Journal of Arid Environments 122 (2015) 161–168

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Influence of scattered Acacia trees on soil nutrient levels in arid Tunisia

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ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form
25 June 2015
Accepted 13 July 2015
Available online 18 July 2015

Keywords:
Acacia raddiana
Islands of fertility
Spatio-temporal scale
Soil nutrients
Arid Tunisia

ABSTRACT

Scattered trees often function as fertile islands in harsh environments such as arid and semiarid lands. To understand their impact on the soil nutrient status, an in-depth study accounting for spatial patterns in nutrient levels was conducted in an *Acacia raddiana* forest-steppe ecosystem in arid Tunisia. Changes in soil organic matter and total N, extractable P and exchangeable K^+ were examined considering a distance gradient in both horizontal and vertical direction. In addition, the effect of tree age was incorporated to determine temporal changes in soil nutrient status after reforestation. Higher organic matter and nutrient levels in the upper soil layer (0–10 cm) were found up to 175% of the canopy radius, especially for trees older than 75 years. Organic matter and nutrient concentrations below canopy were significantly higher up to a depth of 20 cm. Increased levels of organic matter and total N with increasing tree age were found below canopy reaching a maximum after 75 years. Spatial patterns in soil chemical properties exist from underneath to outside the canopy and with increasing depth. When combined with tree age, the impact of scattered *A. raddiana* trees on spatio-temporal changes in resource availability can be studied on a field scale.

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. 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).

Facilitation may occur through improved soil hydraulic properties (De Boever et al., 2014), a more favourable microclimate (Moro et al., 1997; Breshears et al., 1998) and nutrient availability. 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).

The plant macronutrients nitrogen (N), phosphorus (P), and potassium (K) can be limiting in drylands (Saltz et al., 1999). Low

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http://dx.doi.org/10.1016/j.jaridenv.2015.07.006
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soil-water content and high soil alkalinity decrease both soil N and P availability (Noy-Meir, 1973). Compared to N and P, K deficiencies are less common in dryland ecosystems except for savannas with sandy soils exhibiting low cation exchange capacity (Ssali et al., 1986). The occurrence and degree of nutrient limitation for plants 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 (Drenovsky and Richards, 2004).

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 tortilis* subsp. *raddiana* is such an important keystone species, for its 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).

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). In order to investigate the 'fertile island' effect of scattered *Acacia 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 their influence outside the canopy 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 age groups) on organic matter and total N, extractable P and exchangeable K^+ 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 organic matter and nutrient levels with depth for the 0–30 cm soil layer were investigated underneath the canopy at the microsite closest to the tree stem. 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, and (iii) increase with increasing tree age.

2. Materials and methods

2.1. Study site

Bou Hedma National Park (34° 39′ N and 9° 48′ E) is located in central Tunisia and covers an area of 16,488 ha. It was designated as a UNESCO Biosphere Reserve in 1977. The main climatic characteristics of the park are: an average annual rainfall of 180 mm, an average annual temperature of 17.2 °C, and a mean minimum and maximum annual temperature of respectively 3.9 °C (December and January) and 38 °C (July and August). The park has an arid Mediterranean climate with a moderate winter (Le Houérou, 1959). 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). The study was conducted in an integral protected (fenced) zone with a total area of 5114 ha (of which 2000 ha of plains and 3114 ha of mountains). *A. tortilis* (Forssk.) Hayne subsp. *raddiana* (Savi) Brenan is a native tree species in the study area.

The forest steppe of the Bou Hedma region consists of scattered *A. tortilis* ssp. *raddiana* trees 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 *E. papposa, Cenchrus ciliaris* and *Cynodon dactylon* were mainly found below canopy whereas open areas were dominated by annual species (Abdallah et al., 2012).

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.

2.2. Experimental design

A total of 15 *A. raddiana* trees was randomly selected covering an area of approximately 10 ha. To represent the *A. raddiana* population in the park, three crown diameter classes based on the study of Vancoillie et al. (2010) 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. For each canopy size class, crown diameter, basal trunk diameter and tree age are listed in Table 1.

For those 15 trees, five per crown diameter class, five microsites were distinguished for the 0–10 cm soil layer (depth D1): M1, M2, M3 and M4 respectively at 25%, 75%, 125% and 175% of the canopy radius in the northern direction and M5 (interspace) at least 10 m away from the canopy. In addition, two more depths for microsite M1 were distinguished: D2 and D3 respectively at soil depths of 10–20 cm and 20–30 cm.

2.3. Soil analysis

Organic matter (OM) was determined according to Walkley and Black (1934). 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.

Total N content was 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). Extractable phosphorus (P)

Table 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)	64.1 ± 7.3	88.3 ± 11.3	109.1 ± 18.9

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