipitation and simulated transpiration, evaporation and evapotranspiration in relation to the simulated water content are also given for microsite M1 to M3 (Figure 7.10) and microsites M4 and M5 (Figure 7.11). The actual evapotranspiration is limited by the precipitation and in between growing seasons *gs2013* and *gs2014* there is no actual transpiration as no plant cover is present. The total amount of water evaporated from the soil during the observation period increased with increasing distance from the stem (from 19.0 cm at M1 to 24.2 cm at M5) while an opposite trend was found for transpiration (from 13.8 cm at M1 to 12.8 cm at M5). In accordance with the observed values, the simulated soil-water content decreased with increasing depth and a similar pattern was observed across the different soil layers.

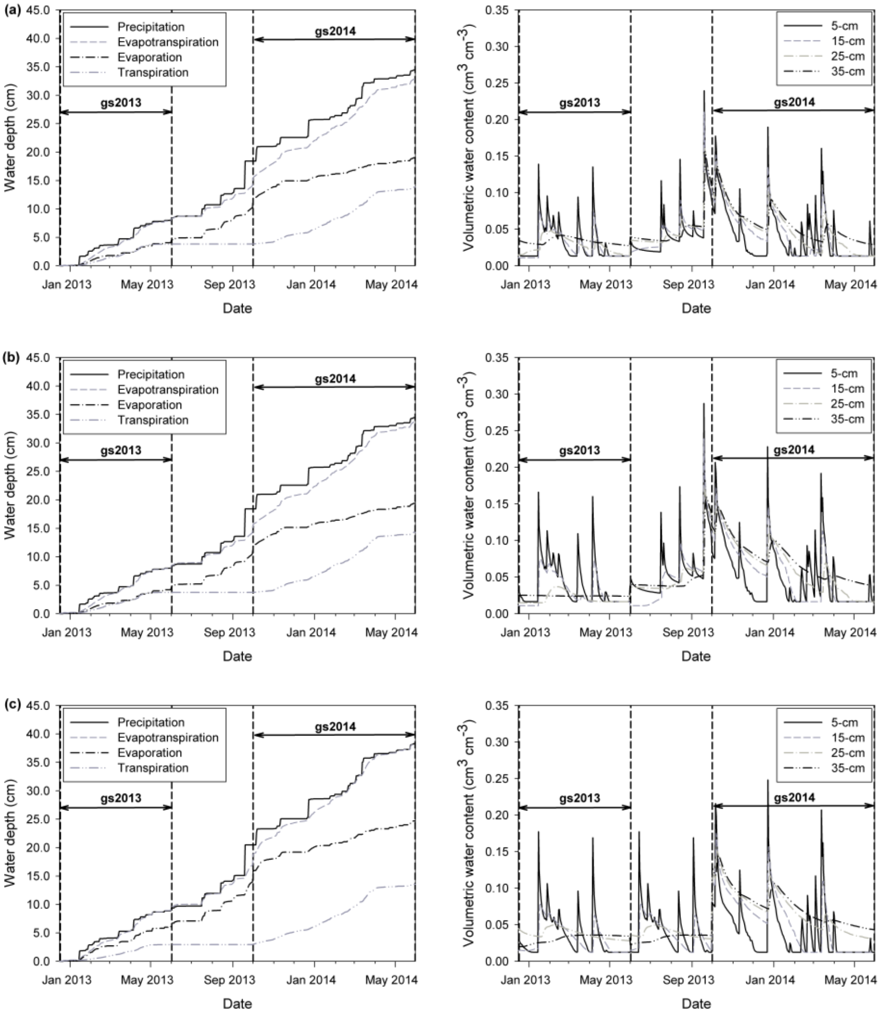

Figure 7.10 Cumulative precipitation and evapotranspiration, and simulated volumetric water content at 5 cm, 15 cm, 25 cm, and 35 cm depth for a single *Acacia raddiana* tree at (a) M1, (b) M2, and (c) M3

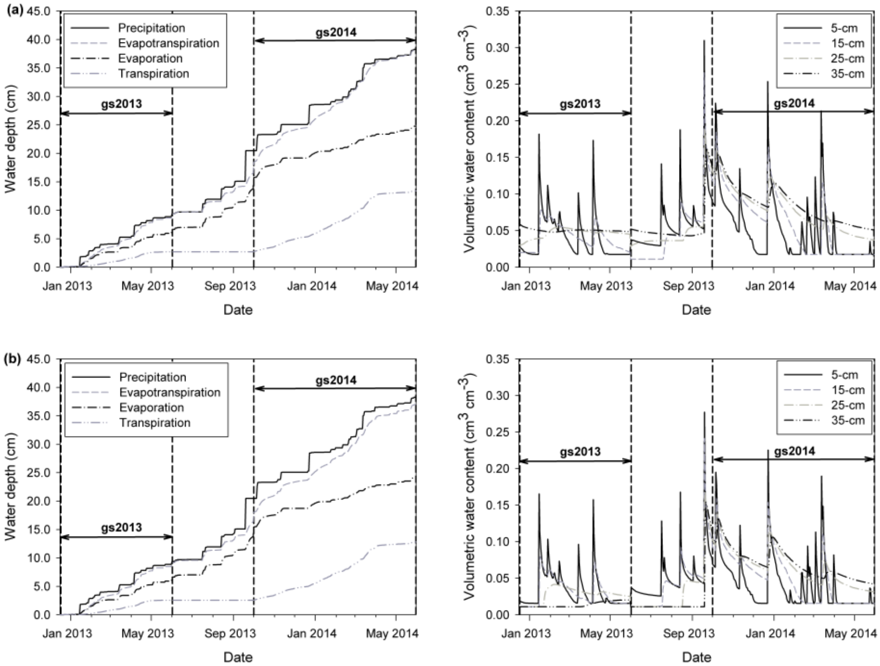

Figure 7.11 Cumulative precipitation and evapotranspiration, and simulated volumetric water content at 5 cm, 15 cm, 25 cm, and 35 cm depth for a single *Acacia raddiana* tree at (a) M4 and (b) M5

7.3.3 Near-surface soil-water balance

Hydrus-1D was used to determine the actual transpiration (T_a), the actual evaporation (E_a), actual evapotranspiration (ET_a) and deep drainage (D_d) at each microsite (Table 7.6).

Table 7.6 Soil-water balance from Hydrus-1D for *spring2013* and *spring2014* in the top 40 cm soil along a gradient from underneath to outside the canopy for a single *Acacia raddiana* tree

		SWC_0 (mm)	P (mm)	D_d (mm)	T_a (mm)	E_a (mm)	ET_a (mm)	T_a/ET_a
M1	*spring2013*	19.1	42.2	8.74×10^{-2}	28.7	23.5	52.2	0.55
	spring2014	10.5	66.4	2.65×10^{-1}	46.6	21.4	68.0	0.69
M2	*spring2013*	18.6	42.2	7.58×10^{-4}	27.6	24.6	52.2	0.53
	spring2014	15.2	66.4	1.18×10^{-1}	47.9	22.5	70.4	0.68
M3	*spring2013*	19.2	46.9	1.98×10^{-2}	23.2	33.2	56.4	0.41
	spring2014	16.3	73.8	3.80×10^{-1}	46.7	29.8	76.5	0.61
M4	*spring2013*	22.8	46.9	5.14×10^{-2}	21.3	32.9	54.2	0.39
	spring2014	19.6	73.8	2.56×10^{-1}	47.1	30.2	77.3	0.61
M5	*spring2013*	15.7	46.9	2.11×10^{-9}	20.8	33.0	53.8	0.39
	spring2014	15.6	73.8	2.46×10^{-1}	45.6	29.5	75.1	0.61

SWC_0: initial soil-water content; P: rainfall; D_d: deep drainage; T_a: actual transpiration; E_a: actual evaporation; ET_a: actual evapotranspiration. M1, M2, M3 and M4: microsites at respectively 25%, 75%, 125% and 175% of the canopy radius in the northern direction; M5: microsite at least 10 m away from the canopy. *spring2013*: from 15 February 2013 till 15 May 2013; *spring2014*: from 15 February 2014 till 15 May 2014.

No runoff (R) was assumed as the study site is laying within the flat area of Bou Hedma National Park. As *gs2013* is incomplete, two equal periods *spring2013* and *spring2014* were used to compare both growing seasons.

The initial total water content (SWC_0) in the top 40 cm at the start of *spring2013* ranged between 15.7 mm (microsite M5) and 22.8 mm (microsite M4). During *spring2013* the rainfall (P) amounted to 42.2 mm at microsites M1 and M2 and 46.9 mm at microsites M3, M4 and M5. Parameters SWC_0 and P form together the water input for the water balance model. The simulated actual transpiration underneath the canopy was higher compared to outside the canopy, whereas for the simulated actual evaporation the opposite was found. This was reflected in the higher values of T_a/ET_a underneath the canopy compared to outside the canopy.

Compared with *spring2013*, a higher water input was found for *spring2014*. SWC_0 at the start of *spring2014* ranged between 10.5 mm (microsite M1) and 19.6 mm (microsite M4), but the rainfall amounted to 66.4 mm at microsites M1 and M2 and to 73.8 mm at the other microsites. The actual transpiration underneath the canopy was not different from outside the canopy. For the actual evaporation, higher values outside compared with underneath the canopy were found. Contrary to *gs2013*, T_a/ET_a values underneath the canopy were not much higher compared to outside the canopy.

In comparison with the actual evapotranspiration, simulated deep drainage was rather low at all five microsites for both *spring2013* and *spring2014* (<0.4 mm).

7.4 Discussion

The area beneath the tree canopy received less solar radiation than outside the canopy for both *gs2013* and *gs2014*. In addition, the relative humidity was higher and both air and soil temperature were lower underneath compared with outside the canopy for both growing seasons. Many studies reported changes in microclimate involving a lower temperature and a higher relative humidity (Mistry, 2000; Akpo *et al.*, 2005) and receiving less near-ground solar radiation (Breshears *et al.*, 1997).

A difference in rooting depth was found between microsites underneath and outside the canopy in the calibrated model. The greater rooting depth underneath the canopy can be related to the higher abundance of drought-resistant perennial grass species with a more profound rooting system. In accordance, Abdallah *et al.* (2012) found more perennial grasses underneath compared to outside the canopy of scattered *A. raddiana* trees in Bou Hedma National Park.

A. raddiana can positively affect the water availability underneath and outside their canopy. The observed water content in the top 40 cm soil after rainfall events was higher and for longer periods available at microsites up to 175% of the canopy radius. This can be related to the improved near-surface soil physical and soil hydraulic properties, especially at 5 and 15 cm depth, in combination with a more favorable microclimate. The combined effect of larger rainfall infiltration at vegetated patches and slower evaporation due to shielding from solar radiation (Breshears *et al.*, 1998; Royer *et al.*, 2012) resulted in greater water availability underneath the canopy (Puigdefábregas, 2005), despite the higher interception of rain.

For all five microsites, the same pattern in soil-water content across the layers for the top 40 cm soil was found during the observation period. Hence, no redistribution of soil water was caused by hydraulic lift contrary to the study of Ludwig *et al.* (2003) for *Acacia tortilis* trees in an East African savanna (see section 3.5).

A. raddiana did not facilitate the actual transpiration of the herbaceous layer outside the canopy. This was mainly due to a less favourable microclimate outside the canopy resulting in more evaporative non-productive water loss. For *spring2013*, the ratio of actual transpiration over actual evapotranspiration was 30% higher underneath compared to outside the canopy. For *spring2014,* the difference in T_a/ET_a ratio between underneath and outside the canopy was minimal. In a year with a normal rainfall amount, as was *spring2014*, a similar T_a/ET_a ratio was found underneath compared to outside the canopy. In a dry year, a higher T_a/ET_a ratio underneath compared to outside the canopy was observed. When assuming a linear relation between transpiration and biomass production (Steduto *et al.*, 2009; Raes *et al.*, 2009), the effect of *A. raddiana* on rehabilitation is more pronounced in a drier year as compared to a normal one. This consistent with the stress-gradient hypothesis (Bertness and Callaway, 1994; Callaway *et al.*, 2002). In accordance, Abdallah and Chaieb (2010) found higher plant biomass and species diversity for the herbaceous layer below canopy of scattered *A. raddiana* trees in Bou Hedma National Park and this positive interaction increased with increased drought stress conditions.

With a more than double plant cover in a dry year (classified with the RAINBOW software; see section 7.2.4) (Abdallah *et al.*, 2012) and a T_a/ET_a ratio only of 30% higher, water was used more efficiently underneath compared to outside the canopy for *spring2013*. For *spring2014*, water was also used more efficiently underneath compared to outside the canopy but the difference was less pronounced. In other words, water productivity is higher underneath compared to outside the canopy as per unit biomass production less water was transpired. In accordance, Shanker *et al.* (2005) found for an agroforestry system that the overstory tree canopy played a significant role in reducing the fraction of rainfall/irrigation water transpired by the understory crop.

Moustakas *et al.* (2013) found for savanna ecosystems that tree effects on grass were facilitative in drier sites, with higher grass biomass underneath than outside the canopy whereas at wetter sites no differences in grass biomass were found. The productivity of the herbaceous layer in the vicinity of the canopy was also positively affected to a limited degree.

7.5 Conclusions

We documented here for a forest steppe in arid Tunisia, that a single *A. raddiana* tree improved the soil-water availability in the top 40 cm at microsites both underneath and outside the canopy up to 175% of the canopy radius. A similar pattern in soil-water content was found across the layers for the top 40 cm soil and hence no water redistribution caused by hydraulic lift occurred. In accordance with the stress-gradient hypothesis, the facilitative effect of *A. raddiana* on the productivity of the herbaceous layer was higher during a dry compared to a normal year as was reflected in the higher difference in T_a/ET_a ratio between underneath and outside the canopy.

A. raddiana can enhance the fraction of rainfall becoming beneficial, i.e. productive green-water, by improving the microclimatic conditions and the near-surface soil physical and hydraulic properties below canopy. In addition, tree shading reduced plant transpiration per unit biomass production resulting in a higher water use efficiency underneath compared to outside the canopy. Due to high evaporative losses, soil-water availability was strongly reduced and higher actual transpiration was only found below canopy. Nevertheless, ephemeral annuals can benefit from higher soil-water availability outside the canopy as they complete their life cycle during a short period. The facilitating role of scattered *A. raddiana* trees with regard to the productivity of the herbaceous layer is therefore not only limited to the area below canopy. Scattered *A. raddiana* trees can act as important central points of ecosystem recovery from which plant succession may radiate outwards into other parts of a given landscape.

Chapter 8. General conclusions and future research

8.1 General conclusions

The general objective of this study was to investigate the facilitating role of scattered *A. raddiana* trees on the productivity of the herbaceous ground vegetation by examining their impact on the soil physical, hydraulic and chemical properties as well as the water balance of the near-surface soil layer, where uptake of water and nutrients by herbaceous roots takes place. Thereby, a distance gradient (both horizontally and vertically) and the effect of tree age were taken into account. The specific objectives were to investigate the influence of scattered *A. raddiana* trees on:

- the near-surface soil hydraulic properties in function of tree age, and their link with the herbaceous vegetation;
- spatial patterns in near-surface soil physical and hydraulic properties in function of tree age;
- spatial patterns (both horizontally and vertically) in near-surface soil nutrient levels in function of tree age;
- the near-surface soil-water balance and the actual transpiration of the herbaceous vegetation.

The impact of scattered *A. raddiana* trees on the soil physical and hydraulic properties was more pronounced with increasing tree age. Significant changes in OM, BD, TP, hydraulic conductivities, soil-water content values at low matric suctions and matrix porosity were found (Chapter 4 and Chapter 5). In accordance, Greenwood and Buttle (2004) reported higher soil organic matter content and porosity with increasing forest plantation age. Higher loads of litter fall from trees with a larger crown diameter resulted in greater inputs of organic matter as was found by McElhinny *et al.* (2010). With regard to the soil chemical properties, increased values of total N, exchangeable K^+ and extractable P were found with increasing tree age (Chapter 6). In general, a significant impact on the soil physical, hydraulic and chemical properties was found for trees older than 75 years with a medium or large crown diameter.

Regarding the distance gradient, greatest differences in soil physical, hydraulic and chemical properties in the top 10 cm soil were found between the microsite closest to the tree stem and the other microsites. Significant changes in OM, TP, BD and soil-water content at saturation and near-saturation were observed with increasing distance from the tree stem (Chapter 5). Saturated and unsaturated hydraulic conductivities were highest closest to the tree stem and significantly decreased with longer distance from the stem in accordance with the soil physical properties (Chapter 5). Enhanced soil physical properties, i.e. significantly higher values for total porosity and significantly lower values for bulk density, were associated with elevated OM levels as was found by Shukla *et al.* (2006). In addition, soil quality indicators like matrix porosity, macroporosity and air capacity were significantly higher underneath than outside the canopy. The better structured soils underneath the canopy resulted in significantly higher saturated and unsaturated hydraulic conductivities and significantly higher values of soil-water retention. Several studies mentioned higher hydraulic conductivities below canopy (e.g., Wilcox *et al.*, 2003; Dunkerley, 2002). Saturated and near-saturated hydraulic conductivities were mainly driven by macropores and large matrix pores. Greenwood and Buttle (2004) suggested that increases in saturated hydraulic conductivities of reforested soils were related to greater macroporosity. With regard to the compass direction, differences in saturated hydraulic conductivities between the four directions were not consistent across tree age groups and were considered as site-specific variations. For the unsaturated hydraulic conductivities, no differences between the compass directions were observed (Chapter 5). Even though a higher abundance of vegetation was observed at the below-canopy northern side by Noumi *et al.* (2012), this was not reflected in the hydraulic properties. Significant decrease in levels of total N, exchangeable K^+ and extractable P with longer distance from the tree stem were found in accordance with other studies (e.g., Ludwig *et al.*, 2004; Belsky, 1994). Levels of OM, total N, K^+ and P also significantly decreased with increasing depth and higher levels were found up to a depth of 20 cm (Chapter 6). Several studies demonstrated highest nutrient levels at the soil surface which rapidly declined with depth (e.g., Schlesinger and Pilmanis, 1998). A close link between OM content and total N, K^+ and P was found similar to the study of Eldridge and Wong (2005). Input of OM from trees and vegetation cover can be considered as the main driver for changes in soil physical, hydraulic and chemical properties. Although enhanced soil physical, hydraulic and chemical properties were found up to 175% of the canopy radius, especially for the trees with a medium and large crown diameter, the differences were not significant outside the canopy (Chapter 4, Chapter 5, Chapter 6).

A spatial pattern in soil physical, hydraulic and chemical properties exists between canopy and open microsites. The impact of scattered *A. raddiana* trees on the soil-water balance of the rootzone of herbaceous vegetation was studied in an integrated way by considering the spatial pattern in soil hydraulic properties and differences in atmospheric forcing (Chapter 7). Soil-water availability improved both underneath and outside the canopy of *A. raddiana* up to 175% of the canopy radius as was reflected by higher water content after rainfall events available for longer periods. Greater water availability below canopy was also reported by Puigdefábregas (2005) and can be related to the improved near-surface soil physical and hydraulic properties, i.e. higher hydraulic conductivities and higher water retention, as reported in Chapter 4 and Chapter 5. In addition, a more favourable microclimate, i.e. higher relative humidity and lower air and soil temperature, was found below canopy similar to other studies (Mistry, 2000; Akpo *et al.*, 2005), reducing non-productive evaporative losses. The actual transpiration of the herbaceous vegetation was higher underneath compared to outside the canopy for both a dry and a normal year. Consistent with the stress-gradient hypothesis (Bertness and Callaway, 1994), the difference in actual transpiration was more pronounced during a dry year. In addition, water was used more efficiently below canopy as per unit biomass production less water was transpired. In accordance, Shanker *et al.* (2005) reported a reduced fraction of water transpired by the understory crop. Incorporating spatial patterns of soil hydraulic properties in hydrological models when applied on ecosystems with scattered trees provided useful information with regard to the extent of influence on water availability in the soil outside the canopy. However, the improved soil-water availability outside the canopy was strongly reduced due to higher evaporative water losses. Hence, the impact of *A. raddiana* on the actual transpiration of the herbaceous layer was mainly occurring underneath their canopy.

Scattered *A. raddiana* trees improve the near-surface soil physical, hydraulic and chemical properties mainly underneath their canopy. However, improved soil hydraulic properties were also found outside the canopy, especially for trees with a medium and large crown diameter, as was reflected in higher soil-water availability (Chapter 7). Due to high evaporative losses, soil-water availability was strongly reduced and higher actual transpiration was only found below canopy. Nevertheless, ephemeral annuals can benefit from higher soil-water availability outside the canopy as they complete their life cycle during a short period. The facilitating role of scattered *A. raddiana* trees with regard to the productivity of the herbaceous layer is therefore not only limited to the area below canopy. Scattered *A. raddiana* trees can act as important central points of ecosystem recovery from which plant succession may radiate outwards into other parts of a given landscape. They possess a valuable restoration potential especially in drier years when their impact on the productivity of the herbaceous layer was more pronounced. This study confirms the findings of Abdallah *et al.* (2008) and Noumi *et al.* (2012) who observed a significantly higher plant cover and productivity of the herbaceous vegetation below canopy in Bou Hedma National Park and this tree-plant interaction increased with more drought stress.

8.2 Future research

Ecological studies investigating the interaction between scattered *A. raddiana* trees and the herbaceous vegetation are mainly conducted in a binary way, i.e. at locations underneath and outside their canopy. To understand the impact of scattered trees on a field scale, spatial patterns in herbaceous vegetation needs to be investigated along a gradient from underneath to outside the canopy. Using GEOBIA (see Chapter 3), the spatial pattern in herbaceous vegetation around the canopy of scattered trees can be determined and linked to the findings in this dissertation on spatial patterns in soil physical, hydraulic and chemical properties. Validation can be carried out based on vegetation sampling along transects from underneath to outside the canopy of scattered trees. Information on the tree-plant interactions obtained on a field scale can be included in restoration strategies with regard to plant spacing between trees.

Our study indicates that scattered *A. raddiana* trees mainly affect the physical and hydraulic properties, and hence water availability, underneath and outside their canopy in the top 10 cm soil. Monitoring the spatial and temporal variability of near-surface soil moisture, based on remote sensing, can therefore provide valuable information in our understanding of the soil-vegetation-atmosphere interaction on a larger scale and the role of soil moisture in the vegetation dynamics of dryland ecosystems such as the Acacia forest steppe in central Tunisia. Moreover, studying spatial patterns in soil physical and hydraulic properties can be used as ground data to validate airborne observations.

In spite of the considerable variability and uncertainty in current climate change projections, there is now reasonable agreement that Africa is at the highest risk from climate change (IPCC, 2007). In this scope, hydrological models such as Hydrus-1D can be used to simulate the soil-water balance and the actual transpiration of the herbaceous vegetation based on different scenarios using historical weather data or future forecasts.

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References

Abdallah F, Chaieb M. 2010. Interactions of *Acacia raddiana* with herbaceous vegetation change with intensity of abiotic stress. *Flora* **205**: 738-744.

Abdallah F, Chaieb M. 2013. Interactions of *Acacia tortilis* (Forsk.) subpsp. *raddiana* (savi) with herbaceous vegetation in relation with tree size under North African presaharan region. *Pakistan Journal of Botany* **45**: 1715-1720.

Abdallah F, Noumi Z, Ouled-Belgacem A, Michalet R, Touzard B, Chaieb M. 2012. The influence of *Acacia tortilis* (Forssk.) ssp. *raddiana* (Savi) Brenan presence, grazing, and water availability along the growing season, on the understory herbaceous vegetation in southern Tunisia. *Journal of Arid Environments* **76**: 105-114.

Abdallah F, Noumi Z, Touzard B, Ouled Belgacem A, Neffati M, 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.

Abdallah F. 2010. Interaction entre la strate arborée et la strate herbacée sous bioclimat aride de la Tunisie: cas de la pseudo-savane d'*Acacia tortilis* (Forssk.) subsp. *raddiana* (savi) Brenan dans la région du Bou Hedma. Thèse de Doctorat, Faculté de Sciences, Sfax, Tunesie, 253 p.

Akpo LE, Goudiaby VA, Grouzis M, Le Houérou HN. 2005. Tree shade effects on soils and environmental factors in a savanna of Senegal. *West African Journal of Applied Ecology* **7**: 41-52.

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration - guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Food and Agricultural Organization, Rome, Italy.

Allington GRH, Valone TJ. 2014. Islands of Fertility: A Byproduct of Grazing? *Ecosystems* **17**: 127-141.

Aronson J, Floret C., LeFloc'h E., Ovalle C., Pontanier R. 1993. Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands. I. A view from the South. *Restoration Ecology* **1**: 8-17.

Arthur E, Cornelis WM, Vermang J, De Rocker E. 2011. Amending a loamy sand with three compost types: impact on soil quality. *Soil Use and Management* **27**: 116-123.

Asbjornsen H, Goldsmith GR, Alvarado-Barrientos MS, Rebel K, Van Osch FP, Rietkerk M, Chen J, Gotsch S, Tobón C, Geissert DR, Gómez-Tagle A, Vache K, Dawson TE. 2011. Ecohydrological advances and applications in plant-water relations research: a review. *Journal of Plant Ecology* **4**: 3-22.

Barnard RO, Fölscher WJ. 1972. The relationship between soil-pH and exchangeable cations. *Agrochemophysica* **4**: 53-56.

Barnes P, Wilson BR, Reid N, Koen TB, Lockwood P, Lamb DW. 2011. Litterfall and associated nutrient pools extend beyond the canopy of scattered eucalyptus trees in temperate pastures. *Plant and Soil* **345**: 339-352.

Batjes NH. 2010. Soil property estimates for Tunisia derived from SOTER and WISE (SOTWIS-Tunisia, ver. 1.0). Report 2010/01. ISRIC - World Soil Information, Wageningen, the Netherlands, 41 p.

Bedford DR, Small EE. 2008. Spatial patterns of ecohydrologic properties on a hillslope-alluvial fan transect, central New Mexico. *Catena* **73**: 34-48.

Belsky A, Amundson R, Duxbury J, Riha S, Ali A, Mwonga S. 1989. The effects of trees on their physical, chemical and biological environments in a semi-arid savanna in Kenya. *Journal of Applied Ecology* **26**: 1005-1024.

Belsky AJ, Canham CD. 1994. Forest gaps and isolated savanna trees: an application of patch dynamics in two ecosystems. *BioScience* **44**: 77-84.

Belsky AJ, Mwonga SM, Amundson RG, Duxbury JM, Ali AR. 1993. Comparative effects of isolated trees on their understorey environments in high- and low-rainfall savannas. *Journal of Applied Ecology* **30**: 143-155.

Belsky AJ. 1994. Influences of trees on savanna productivity: tests of shade, nutrients, and tree-grass competition. *Ecology* **75**: 922-932.

Bensaid S, Lynda AM, Badria E. 1996. Evolution spatio-temporelle des peuplements d'*Acacia tortilis* (Forsk.) Hayne *raddiana* (Savi) Brenan dans les monts Ougarta (Sahara nord-occidental). *Sécheresse* **7**: 173-178.

Bernhard-Reversat F. 1982. Biogeochemical cycles of nitrogen in a semi-arid savanna. *Oikos* **38**: 321-332.

Bertness MD, Callaway RM. 1994. Positive interactions in communities. *Trends in Ecology & Evolution* **9**: 191-193.

Bhark EW, Small EE. 2003. Association between plant canopies and the spatial patterns of infiltration in shrubland and grassland of the Chihuahuan Desert, New Mexico. *Ecosystems* **6**: 185-196.

Bond WJ, Midgley GF, Woodward FI. 2003. The importance of low atmospheric CO_2 and fire in promoting the spread of grasslands and savannas. *Global Change Biology* **9**: 973-982.

Booth CA, King GW, Sanchez-Bayo F. 1996. Establishment of woody weeds in western New South Wales: 1. Seedling emergence and phenology. *Rangeland Journal* **18**: 58-79.

Breckle SW. 2002. Walter's Vegetation of the Earth. Springer-Verlag: Berlin, Germany.

Brenan JPM. 1983. Manual on taxonomy of Acacia species. Present taxonomy of four species of Acacia (*A. albida, A. senegal, A. nilotica, A. tortilis).* FAO, Rome, Italy, 47 p.

Breshears DD, Nyhan JW, Heil CE, Wilcox BP. 1998. Effects of woody plants on microclimate in a semiarid woodland: soil temperature and evaporation in canopy and intercanopy patches. *International Journal of Plant Science* **159**: 1010-1017.

Breshears DD, Rich PM, Barnes FJ, Campbell K. 1997. Overstory-imposed heterogeneity in solar radiation and soil moisture in a semiarid woodland. *Ecological Applications* **7**: 1201-1215.

Bridgewater P, Higgs ES, Hobbs RJ, Jackson ST. 2011. Engaging with novel ecosystems. *Frontiers in Ecology and the Environment* **9:** 423-423.

Brooker RW, Callaghan TV. 1998. The balance between positive and negative plant interactions and its relationship to environmental gradients: a model. *Oikos* **81**: 196-207.

Buckingham K. 2014. The difference one tree can make. Devex, 28 July 2014.

Caldwell MM, Dawson TE, Richards JH. 1998. Hydraulic lift: consequences of water efflux for the roots of plants. *Oecologia* **113**: 151-161.

Caldwell MM, Richards JH. 1989. Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. *Oecologia* **79**: 1-5.

Caldwell TG, Young MH, Zhu JT, McDonald EV. 2008. Spatial structure of hydraulic properties from canopy to interspace in the Mojave Desert. *Geophysical Research Letters* **35**: 6p.

Callaway RM, Brooker RW, Choler P, Kikvidze Z, Lortie CJ, Michalet R, Paolini L, Pugnaire FI, Newingham B, Aschehoug ET, Armas C, Kikodze D, Cook BJ. 2002. Positive interactions among alpine plants increase with stress. *Nature* **147**: 844-848.

Caron S. 2001. Suivi écologique de l'Oryx algazelle (*Oryx dammah*) dans le parc National de Bou-Hedma (Tunisie) et notes sur les autres Ongulés sahélo-Sahariens du parc. Travail de fin d'étude en vue de l'obtention du grade académique de Diplôme d'Etudes Supérieures Spécialisées. Université des Sciences et technologies de Lille, France.

Carsel RF, Parrish RS. 1988. Developing joint probability distributions of soil water retention characteristics. *Water Resources Research* **24**: 755-769.

Cobos DR, Chambers C. 2010. Calibrating ECH$_2$O Soil Moisture Sensors. Application note. Decagon Devices, Pullman, WA.

Cockroft B, Olsson KA. 1997. Case study of soil quality in southeastern Australia: management of structure for roots in duplex soils. *In:* Gregorich EG, Carter MR. (*Eds.*) Soil quality for crop production and ecosystem health. Developments in Soil Science, vol. 25. Elsevier, New York, USA, 339–350.

Cooke RU, Warren A, Goudie A. 1993. Desert Geomorphology. UCL Press, London, United Kingdom, 526 p.

Cornelis WM, 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.

Cortina J, Amat B, Castillo V, Fuentes D, Maestre FT, Padilla FM, Rojo L. 2011. The restoration of vegetation cover in the semi-arid Iberian southeast. *Journal of Arid Environments* **75**: 1377-1384.

Cortina J, Maestre FT. 2005. Plant effects on soils in drylands. Implications for community dynamics and dryland restoration. *In*: Binkley D, Menyailo O. (*Eds.*) Tree Species Effects on Soils: Implications for Global Change. NATO Science Series, Kluwer Academic Publishers: Dordrecht, The Netherlands, 85-118.

Cottenie A, Verloo M, Kiekens L, Velghe G, Camerlynck R. 1982. Chemical analysis of plants and soils. IWONL, Brussels, Belgium.

Cui Y., Jia L. 2014. A modified gash model for estimating rainfall interception loss of forest using remote sensing observations at regional scale. *Water* **6**: 993-1012.

D'Odorico P, Okin G, Bestelmeyer BT. 2012. A synthetic review of feedbacks and drivers of shrub encroachment in arid grasslands. *Ecohydrology* **5**: 520-530.

Daryanto S, Eldridge DJ, Wang L. 2013. Spatial patterns of infiltration vary with disturbance in a shrub-encroached woodland. *Geomorphology* **194**: 57-64.

Daryanto S, Eldridge DJ. 2012. Shrub hummocks as foci for small animal disturbances in an encroached shrubland. *Journal of Arid Environments* **80**: 35-39.

Dawson TE. 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. *Oecologia* **95**: 565-574.

de Witt NMM, McQueen DJ. 1992. Compactibility of materials for land rehabilitation. DSIR Land Resources Scientific Report 7.

Dean WRJ, Milton SJ, Jeltsch F. 1999. Large trees, fertile islands, and birds in arid savanna. *Journal of Arid Environments* **41**: 61-78.

Deans JD, Diagne O, Lindley DK, Dione M, Parkinson JA. 1999. Nutrient and organic-matter accumulation in *Acacia senegal* fallows over 18 years. *Forest Ecology and Management* **124**: 153-167.

Deans JD, Edmunds WM, Lindley DK, Gaye CB, Dreyfus B, Nizinski J, Neyra M, Munro RC, Ingleby K. 2005. Nitrogen in interstitial waters in the Sahel: natural baseline, pollutant or resource? *Plant and Soil* **271**: 47-62.

Delaplace K. 2010. Monotemporal assessment of amount of *Acacia*'s (individuals, tree groups) and estimation of crown diameter classes of *Acacia raddiana* in Bou-Hedma National Park, Tunisia. Master thesis, Ghent University, Belgium, 96 p.

Direction Générale des Forêts. 2005. Plan d'aménagement et de gestion du Parc National de Bou Hedma et sa périphérie. Répartition de sous-zones. Ministère de l'agriculture et des ressources hydrauliques. République Tunisienne.

Do FC, Rocheteau A, Diagne AL, Goudiaby V, Granier A, Lhomme JP. 2008. Stable annual pattern of water use by *Acacia tortilis* in Sahelian Africa. *Tree Physiology* **28**: 95-104.

Dohn J, Dembélé F, Karembé M, Moustakas A, Amévor KA, Hanan NP. 2013. Tree effects on grass growth in savannas: competition, facilitation and the stress-gradient hypothesis. *Journal of Ecology* **101**: 202-209.

Dregne HE. 1976. Soils of arid regions. Elsevier, Amsterdam, The Netherlands.

Drenovsky RE, Richards JH. 2004. Critical N:P values: Predicting nutrient deficiencies in desert shrublands. *Plant and Soil* **259**: 59-69.

Dunkerley D. 2013. Stemflow on the woody parts of plants: dependence on rainfall intensity and event profile from laboratory simulations. *Hydrological Processes*, doi:10.1002/hyp.10050.

Dunkerley DL. 2000. Assessing the influence of shrubs and their interspaces on enhancing infiltration in arid Australian shrubland. *Rangeland Journal* **22**: 58-71.

Dunkerley DL. 2002. Infiltration rates and soil moisture in a groved mulga community near Alice Springs, arid central Australia: evidence for complex internal rainwater redistribution in a runoff–runon landscape. *Journal of Arid Environments* **51**: 199-219.

Dunn RR. 2000. Isolated trees as foci of diversity in active and fallow fields. *Biological Conservation* **95**: 317-321.

Dupuy N, Detrez C, Neyra M, De Lajudie P, Dreyfus B. 1991. Les Acacias fixateurs d'azote du Sahel. *La Recherche* **22**: 802-804.

Eagleson PJ. 1982. Ecological optimality in water limited natural soil-vegetation systems. *Water Resources Research* **18**: 325-340.

Eamus D, Cleverly J, Boulain N, Grant N, Faux R, Villalobo-Vega R. 2013. Carbon and water fluxes in an arid-zone *Acacia* savanna woodland: An analysis of seasonal patterns and responses to rainfall events. *Agricultural and Forest Meteorology* **182-183**: 225-238.

Eamus D, Prior L. 2001. Ecophysiology of trees of seasonally dry tropics: comparisons among phenologies. *Advances in Ecological Research* **32**: 113-197.

EC JRC. 2013. World Atlas of Desertification. Joint Research Centre, Ispra, Italy.

Eldridge D, Wong V. 2005. Clumped and isolated trees influence soil nutrient levels in an Australian temperate box woodland. *Plant and Soil* **270**: 331-342.

Eldridge DJ, Bowker MA, Maestre FT, Roger E, Reynolds JF, Whitford WG. 2011. Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis. *Ecology Letters* **14**: 709-722.

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

Emerman SH, Dawson TE. 1996. Hydraulic lift and its influence on the water content of the rhizosphere: an example from sugar maple, *Acer saccharum*. *Oecologia* **108**: 273-278.

European Soil Bureau Network/European Commission. 2005. Soil Atlas of Europe. Luxembourg, Office for Official Publications of the European Communities.

Facelli JM, Brock DJ. 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.

Falkenmark M. 1995. Coping with water scarcity under rapid population growth. Paper presented at Conference of SADC Ministers, Pretoria, South Africa, November 23-24, 1995.

FAO. 1989. Arid zone forestry: A guide for field technicians. *FAO Conservation Guide* **20**, Rome, Italy.

FAO. 1993. Soil tillage in Africa: needs and challenges. *FAO Soils Bulletin* **69**, Rome, Italy.

FAO. 2004. Carbon sequestration in dryland soils. *World Soils Resources Reports* **102**, Rome, Italy.

Feddes RA, Kowalik PJ, Zaradny H. 1978. Simulation of field water use and crop yield. *Simulation Monographs*, PUDOC, Wageningen, The Netherlands, 189 p.

Finney DJ. 1941. On the distribution of a variate whose logarithm is normally distributed. *Supplement Journal of the Royal Statistical Society* **7**: 155-161.

Floret C, Pontanier R. 1982. L'Aridité en Tunisie présaharienne. Travaux et Documents no. 150, ORSTOM, Paris, France, 544 p.

Fterich A, Mahdhi M, Mars M. 2012. Impact of grazing on soil microbial communities along a chronosequence of *Acacia tortilis* subsp. *raddiana* in arid soils in Tunisia. *European Journal of Soil Biology* **50**: 56-63.

Garba M, Cornelis WM, Steppe K. 2011. Effect of termite mound material on the physical properties of sandy soil and on the growth characteristics of tomato (*Solanum lycopersicum* L.) in semi-arid Niger. *Plant and Soil* **338**: 451-466.

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

Gee GW, Or D. 2002. Particle-size analysis. *In*: Dane JH, Topp GC. (*Eds.*) Methods of soil analysis. Part 4. Physical methods. SSSA Book Series 5, Soil Science Society of America: Madison, USA, 235-295.

Gillson L, Hoffman MT. 2007. Rangeland ecology in a changing world. *Science* **315**: 53-54.

Goodale CL, Davidson EA. 2002. Uncertain sinks in the shrubs. *Nature* **418**: 593-594.

Gowda JH, Albrectsen BR, Ball JP, Sjoberg M, Palo RT. 2003. Spines as a mechanical defence: the effects of fertiliser treatment on juvenile *Acacia tortilis* plants. *Acta Oecologica-International Journal of Ecology* **24**: 1-4.

Greene RSB. 1992. Soil physical properties of three geomorphic zones in a semi-arid mulga woodland. *Australian Journal of Soil Research* **30**: 55-69.

Greenwood WJ, Buttle JM. 2014. Effects of reforestation on near-surface saturated hydraulic conductivity in a managed forest landscape, southern Ontario, Canada. *Ecohydrology* **7**: 45-55.

Grossman RB, Reinsch TG. 2002. Bulk density and linear extensibility. *In*: Dane JH, Topp GC. (*Eds.*) Methods of Soil Analysis. Part 4. Physical methods. SSSA: Madison Wisconsin, USA, 201-228.

Grouzis M, Le Floc'h E. 2003. Un arbre au désert, *Acacia raddiana*. IRD Editions, Paris, France, 313 p.

Güsewell S. 2004. N:P ratios in terrestrial plants: variation and functional significance. *New Phytologist* **164**: 243-266.

Gutiérrez JL, Jones CG. 2006. Physical ecosystem engineers as agents of biogeochemical heterogeneity. *Bioscience* **56**: 227-236.

Hassan RM, Scholes R, Ash N. 2005. Ecosystems and human well-being: current state and trends: findings of the Condition and Trends Working Group. Island Press, USA.

Hay GJ, Castilla G. 2006. Object-based image analysis: Strengths, Weaknesses, Opportunities and Threats (SWOT). 1st International conference on object based image analysis (OBIA 2006), July 4-5, 2006, Salzburg University, Austria.

Higgins SI, Bond WJ, Trollope WSW. 2000. Fire, resprouting and variability: a recipe for grass-tree coexistence in savanna. *Journal of Ecology* **88**: 213-229.

Howard KSC, Edridge DJ, Soliveres S. 2012. Positive effects of shrubs on plant species diversity do not change along a gradient in grazing pressure in an arid shrubland. *Basic and Applied Ecology* **13**: 159-168.

IAASTD. 2009. Agriculture at Crossroads. Volume V: Sub-Saharan Africa. Island Press, Washington DC, USA.

IBRD/World Bank. 2010. Word Development Report 2010: Development and Climate Change. Washington D.C., USA.

IPCC. 2007. Summary for Policymakers: *In:* Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt MB, Tignor M, Miller HL (*Eds.*) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

IUSS Working Group WRB. 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome, Italy.

Jackson RB, Canadell J, Ehleringer JR, Mooney HA, Sala OE, Schulze ED. 1996. A global analysis of root distributions for terrestrial biomes. *Oecologia* **108**: 389-411.

Jones CG, Callaway RM. 2007. The third party. *Journal of Vegetation Science* **18**: 771-776.

Jury WA, Horton R. 2004. Soil Physics. Sixth Edition. John Wiley & Sons, Inc. Hoboken, New Jersey, USA.

Kakembo V, Ndlela S, Cammeraat E. 2012. Trends in vegetation patchiness loss and implications for landscape function: the case of *Pteronia incana* invasion in the Eastern Cape Province. Land Degradation & Development **23**: 548-556.

Kellman M. 1979. Soil enrichment by neotropical savanna trees. *Journal of Ecology* **67**: 565-577.

Kneitel JM, Chase JM. 2004. Trade-offs in community ecology: linking spatial scales and species coexistence. *Ecology Letters* **7**: 69-80.

Lajtha K, Schlesinger WH. 1986. Plant response to variations in nitrogen availability in a desert shrubland community. *Biogeochemistry* **2**: 29-37.

Lavauden L. 1927. Les forêts du Sahara (Extrait de la *Revue des Eaux et Forêts*). *Revue Eaux et Forêts*, Berger-Levrault, Nancy-Paris-Strasbourg, 26 p.

Lavauden L. 1928. La forêt de gommiers du bled talha (Sud-tunisien). *Revue des Eaux et Forêts* **66**: 699-713.

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*. IRD éditions, Paris, France, 21-58.

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

Le Houérou HN. 1968. La désertisation du Sahara septentrional et des steppes limitrophes (Libye, Tunisie, Algérie). Programme Biologique International, Section C.T., Colloque Hammamet, Tunisia. Unesco/Paris, 1968.

Lhote H. 1961. Au sujet de l'arbre du Ténéré. *Bulletin de liaison Saharienne* **12**: 49-54.

Li J, Okin G, Alvarez L, Epstein H. 2008. Effects of wind erosion on the spatial heterogeneity of soil nutrients in two desert grassland communities. *Biogeochemistry* **88**: 73-88.

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

Ludwig F, Dawson TE, Kroon H, Berendse F, Prins HHT. 2003. Hydraulic lift in *Acacia tortilis* trees on an East African savanna. *Oecologia* **134**: 293-300.

Ludwig F, de Kroon H, Berendse F, Prins HHT. 2004. The influence of savanna trees on nutrient, water and light availability and the understorey vegetation. *Plant Ecology* **170**: 93-105.

Ludwig F, de Kroon H, Prins HHT, Berendse F. 2001. Effects of nutrients and shade on tree-grass interactions in an East African savanna. *Journal of Vegetation Science* **12**: 579-588.

Lyford FP, Qashu HK. 1969. Infiltration rates as affected by desert vegetation. *Water Resources Research* **5**: 1373-1376.

Madsen MD, Chandler DG, Belnap J. 2008. Spatial gradients in ecohydrologic properties within a pinyon-juniper ecosystem. *Ecohydrology* **1**: 349-360.

Maes WH; Heuvelmans G, Muys B. 2009. Assessment of Land Use Impact on Water-Related Ecosystem Services Capturing the Integrated Terrrestrial-Aquatic System. *Environmental Science & Technology* **43**: 7324-7330.

Maestre FT, Bowker MA, Puche MD, Hijonosa MB, Martinez I, Garcia-Palacios P, Castillo AP, Soliveres S, Luzuriaga AL, Sanchez AM, Carreira JA, Gallardo A, Escudero A. 2009. Shrub encroachment can reverse desertification in semi-arid Mediterranean grasslands. *Ecology Letters* **12**: 930-941.

Maestre FT, Quero JL, Gotelli NJ, Escudero A, Ochoa V, Delgado-Baquerizo M, García-Gómez M, Bowker MA, Soliveres S, Escolar C, García Palacios P, Berdugo M, Valencia E, Gozalo B, Gallardo A, Aguilera L, Arredondo T, Blones J, Boeken B, Bran D, Conceicão AA, Cabrera O, Chaieb M, Derak M, Eldridge DJ, Espinosa CI, Florentino A, Gaitán J, Gatica M.G, Ghiloufi W, Gómez-González S, Gutiérrez JR, Hernández RM, Huang X, Huber-Sannwald E, Jankju M, Miriti M, Monerris J, Mau RL, Morici E, Naseri K, Ospina A, Polo V, Prina A, Pucheta E, Ramírez-Collantes DA, Romão R, Tighe M, Torres-Díaz C, Val J, Veiga JP, Wang D, Zaady E, 2012. Plant species richness and ecosystem multifunctionality in global drylands. *Science* **335**: 214-218.

Manning AD, Fischer J, Lindenmayer DB. 2006. Scattered trees are keystone structures – Implications for conservation. *Biological Conservation* **132**: 311-321.

Mapa RB. 1995. Effect of reforestation using *Tectona grandis* on infiltration and soil water retention. *Forest Ecology and Management* **77**: 119-125.

McElhinny C, Lowson C, Schneemann B, Pachón C. 2010. Variation in litter under individual tree crowns: Implications for scattered tree ecosystems. *Austral Ecology* **35**: 87-95.

Merou TP, Papanastasis VP. 2009. Factors affecting the establishment and growth of annual legumes in semi-arid mediterranean grasslands. *Plant Ecology* **201**: 491-500.

Middleton N. 2009. Deserts: A very short introduction. Oxford, Oxford University Press, United Kingdom.

Mihidjay AS. 1999. Étude de la morphogenèse d'*Acacia tortilis* (Forsk.) Hayne ssp. *raddiana* (Savi) Brenan et essais de régénération *in vitro*. Mémoire de diploma d'études approfondies en physiologie végétale. Université de Tunis II, Tunisia.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Desertification synthesis. World Resource Institute, Washington D.C., USA.

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

Moro MJ, Pugnaire FI, Haase P, Puigdefábregas J. 1997. Effect of the canopy of *Retama sphaerocarpa* on its understorey in a semiarid environment. *Functional Ecology* **11**: 425-431.

Morris JW, Bezuidenhout JJ, Furniss PR. 1982. Litter decomposition. *In*: Huntley BJ, Walker BH. (Eds.) Ecology of tropical savannas. Springer-Verlag: Berlin, Germany, 535-553.

Moustakas A, Kunin WE, Cameron TC, Sankaran M. 2013. Facilitation or competition? Tree effects on grass biomass across a precipitation gradient. *PLoS ONE* **8**, e57025.

Mualem Y. 1976. A new model predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research* **12**: 513-522.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models part I - a discussion of principles. *Journal of Hydrology* **10**: 282-290.

Nicholson SE. 2011. Dryland Climatology. Cambridge University Press, United Kingdom, 516 p.

Nizinski J, Morand D, Fournier C. 1992. Le rôle du couvert ligneux sur le bilan hydrique d'une steppe (Nord du Sénégal). *Cahiers ORSTOM*, *Série Pédologie* **27** : 225-236.

Noumi Z, Abdallah L, Touzard B, Chaieb M. 2012. *Acacia tortilis* (Forssk.) subsp. *raddiana* (Savi) Brenan as a foundation species: a test from the arid zone of Tunisia. *Rangeland Journal* **34**: 17-25.

Noumi Z, Chaieb M. 2012. Dynamics of *Acacia tortilis* (Forssk.) Hayne subsp. *raddiana* (Savi) Brenan in arid zones of Tunisia. *Acta Botanica Gallica* **159**: 121-126.

Noumi Z, Touzard B, Michalet R, Chaieb M. 2010. The effects of browsing on the structure of *Acacia tortilis* (Forssk.) Hayne ssp. *raddiana* (Savi) Brenan along a gradient of water availability in arid zones of Tunisia. *Journal of Arid Environments* **74**: 625-631.

Noumi Z. 2010. *Acacia tortilis* (Forssk.) subsp. *raddiana* (savi) Brenan en Tunisie pré-saharienne: structure du peuplement, réponses, et effets biologiques et environnementaux. Thèse de Doctorat, Faculté de Sciences, Sfax, Tunisie, 251 p.

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

Oba G, Post E, Syvertsen PO, Stenseth NC. 2000. Bush cover and range condition assessments in relation to landscape and grazing in southern Ethiopia. *Landscape Ecology* **15**: 535-546.

Olness A, Clapp CE, Liu R, Palazzo AJ. 1998. Biosolids and their effects on soil properties. *In:* Wallace A, Terry RE. (*Eds.*) Handbook of Soil Conditioners. Marcel Dekker, New York, USA, 141-165.

Olness A, Clapp CE, Liu R, Palazzo AJ. 1998. Biosolids and their effects on soil properties. *In:* Wallace A, Terry RE. (*Eds.*) Handbook of Soil Conditioners. Marcel Dekker, New York, USA, 141-165.

Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, D'Amico JA, Itoua I, Strand HE, Morrison JC, Colby JL, Allnutt TF, Ricketts TH, Kura Y, Lamoreux JF, Wettengel WW, Hedao P, Kassem KR. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. *BioScience* **51**: 933-938.

Ouarda HE, Walker DJ, Khouja ML, Correal E. 2009. Diversity analysis of *Acacia tortilis* (Forsk.) Hayne ssp *raddiana* (Savi) Brenan (Mimosaceae) using phenotypic traits, chromosome counting and DNA content approaches. *Genetic Resources and Crop Evolution* **56**: 1001-1010.

Paço TA, Teresa SD, Henriques MO, Pereira JS, Valente F, Banza J, Pereira FL, Pinto C, David JS. 2009. Evapotranspiration from a Mediterranean evergreen oak savannah: The role of trees and pasture. *Journal of Hydrology* **369**, doi:10.1016/j.jhydrol.2009.02.011.

Padilla FM, Pugnaire FI. 2006. The role of nurse plants in the restoration of degraded environments. *Frontiers in Ecology and the Environment* **4**: 196-202.

Parkin TB, Meisinger JJ, Starr JL, Chester ST, Robinson JA. 1988. Evaluation of statistical estimation methods for lognormally distributed variables. *Soil Science Society of America Journal* **52**: 323-329.

Parsons AJ, Abrahams AD, Simanton JR. 1992. Microtopography and soil-surface materials on semi-arid piedmont hillslopes, southern Arizona. *Journal of Arid Environments* **22**: 107-115.

Peel MC, Finlayson BL, McMahon TA. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* **11**: 1633-1644.

Potts DL, Scott RL, Bayram S, Carbonara J. 2010. Woody plants modulate the temporal dynamics of soil moisture in a semi-arid mesquite savanna. *Ecohydrology* **3**: 20-27.

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

Puigdefábregas J. 2005. The role of vegetation patterns in structuring runoff and sediment fluxes in drylands. *Earth Surface Processes and Landforms* **30**: 133-147.

Raes D, Mallants D, Song Z. 1996. RAINBOW-a software package for analysing hydrologic data. *In*: Blain WR. (*Ed*.) Hydraulic Engineering Software VI. Computational Mechanics Publications, Southampton, Boston, USA, 525-534.

Raes D, Steduto P, Hsiao TC, Fereres E. 2009. AquaCrop - The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal* **101**: 438-447.

Raes D, Willems P, Gbaguidi F. 2006. RAINBOW-a software package for analyzing data and testing the homogeneity of historical data sets. *In:* Proceedings of the Fourth International Workshop on 'Sustainable management of marginal drylands'. Islamabad, Pakistan, 27-31 January, 41-55.

Reid KD, Wilcox BP, Breshears DD, MacDonald L. 1999. Runoff and erosion in a piñon–juniper woodland: influence of vegetation patches. *Soil Science Society of American Journal* **63**: 1869-1879.

Reij C. 2012. Building on successes with regreening in the West African Sahel. Scaling up in agriculture, rural development and nutrition. International Food Policy Research Institute. *Focus* **19**, *Brief* **6**.

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.

Reynolds WD, Bowman BT, Brunke RR, Drury CF, Tan CS. 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. *Soil Science Society of America Journal* **64**: 478-484.

Richards JH, Caldwell MM. 1987. Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. *Oecologia* **73**: 486-489.

Richards LA. 1954. Diagnosis and Improvement of Saline and Alkali Soils, Handbook 60. U.S. Department of Agriculture, Washington, D.C., US, 160 p.

Richardson DM, Rejmánek M. 2011. Trees and shrubs as invasive alien species - a global review. *Diversity and Distributions* **17**: 788-809.

Richmond GS, Chinnock RJ. 1994. Seed germination of the Australian desert shrub *Eremophila* (Myoporaceae). Botanical Review **60**: 483-503.

Rockström J, Gordon L. 2001. Assessment of green water flows to sustain major biomes of the world: Implications for future ecohydrological landscape management. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* **26**: 843-851.

Rodriguez-Iturbe I, D'Odorico P, Porporato A, Ridolfi L. 1999. Tree–grass coexistence in savannas: the role of spatial dynamics and climate fluctuations. *Geophysical Research Letters* **26**: 247-250.

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

Roth CH, Prosser I, Post D, Gross J, Webb M. 2003. Reducing sediment and nutrient export from grazed land in the Burdekin Catchment for sustainable beef production. Final report to Meat and Livestock Australia. Prepared by CSIRO Land and Water, Townsville, Australia.

Royer PD, Breshears DD, Zou CB, Villegas JC, Cobb NS, Kurc SA. 2012. Density-dependent ecohydrological effects of Piñon-Juniper woody canopy cover on soil microclimate and potential soil evaporation. *Rangeland Ecology & Management* **65**: 11-20.

Rundel PW, Dickie IA, Richardson DM. 2014. Tree invasions into treeless areas: mechanisms and ecosystem processes. *Biological Invasions* **16**: 663-675.

Ryan PJ, McGarity JW. 1983. The nature and spatial variability of soil properties adjacent to large forest eucalypts. *Soil Science Society of America Journal* **47**: 286-292.

Safriel U, Adeel Z, Niemeijer D, Puigdefábregas J, White R, Lal R, Winslow M, Ziedler J, Prince S, Archer E, King C. 2005. Chapter 22: Dryland systems. *In*: Hassan R, Scholes R, Ash E (*Eds.*) Millennium Ecosystem Assessment Vol. 1. Ecosystems and human well-being: Current state and trends. World Resources Institute, Washington DC, USA, 623-662.

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

Sankaran M, Anderson TM. 2009. Management and restoration in African savannas: interactions and feedbacks. *In*: Hobbs RJ, Suding KN (*Eds.*) *New Models for Ecosystem Dynamics and Restoration*, pp. 136-155. Island Press, Washington DC, USA.

Sayer J, Kapos V, Mansourian S, Maginnis S. 2003. Forest landscape restoration: the role of forest restoration in achieving multifunctional landscapes. *In:* XII World Forestry Congress, Quebec City, Canada.

Schaaf T, Cardenas MR, Lee C. 2013. Innovative ways for a sustainable use of drylands: final report of the SUMAMAD project. UNESCO, Paris, France, 184 p.

Schlesinger WH, Abrahams AD, Parsons AJ, Wainwright J. 1999. Nutrient losses in runoff from grassland and shrubland habitats in Southern New Mexico: I. Rainfall simulation experiments. *Biogeochemistry* **45**: 21-34.

Schlesinger WH, Pilmanis AM. 1998. Plant-soil interactions in deserts. *Biogeochemistry* **42**: 169-187.

Scholes RJ, Archer SR. 1997. Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics* **28**: 517-544.

Scholes RJ. 1990. The influence of soil fertility on southern African Dry Savannas. *Journal of Biogeography* **17**: 415-419.

Shachak M, Boeken B, Groner E, Kadmon R, Lubin Y, Meron E, Ne'eman J, Perevolotsky A, Shkedy Y, Ungar ED. 2008. Woody species as landscape modulators and their effect on biodiversity patterns. *Bioscience* **58**: 209-221.

Shafer DS, Young MH, Zitzer SF, Caldwell TG, McDonald EV. 2007. Impacts of interrelated biotic and abiotic processes during the past 125 000 years of landscape evolution in the northern Mojave Desert, Nevada, USA. *Journal of Arid Environments* **69**: 633- 657.

Shanker AK, Newaj R, Rai P, Solanki KR, Kareemulla K, Tiwari R, Ajit. 2005. Microclimate modifications, growth and yield of intercrops under *Hardwickia binata* Roxb. based agroforestry system. *Archives of Agronomy and Soil Science* **51**: 281-290.

Shukla MK, Lal R, Ebinger M. 2006. Determining soil quality indicators by factor analysis. *Soil and Tillage Research* **87**: 194-204.

Šimůnek J, Šejna M, Saito H, Sakai M, van Genuchten MT. 2008. The Hydrus-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 4.0, Hydrus Series 3. Department of Environmental Sciences, University of California Riverside, Riverside, CA, USA.

Soil Survey Staff, 1999. Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys, 2nd ed. USDA, NRCS: Washington, DC.

Standish RJ, Cramer VA, Yates CJ. 2009. A revised state-and-transition model for the restoration of woodlands in Western Australia. *In*: Hobbs RJ, Suding KN (*Eds.*) *New Models for Ecosystem Dynamics and Restoration*, pp. 169-188. Island Press, Washington, DC.

Steduto P, Hsiao TC, Raes D, Fereres E. 2009. *Aquacrop* - The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal* **101**: 426-437.

Taylor SA, Ashcroft GM. 1972. Physical edaphology: The physics of irrigated and nonirrigated soils. W.H. Freeman, San Francisco, California, USA.

Thomas DS, Eamus D, Bell D. 1999. Optimization theory of stomatal behaviour—II. Stomatal responses of several tree species of north Australia to changes in light, soil and atmospheric water content and temperature. *Journal of Experimental Botany* **50**: 393-400.

Throop HL, Reichmann LG, Sala OE, Archer SR. 2012. Response of dominant grass and shrub species to water manipulation: an ecophysiological basis for shrub invasion in a Chihuahuan Desert Grassland. *Oecologia* **169**: 373-383.

Tiessen H, Menezes RSC, Salcedo IH, Wick B. 2003. Organic matter transformations and soil fertility in a treed pasture in semiarid NE Brazil. *Plant and Soil* **252**: 195-205.

Tirado R, Pugnaire FI. 2003. Shrub spatial aggregation and consequences for reproductive success. *Oecologia* **136**: 296-301.

Tobella AB, Reese H, Almaw A, Bayala J, Malmer A, Laudon H, Ilstedt U. 2014. The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. *Water Resources Research* **50**: 3342-3354.

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.

UNCCD. 1994. United Nations Convention on Combating Desertification: Part I: Introduction - Article 1: Use of terms. Bonn, Germany.

UNCCD. 2011. Land and soil in the context of a green economy for sustainable development, food security and poverty eradication. Submission of the UNCCD Secretariat to the Preparatory Process for the Rio+ 20 Conference, 18 November 2011.

UNCCD. 2012. Zero Net Land Degradation. A Sustainable Development Goal to Rio +20. Recommendations for policy makers, May 2012.

UNCCD/UNDP/UNEP. 2009. Climate change in the African drylands: options and opportunities for adaptation and mitigation. Bonn, Germany.

UNDP/UNCCD. 2011. The forgotten billion: MDG achievement in the drylands. New York, USA.

UNEP. 1992. World Atlas of Desertification. Edward Arnold, London, United Kingdom, 69 p.

UNEP. 2006. Africa Environment Outlook 2 - Our Environment, Our Wealth. UNEP, Nairobi, Kenya.

Van Auken OW. 2000. Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics* **31**: 197-215.

Van Auken OW. 2009. Causes and consequences of woody plant encroachment into western North American grasslands. *Journal of Environmental Management* **90**: 2931-2942.

van Genuchten MT, Leij FJ, Yates SR. 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, USA.

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

van Wijk MT, Rodriguez-Iturbe I. 2002. Tree–grass competition in space and time: insights from a simple cellular automata model based on ecohydrological dynamics. Water Resources Research, doi:10.1029/2001WR000768.

Vassal J. 2003. Introduction. *In:* Grouzis M, Le Floc'h E. (*Eds.*) Un arbre au désert. *Acacia raddiana*. IRD éditions, Paris, France, 13-17.

Verbist KMJ, Cornelis WM, Torfs S, Gabriels D. 2012. Comparing methods to determine hydraulic conductivities on stony soils. *Soil Science Society of America Journal* **77**: 25-42.

Vetaas OR. 1992. Micro-site effects of trees and shrubs in dry savannas. *Journal of Vegetation Science* **3**: 337-344.

Wahbi J. 2006. Régénération de l'*Acacia tortilis* ssp *raddiana* dans le parc national de Bou Hedma et son adaptation aux différentes contraintes abiotiques au stade de germination. Mémoire de mastère. Institut national agronomique de Tunisie.

Walkley A, Black IA. 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.

Wang L, Okin GS, Caylor KK, Macko SA. 2009. Spatial heterogeneity and sources of soil carbon in southern African savannas. *Geoderma* **149**: 402-408.

Ward RC, Robinson M. 2000. Principles of Hydrology, fourth ed. McGraw-Hill, Berkshire, United Kingdom, 450 p.

Warnock AD, Westbrooke ME, Florentine SK, Hurst CP. 2007. Does *Geijera parviflora* Lindl (Rutaceae) facilitate understorey species in semi-arid Australia? *Rangeland Journal* **29**: 207-216.

Warrick AW, Nielsen DR. 1980. Spatial variability for soil physical properties in the field. *In*: Hillel D. (*Ed.*) Applications of soil physics. Academic Press: Toronto, Canada, 319-344.

Weltzin JF, Coughenour MB. 1990. Savanna tree influences on understorey vegetation and soil nutrients in northwestern Kenya. *Journal of Vegetation Science* **3**: 337-344.

Whitford WG, Anderson J, Rice PM. 1997. Stemflow contribution to the 'fertile island' effect in creosotebush, *Larrea tridentata*. *Journal of Arid Environments* **35**: 451-457.

Wilcox BP, Breshears DD, Turin HJ. 2003. Hydraulic conductivity in a piñon–juniper woodland: influence of vegetation. *Soil Science Society of America Journal* **67**: 1243–1249.

Wilson B, Growns I, Lemon J. 2007. Scattered native trees and soil patterns in grazing land on the Northern Tablelands of New South Wales, Australia. *Australian Journal of Soil Research* **45**: 199-205.

Wilson B. 2002. Influence of scattered paddock trees on surface soil properties: a study of the Northern Tablelands of NSW. *Ecological Management & Restoration* **3**: 211-219.

Wooding RA. 1968. Steady infiltration from a shallow circular pond. *Water Resources Research* **4**: 1259-1261.

World Resources Institute. 2010. South Dakota State University, the IUCN and the Global Partnership on Forest Landscape Restoration. http://www.wri.org/resources/maps/global-map-forest-landscape-restoration-opportunities

Xu L, Baldocchi DD. 2003. Seasonal trend of photosynthetic parameters and stomatal conductance of blue oak (*Quercus douglasii*) under prolonged summer drought and high temperature. *Tree Physiology* **23:** 865-877.

Zaafouri MS, Zouaghi M, Akrimi N, Jeder H. 1996. La foret 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 aride. Jerba, 5-6-7 Décembre 1996, 258-271.

Curriculum Vitae

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Born on November 2, 1982 in Melle, Belgium.

Education

Ghent University

Master in Environmental sanitation	2006-2007
Master in Bioscience Engineering: soil and water management	2000-2005

Positions

Practical assistant at Ghent University, Belgium **Oct 2013-Sep 2014**

Assisting practical exercises Soil Physics and Land Information Systems.

Responsible for educational innovations.

Scientific assistant at Ghent University, Belgium **Oct 2010-Sep 2014**

PhD research on influence of scattered Acacia trees on topsoil physico-chemical properties and water balance in Bou Hedma National Park (central Tunisia).

Project on monitoring dust immission in an industrial setting in harbours of Ghent and Antwerp (Belgium) in corporation with SEA-invest and Stad Gent.

Scientific assistant at ILVO, Belgium **May 2010-Sep 2010**

Project on derogation permits in Flemish manure policy in corporation with Ghent University.

Core Organic EU project on stakeholder involvement in organic farming.

Scientific assistant at Ghent University, Belgium **Nov 2009-Dec 2009**

Responsible for in-situ measurements in Bou Hedma National Park (central Tunisia) in order to investigate the influence of Acacia trees on the below-canopy microclimate.

Scientific assistant at Ghent University, Belgium **Dec 2007-Oct 2009**

Flanders' Food project about improving the colour stability of meat from Belgian Blue double-muscled cattle.

Scientific assistant at Ghent University, Belgium Feb 2006-Jul 2006

Responsible for elaborating concentration maps of different heavy metals for industrial sites in Belgium with non-ferro activities in collaboration with the Public Waste Agency of Flanders and environmental consultant agencies.

Conferences

(Poster) EGU General Assembly, Vienna, Austria	May 2014
(Presentation) DesertLand, Ghent, Belgium	Jun 2013
(Presentation) UNCCD, 2nd Scientific conference, Bonn, Germany	Apr 2013
(Presentation) Young Soil Scientists Day, Brussels, Belgium	Feb 2013
(Poster) 4th International Congress EuroSoil, Bari, Italy	Jul 2012
(Presentation) 4th Conference on Desertif. and Land Degr., Ghent, Belgium	Jun 2012
(Organizer) 2nd ETS Field days, Ghent University, Belgium	Apr 2011
(Poster) ICoMST 2009, Copenhagen, Denmark	Aug 2009

International Training

Management Committee Meeting 4 COST Action ES1104, Valenzano, Italy	Sep 2013
Training 'STSM COST Action ES1104 WOCAT', Bern, Switzerland	Apr 2013
Course 'Merging measurements and modelling in soil physics', Aarhus, Denmark	Mar 2012

Publications

Articles - a1 - published

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2014. Influence of Acacia trees on near-surface soil hydraulic properties in arid Tunisia. *Land Degradation & Development*, doi:10.1002/ldr.2302.

Pastsart U, **De Boever M**, Claeys E, De Smet S. 2013. Effect of muscle and post-mortem rate of pH and temperature fall on antioxidant enzyme activities in beef. *Meat Science* **93**: 681-686.

Van Meirvenne M, Meklit T, Verstraete S, **De Boever M**, Tack F. 2007. Could shelling in the first World War have increased copper concentrations in the soil around Ypres? *European Journal of Soil Science* **59**: 372-379.

Articles - a1 - in process

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2014. Influence of scattered Acacia trees on soil nutrient levels in arid Tunisia. *Journal of Arid Environments*, *under revision*.

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2014. Spatial gradients in near-surface soil physical and hydraulic properties as affected by Acacia trees in arid Tunisia. *Ecohydrology*, *under revision*.

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2014. Influence of Acacia trees on near-surface soil-water balance in arid Tunisia. *Vadose Zone Journal*, *under revision*.

Books - b1

Van der Straeten B, **De Boever M**, Buysse J, Claeys D, Lauwers L, Van Huylenbroeck G. 2011. Derogatie in het Vlaamse mestbeleid. *Mededeling ILVO* **88**: Merelbeke, Belgium, 35 p.

Books - b2

Ouessar M, Sghaier M, **De Boever M**, Gabriels D. 2014. Watershed of Zeuss-Khoutine and Bou-Hedma Biosphere Reserve. *In*: Schaaf T, Cardenas MR, Lee C (Eds.) Innovative ways for a sustainable use of drylands: final report of the SUMAMAD project. UNESCO, Paris, France, 166-184.

Books - b3

De Boever M, Khlosi M, Delbecque N, De Pue J, Ryken N, Verdoodt A, Cornelis W, Gabriels D. 2013. Desertification and land degradation: processes and mitigation. Ghent University, UNESCO Chair of Eremology, Ghent, Belgium, 159 p.

Vermang J, Gabriels D, Cornelis W, **De Boever M.** 2011. Land degradation processes and assessment: wind erosion, interrill erosion, gully erosion, land cover features. Ghent University, UNESCO Chair of Eremology, Ghent, Belgium, 173 p.

Other publications - c1

De Boever M, Cornelis W, Ouessar M, Gabriels D. 2013. Influence of Acacia canopy cover on soil hydraulic properties in an arid zone of Tunisia. *In*: **De Boever M**, Khlosi M, Delbecque N, De Pue J, Ryken N, Verdoodt A, Cornelis W, Gabriels D (Eds.) Desertification

and land degradation: processes and mitigation. Ghent University, UNESCO Chair of Eremology, Ghent, Belgium, 94-104.

Youssef F, Visser SM, Karssenberg D, Erpul G, Cornelis W, Gabriels D, Poortinga A, **De Boever M.** 2012. The effect of vegetation patterns on Aeolian mass flux at regional scale: a wind tunnel study. *In*: Ringersma J and Stroosnijder L (Eds.) Agro Environ 2012. Wageningen, The Netherlands, 5 p.

Pastsart U, **De Boever M**, Lescouhier S, Claeys E, De Smet S. 2011. Effect of hot boning on colour stability and antioxidant enzyme activities in beef inner and outer biceps femoris. *In*: Meat Science and Technology, 57th International congress, Proceedings. Ghent, Belgium, 4 p.

Pastsart U, **De Boever M**, Claeys E, De Smet S. 2010. Effect of muscle and rate of pH and temperature fall on antioxidant enzyme activities in beef. *In*: ICoMST 2010: 56th International congress of meat science and technology. Jeju, Korea, 4 p.

De Boever M, Lescouhier S, De Smet S. 2009. Influence of post mortem glycolysis and cooling on colour and colour stability in different muscles of Belgian Blue beef. *In*: ICoMST 2009: 55th International congress of meat science and technology. Copenhagen, Denmark, 772-776.

Other publications - c3

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2014. Influence of Acacia trees on soil nutrient levels in arid lands. Geophysical Research Abstracts, EGU General Assembly, 28 April-5 May 2014, Vienna, Austria.

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2013. Effect of tree stand age on soil hydraulic properties in an arid zone of Tunisia. Young Soil Scientists Day, Book of abstracts, 20 February 2013, Brussels, Belgium.

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2013. Spatial gradient in soil hydraulic properties as influenced by Acacia trees in an arid zone of Tunisia. DesertLand , Abstracts, p. 73, 17-18 June 2013, Ghent, Belgium.

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2013. Acacia trees as keystone structures in the restoration of arid zones. UNCCD, 2nd Scientific conference, Abstracts, 9-12 April 2013, Bonn, Germany.

De Boever M, Gabriels D, Ouessar M, Cornelis W. 2012. Influence of Acacia plantations on the soil-water content in arid zones of Tunisia. Desertification and Land Degradation, 4th Conference, Book of abstracts, 25-26, 19 June 2012, Ghent, Belgium.

De Boever M, Gabriels D, Cornelis W. 2012. Acacia canopy effect on the water balance of an ecosystem in a semi-arid region of Tunisia. European Confederation of Soil Science Societies, 4th International congress, Abstracts, 2-6 July 2012, Bari, Italy.

De Smet S, **De Boever M**, Lescouhier S. 2010. Two-toned colour in the biceps femoris of Belgian Blue double-muscled cattle. ProSafeBeef 4th annual general assembly, Proceedings, p. 65, 5-7 October 2010, Aberystwyth, Wales, UK.