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Impact of *Acacia tortilis ssp. raddiana* tree on wheat and barley yield in the south of Tunisia

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ABSTRACT

In the past, *Acacia tortilis ssp. raddiana* (Savi) Brenan colonised thousands of hectares in central and southern Tunisia. Nowadays, the geographical distribution of *A. tortilis ssp. raddiana* is restricted to the National Park of Bou-Hedma (central Tunisia). The *Acacia* is of considerable interest for local populations and may be considered as a "foundation species" under arid climate. This study examines the effects of *Acacia* canopy on soil fertility and cereal productivity. The improvement in soil fertility and microclimate provided by *A. tortilis ssp. raddiana* is known to facilitate the establishment of new species, but little is known about the interaction between the tree species and the cereals cultivated by local farmers. We studied the effect of *A. tortilis ssp. raddiana* canopy on the yield of three cereals crops (*Hordeum vulgare* L., *Triticum sativum* L. and *Triticum aestivum* L.). We seeded 168 plots (15 × 15 m) under the tree canopy and in open areas on four different landform types (glacis, plain, wadis, and jessours) and measured cereal yield over two contrasting years (wet and dry). We found that: (1) precipitation and geomorphology are more important in determining cereal yield than canopy cover, (2) these effects on water availability are species-specific with no effect on the stress-tolerant barley. We finally discuss the potential negative effects of *Acacia* trees which may have balanced the positive effects found for nutrient in our study.

1. Introduction

The overall effect of trees on understory vegetation depends on the balance between their positive (facilitation) and negative (competition) effects (Callaway and Walker, 1997). The net result of this balance is mostly dependent on the tree species, tree density, and the nature of the associated species and environmental factors (Gea-Izquierdo et al., 2009).

Positive effects are often expected in arid areas, where trees improve seed trapping, nutrient and moisture availability, and protection from browsing or trampling (Flores and Jurado, 2003).

Trees can also reduce soil erosion (with their strong root system) and prevent desertification in arid zones (Young, 1989). Furthermore, they create subhabitats which differ from the surrounding vegetation and exert different influences on the herbaceous layer (Belsky, 1990). Legume tree species, such as *Acacia* species, are also known to improve soil nutrient availability (Gedda, 2003), which is firstly due to their ability to fix atmospheric nitrogen and thus improve soil fertility (increasing potentiality to produce); and secondly to their improvement of soil water availability by reduction of actual evapotranspiration (Munzbergova and Ward, 2002). Considerable research has been conducted on the effects of trees on understory crop yields in Africa. For example, in semi-arid areas of South Africa, *Faidherbia albida* has been shown to frequently raise yields of millets, maize and sorghum and is widely cultivated by farmers in parts of the Sahel and in southern Africa. Reasons for yield effect include higher nitrogen and phosphorus availability, moisture conservation and lower soil temperatures beneath canopies (Payne et al. 1998). A key feature of the "*albida system*" (Vandenbeldt, 1992) is that the understory cereals are not shaded since leaf fall takes place before cereal cropping and the tree canopy fills late or after cropping (Kho et al. 2001).

Other studies have demonstrated that the impact of trees on the understory vegetation could be negative (Belsky, 1990). For example, the roots compete for water and nutrients with understory vegetation. A reduction of soil water availability under

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savannah trees is often due to a high tree water uptake (Anderson et al., 2001). The role played by competition from tree roots is likely to be influential in the reduction of available soil moisture and hence in the reduction of plant growth (Moreno, 2008). Trees can also reduce light availability (Vetaas, 1992), which can also limit plant production (Anderson et al., 2001). Moreover, Rafiqul-Hoque et al. (2003) have shown that certain trees contain higher levels of bioactive chemicals, suggesting a large inhibitory potential (Barnes et al., 1996). Allelopathic interactions involve the production and release of chemical substances which can inhibit the growth and the development of the understory vegetation (Shaukat et al., 2003).

Agroforestry has drawn considerable attention because of its potential to maintain or increase biological productivity in areas characterised by large-scale extensive agriculture (Kidd and Pimentel, 1992). It is often assumed that appropriate agroforestry systems can provide the essential ecological functions needed to ensure sustainability and maintain favourable microclimatic influences. Such benefits may outweigh their greater use of water in areas of limited water availability. Cannell et al. (1996) argued that agroforestry may increase productivity because trees can capture resources which are underused by crops. Ovalle and Avendano (1987) reported that trees increase understory herbaceous productivity.

In many ecosystems of the world, the genus *Acacia* is widely distributed (Ross, 1981) and is economically important. Under arid and Saharan climates, *A. tortilis ssp. raddiana* plays a key role in ecosystem functioning and stability. This species may be considered as a foundation species (i.e. species that structure a community by creating locally stable conditions for other species, and by modulating and stabilising fundamental ecosystem processes, Ellison et al. 2005). For instance, in the African Saharan region, *A. tortilis ssp. raddiana* provides food and shelter to many desert animals, while the species is also a major source of fuel, fodder and remedies for local Bedouin people and their livestock (Ashkenazi, 1995).

The present study aims to assess the effect of *A. tortilis ssp. raddiana* (Mimosaceae) on cereal production. In southern Tunisia's arid ecosystems, the traditional *Acacia* agroforestry system, practiced for many decades, can be seen as a complex and dynamic resilient system reacting to a wide variety of long-term external changes and short-term disturbances related to climate, topography, soil texture and gemorphological variability.

In the Bled Talah region, agroforestry systems are based on cereal growing in association with native plantations of *Acacia* trees. Farmers commonly grow cereals under *Acacia* trees.

The most important cereals are barley (*Hordeum vulgare* L.), softwheat (*Triticum sativum* L.) and hardwheat (*Triticum aestivum* L.), and cereal production plays an important role in the family economy in South Tunisia.

Our main hypothesis was that *A. tortilis ssp. raddiana* could facilitate the growth of crops under an arid climate by improving ecological conditions under its canopy. In particular, *A. tortilis ssp. raddiana* was expected to enhance soil nutrient content and improve soil structure by adding organic matter to the soil. Moreover, the tree reduces water loss by soil evaporation, mainly in spring, when cereals are in a maximum growth period. Thus, we hypothesized that an improvement in the performance of seedlings growing under the *A. tortilis ssp. raddiana* canopy would indicate the prevalence of facilitation over competitive interactions.

Also, the objectives of this study were to determine whether *Acacia* trees modified the availability of certain resources (nutrients, water) to the point of promoting cereal yield and how this capacity is affected by site conditions (geomorphology, rainfall, type of cereal species).

2. Materials and methods

2.1. Study area and habitats

The study area is located in the Governorate of Sidi Bouzid, in central and southern Tunisia in the region of the Bou-Hedma National Park (33°30′N and 9°38′E). Following Emberger's classification (Emberger, 1955), the climate is Mediterranean arid with temperate winters. The average annual rainfall varies from 150 mm in the plain (a. s. l. 100 m) to 300 mm on the highest peak of the mountain range (a. s. l. 800 m). However, like in other arid Mediterranean climates, inter-annual variability in precipitation is high (151 mm ± 21 between the years 1996 and 2008). Mean minimum temperature of the coldest month (January) is 3.9 °C and mean maximum temperature of the warmest month (August) is 36.2 °C. *A.tortilis spp. raddiana* is a native tree species in the study area. According to Le Houérou (1969), the *A. tortilis* population is considered as a pseudo-savannah, with scattered tree or shrub individuals of *A. tortilis* associated with several species of grasses, shrubs and ligneous chamaephytes.

In the study area, according to the geomorphological structure, four habitats were identified (glacis, plain, wadis and jessours) where strong differences in soil water availability were observed. The glacis corresponds to an extension of the pediment composed of villafranchian calcareous crust and covered by shallow loamy soils. It receives water draining from the adjacent mountains. The plain is a large area with a gentle slope that does not receive streaming water. The wadis corresponds to wide depressions, accumulating water by flowing and streaming. The jessours is a man-made contour bank of earth with or without a wide spillway group of stones and earth walls that collect and retain soil washed down hillsides by torrential rains (Alaya et al., 1993).

Unpublished data (Abdallah et al., 2010) in the plain showed that the light (expressed in Lux) is significantly weaker ($F = 785.11$, $P < 0.0001$) beneath canopies (45.93 ± 1.13 Lux) than beyond tree canopies (135.13 ± 2.98 Lux). Light transmission is only 35% below the *Acacia*. Moreover, the soil water content is significantly higher ($F = 16.44$, $P < 0.001$) under the trees (1.78 ± 0.16 ml of water per 100 ml of soil) as compared to uncanopied areas (1.08 ± 0.007 ml of water per 100 ml of soil).

In order to verify soil water availability in the four habitats, soil moisture (volumetric soil water content) was measured in each habitat at a depth of 10 cm with an FDR probe (ThetaProbe ML2x, Delta T, Cambridge, UK). Ten measurements were made at random points per habitat type at different times. The first measures were made during the dry period (before rainfall), whereas the others were sampled after a 30-mm rain event, at the intervals of 2 and 4 days after the rain.

2.2. Cereal species

Three species of cereals were used for experiments: barley (*H. vulgare* L.), softwheat (*T. sativum* L.) and hardwheat (*T. aestivum* L.). The selection of these species was made in accordance with the characteristics of the agroforestry system in the Bled Talah region. The cereal crops are naturally grown in all four habitats. In arid Tunisia, cereals are annual species sown in October or November (Fig. 1). The height of the seedlings remains very low during the first part of the winter period. The growing season begins during the second part of the winter and ends quickly in the spring. Generally, the number of stems per plant is relatively low (five or six stems per plant). According to Floret and Pontanier (1982), a yield of 500–1000 kg ha^{-1} can only be observed once every 5 years. These low yields are due to a quick heading (in March) and a premature maturation (mid-April) induced by water stress which

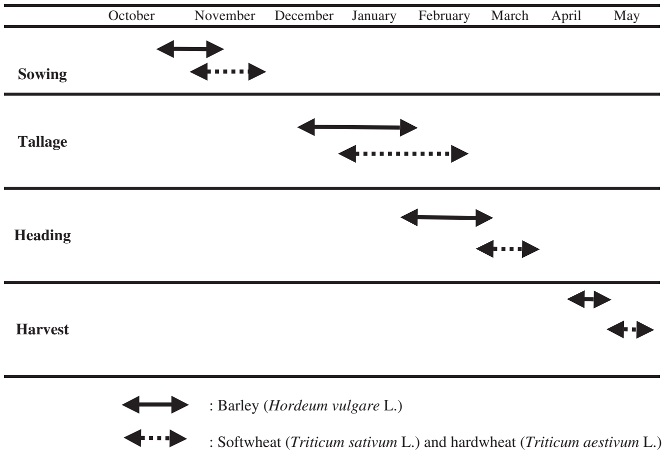

Fig. 1. The growth cycle duration of the three cultivars of cereals (barley: *H. vulgare* L.; softwheat: *T. sativum* L.; hardwheat: *T. aestivum* L.).

is very high in this period. The harvest takes place at the end of April for barley and in the middle of May for softwheat and hardwheat. In southern Tunisia, the length of the biological cycle of the cereals is then very short, in contrast to northern Tunisia where rainfall is greater.

2.3. Experimental design

The intercropping between *A. tortilis* and cereals was conducted during two contrasting years (from October 2002 to June 2004) when the rainfall patterns differed greatly (Fig. 2). The rainfall was the main contributing recharging source of soil water, since the surface of the groundwater was not directly available to the plants. Throughout the first year (wet year), the total rainfall was 272 mm, which fell in 47 days, while the second year (dry year) was characterised by a total rainfall amounting to 220 mm, which fell in 34 days. Strong rains fell during September (51 mm in the first year and 64 mm in the second year). Precipitation during the fall (September, October and November) is necessary for the germination of the cereal seeds because this period coincides with the sowing period. The same explanation is true for spring when cereals are in a maximum period of growth. Consequently, these two seasons strongly influenced the cereal productivity under the arid climate. These data were supplied by the meteorological station of the National Park of Bou-Hedma (Annual Reports).

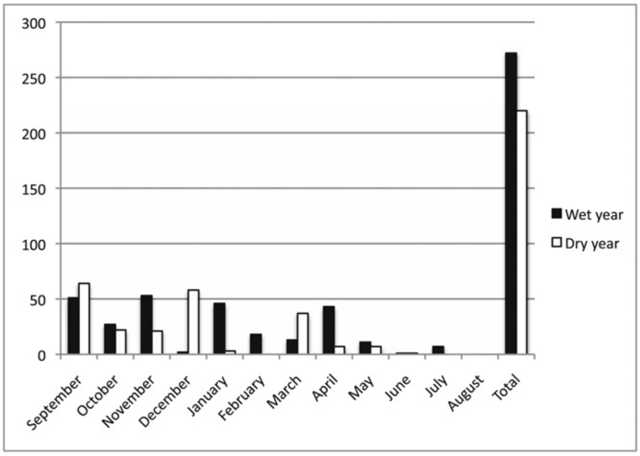

Fig. 2. Monthly rainfall (mm) recorded at Bou-Hedma region during the two years of experiments (wet year and dry year).

Cereal seeds were directly sown to a depth of ca 10 cm, without addition of fertilizers, on agricultural lands chosen in the four types of habitats.

All seeds came from the same local producer. For each species of cereal, seven replicates (size of one replicate: 15 m × 15 m) per habitat (glacis, plain, wadis and jessours) and per land form (under tree canopy *vs* outside tree canopy) were established for each year. We used a completely randomized design to select a total of 168 plots (three species × four habitats × two land forms × seven replicates). When reaching maturity, cereals were manually harvested. The grains of each cereal species were dried to constant weight at 65 °C in the laboratory and weighed in order to estimate the grain yield. Generally, no grazing occurred during the growth of the cereals because the farmers protected the plots. However, the experimental protocol failed during the dry year for the jessours (no data recorded) due to accidental grazing by sheep.

Moreover, tree density of *A. tortilis ssp. raddiana* was randomly measured in the four types of habitats by counting all individuals in four 1-ha plots per habitat type.

In the sandy plain, 72 random soils samples (36 below tree canopies and 36 in the open areas) were taken at six different depths (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm and 100–120 cm) with six replicates per depth. The soil samples were kept in plastic bags, labelled, sealed and transported to the Medenine Institute of Arid Regions (Tunisia). Soils were air-dried and sieved with a 2 mm sieve. Soil pH and electrical conductivity were determined (saturated paw method, AFNOR, 1987) by pH meter and conductivity meter, respectively. Total nitrogen (N) (Kjeldahl method, Jackson, 1958), % of organic matter (Walkley–-Black method, Walkley and Black, 1934) and phosphorus (colorimetric method, Murphy and Riley, 1962) were also determined. Potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^+) were determined by ashing soil samples on filters at 550 °C followed by extraction with HCl. The HCl extract was then measured by atomic absorption spectrometry (AA 6800, Shimadzu Corporation, Japan).

2.4. Statistical analyses

In our study, four independent variables were considered: the presence or absence of *Acacia* trees, the type of cereal species (barley, softwheat, hardwheat), the geomorphological habitats (glacis, plain, wadis and jessours) and the year of harvest (wet or dry year). ANOVA tests were performed to assess simple and interaction effects between these four independent variables on the cereal yield (dependent variable). Because the barley yield did not significantly change during the two years of experiments, we explored the effect of geomorphology by restricting our analysis to wheat species (*T. aestivum* L. and *T. sativum* L.).

Since the experimental protocol failed during the dry year for the jessours (no data recorded) due to accidental grazing by sheep, we tested the geomorphology effect for each year with simple ANOVA. We also used ANOVA to analyse the effect of the geomorphology on soil parameters (nutrients and soil moisture). ANOVA tests were performed using the R statistical package (R Development Core Team, 2005). The values of the probability lower than 0.05 ($P < 0.05$) were regarded as statistically significant.

3. Results

3.1. Soil water availability in the four habitats

Before rainfall and immediately after a rainfall of 30 mm, there were no significant differences in soil moisture among habitats ($F = 0.39$, $P = 0.76$ and $F = 0.75$, $P = 0.53$, respectively, Fig. 3). Two

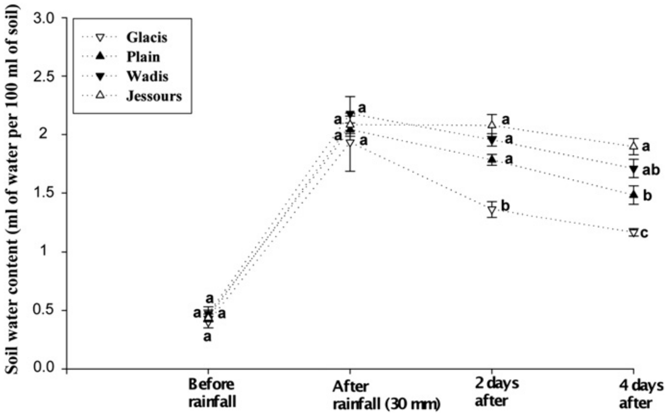

Fig. 3. Temporal evolution of soil water content measured in the four geomorphological habitats (glacis, plain, wadis and jessours). Mean values which are not followed by the same letter are statistically significant (Tukey's HSD-test at $P < 0.05$).

days after rainfall, the glacis was significantly drier ($F = 23.50$, $P < 0.001$) than the other three habitats. Four days after the rain, we observed significant differences ($F = 21.55$, $P < 0.001$) between the glacis (the driest), the plain (intermediate position) and the jessours (the wettest). The wadis was not significantly different from the plain and the jessours.

3.2. Soil properties and fertility

Measurements concerning soil chemical properties differed for all parameters (Table 1) with the highest values found under canopied subhabitats. Soil under *Acacia* trees had more organic matter (OM), more N content and more extractable P content than those in the uncanopied subhabitat. In the same way, significant differences were found between the two subhabitats (CS and US), for the exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) with a higher cations content in the canopied soils compared to the uncanopied ones. In contrast, there were no significant differences between canopied subhabitats and uncanopied subhabitats for pH and electrical conductivity.

3.3. Density of Acacia trees in the four types of habitats

There was a significant effect of the habitat type on the mean density of *A. tortilis* ($F = 65.35$, $P < 0.001$). Mean density ranged between 28 ± 2.85 individuals ha^{-1} in the jessours to 2.5 ± 0.64 individuals ha^{-1} in the glacis. Wadis (13.5 ± 0.64 individuals ha^{-1}) and plain (9 ± 0.7 individuals ha^{-1}) had densities intermediate between the jessours and the glacis, and were not significantly different from each other.

3.4. Cereal yield

There were no significant effects of both the presence of *Acacia* trees ($F = 0.17$, $P = 0.68$) and geomorphology ($F = 1.34$, $P = 0.26$) on cereal yield.

However, we observed a highly significant difference in cereal yield due to the type of cereal ($F = 151.42$, $P < 0.001$, Fig. 4) with the highest values observed for the two species of wheat (*T. sativum* and *T. aestivum*) as compared to barley (*H. vulgare*). Moreover, there was a significant effect of the year of experiment on cereal yield, with an overall decrease in cereal yield during the dry year ($F = 63.85$, $P < 0.001$, Fig. 4). However, this decrease was only significant for the yield of wheat species (softwheat: *T. sativum*, hardwheat: *T. aestivum*) but not for barley (*H. vulgare*), as shown by

Table 1
Chemical properties of soils occurring under *Acacia tortilis ssp. raddiana* canopies and in open areas with depth (CS: Canopied Subhabitat; US: Uncanopied Subhabitat; ns: no significance; *: $P < 0.05$; **: $P < 0.01$).

Depth (cm)	Organic matter (%)			Nitrogen (%)			Phosphorus (mg kg^{-1})			Ca^{2+} (mg 100 g^{-1})			K+ (mg 100 g^{-1})			Na^{+} (mg kg^{-1})			Mg^{2+} (mg kg^{-1})			pH			Conductivity (mS cm^{-1})		
	CS	US	P	CS	US	P	CS	US	P	CS	US	P	CS	US	P	CS	US	P	CS	US	P	CS	US	P	CS	US	P
0–20	1.51	0.40	**	0.34	0.26	*	49.13	30.28	**	28.84	21.79	*	29.88	14.37	**	18.3	13.99	*	6.06	4.93	*	7.85	7.75	ns	1.11	0.97	ns
20–40	0.70	0.13	*	0.33	0.25	*	39.24	27.19	**	25.96	20.69	*	28.89	15.04	**	15.6	13.60	*	4.46	2.85	*	7.81	7.72	ns	0.91	0.88	ns
40–60	0.50	0.20	*	0.31	0.22	*	37.55	22.26	**	22.96	20.66	*	18.30	13.32	*	15.70	11.28	*	4.48	3.07	*	7.77	7.61	ns	0.69	0.64	ns
60–80	0.33	0.06	*	0.24	0.20	*	31.32	17.16	**	20.95	14.50	*	19.88	11.32	*	16.4	4.94	**	3.70	1.80	*	7.65	7.56	ns	0.59	0.45	ns
80–100	0.33	0.06	*	0.25	0.20	*	26.22	10.94	**	21.98	10.51	**	19.13	13.25	*	11.97	5.28	*	4.25	2.08	*	7.65	7.50	ns	0.55	0.45	ns
100–120	0.33	0.06	*	0.22	0.21	ns	15.07	6.41	*	19.18	10.30	*	12.99	12.55	ns	10.94	5.28	*	3.89	1.92	*	7.54	7.45	ns	0.48	0.40	ns
Mean	0.61	0.15	*	0.28	0.22	*	33.09	19.04	*	23.32	16.41	*	21.51	13.31	*	14.81	9.06	*	4.47	2.77	*	7.71	7.60	ns	0.72	0.63	ns

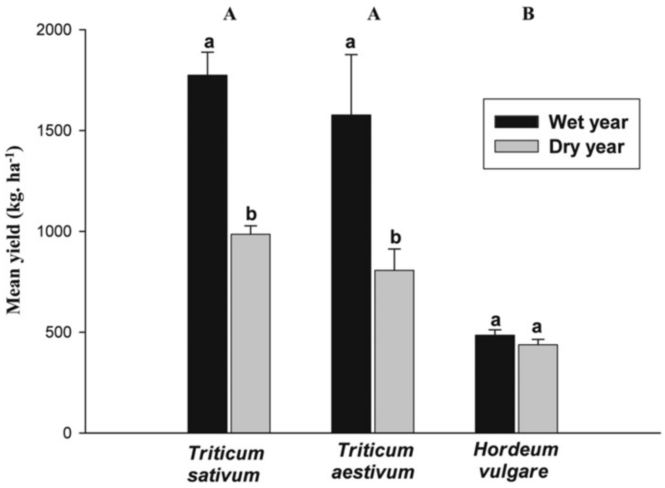

Fig. 4. Mean yield of the three cultivars of cereals (barley: *H. vulgare* L.; softwheat: *T. sativum* L.; hardwheat: *T. aestivum* L.) during the wet year and the dry year. Capital letters (A, B) concern the species effect and lower-case letters (a, b) the year effect on the mean yield of each cereal species. Mean values which are not followed by the same letter are statistically significant (Tukey's HSD-test at $P < 0.05$).

the significant cereal type * year interaction ($F = 19.03$, $P < 0.001$, Fig. 4).

By comparing the softwheats yield in the four habitats, the results showed again the significant effect of the year on the yield of cereal, with much higher yield during the wet year than during the dry year ($F = 62.14$, $P < 0.001$, Fig. 5). Moreover, there was a significant effect of the geomorphology ($F = 64.98$, $P < 0.001$) during the wet years only, with the highest yields observed in the jessours and wadis and the smallest in the glacis. The plain produced an intermediate yield between the jessours, wadis and the glacis. There was no effect of the geomorphology ($F = 0.59$, $P = 0.56$) during the dry year.

4. Discussion

The main focus of this study was to determine whether *Acacia* trees modified the availability of certain resources (nutrients, water) to the point of promoting cereal yield and how this capacity is affected by site conditions (geomorphology, rainfall, type of cereal species).

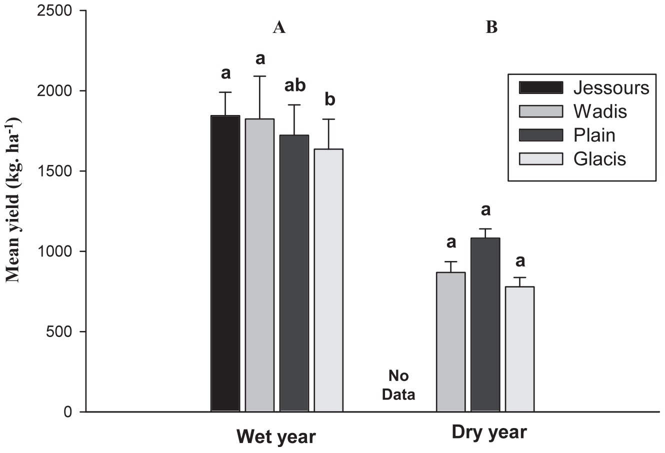

Fig. 5. Mean yield measured in the four habitats (jessours, wadis, plain and glacis) during the wet year and the dry year. This analysis was restricted to wheat species (*T. aestivum* L. and *T. sativum* L.) because the barley yield did not significantly change during the two years of experiments (see Fig 4.). The experimental protocol failed during the dry year for the jessours (no data recorded) due to accidental grazing by sheep. Capital letters (A, B) concern the year effect and lower-case letters (a, b, c) the habitat effect on the mean yield of each experimental year. Mean values which are not followed by the same letter are statistically significant (Tukey's HSD-test at $P < 0.05$).

4.1. Effect of rainfall, geomorphology, and cereal species on cereal yields

Our study revealed that the yield of cereals could be influenced by several factors such as annual rainfall, geomorphology and the type of cereal species.

The amount of rainfall per year significantly affected the yield of two cereals only (significant interaction between the year of sowing and the type of cereal species). Indeed, for softwheat (*T. sativum* L.) and hardwheat (*T. aestivum* L.), yields were greater during the wet year than during the dry year. In contrast, barley (*H. vulgare* L.) exhibited the same yield during the two years of experiments, which suggests that this cereal has a clear adaptation to drought. It is generally known that soil water composition (in particular soil water storage) is extremely important for crop growth and especially before the sowing of an annual crop. Our results agree with other findings, in Mediterranean-type ecosystems (Larcher, 2000), which showed that soil water availability was the most important factor determining seedling recruitment and consequently the yield of a crop. However, we showed that stress-tolerant cereal species such as barley are not sensitive to inter-annual rainfall variability, consistent with Grime (1974)'s model.

Concerning the geomorphology impact, our results showed that the yield of cereal differed significantly between the four habitats, during the wet year only. These habitats were not all favourable to cereal production. During the wet year, the cereal yield was greater in the jessours and the wadis which benefit from more water accumulation as compared to the other habitats. In contrast, the glacis, with lower water storage in the soil, exhibited a lower cereal yield as shown by mean soil moisture. The measures of the density of *Acacia* trees brought additional information concerning the ability of habitats to produce cereals. Tree density was considerably affected by geomorphology (higher density in the jessours, lower density in the glacis and intermediate values for the wadis and the plain). Thus, the jessours is the most favourable habitat characterised by higher amounts of water input and higher density of trees in contrast to the glacis. Other studies reported that an increase in *A. tortilis ssp. raddiana* density under natural conditions depends on ecological factors, and in particular on soil water availability (Lahav-Ginott et al., 2001). Moreover, it is generally known that natural regeneration of woody species is threatened by variation in water availability (Larwanou and Saadou, 2005). Comparable results were found by Lahav-Ginott et al. (2001), in the Negev Desert, who demonstrated that the jessours constitutes a habitat with a high density of *A. tortilis ssp. raddiana* compared to terraces. Our results agree with other observations showing that the main factor for crop production in a semi-arid region is the supply of water (O'Leary and Connor, 1997). However, we showed that soil water availability may increase the yield of crop species only during a wet year.

4.2. Impact of Acacia tree on soil fertility

Under arid climates, nutrients such as nitrates, phosphorus, other anions and cations and various trace elements, are essential for the nutrition of plants, and act as determinants in the productivity of cereals. In particular, nitrogen is one of the key elements in ecosystem functioning and productivity (Tietema et al., 1992). In this context, our study showed that the various soil fertility indices (Organic Matter, N, P, K^+, Ca^{2+} and Mg^{2+}) were significantly higher below the canopy area of *A. tortilis ssp. raddiana* compared to the open areas. More recent studies have shown that both soil and grass nitrogen and phosphorus contents were elevated beneath tree canopies compared to inter-canopy areas (Treydte et al., 2008). Conversely, some studies did not find any or only slight differences in soil properties between canopy and inter-canopy sites (Witkowski and Garner 2000). The abundance of understory plants under the *Acacia* tree canopies and in the open subhabitats may also have an influence on the status of soil nutrients. The occurrence of N fixation due to microbial activity under leguminous trees is a major source of N enrichment (Palm 1995). *A. tortilis ssp. raddiana* is classified among the trees with a high N_2-fixing potential (Gueye and Ndoye, 2003). It was also shown by Deans et al. (2003), that the N concentration in leaves was substantially higher for *A. tortilis ssp. raddiana* than other N_2-fixing woody species such as *Acacia aneura*, *Acacia nilotica* and *Acacia indica*. Following the fall of leaves and with the decomposition of litter, the first rains caused a flush of nitrification (Diouf et al., 2003). The exact source of the nutrient enrichment of the soils under tree canopies remains largely unexplained. It was probably due, in part, to nutrient inputs by tree litter (Belsky et al., 1989). The droppings from birds and dung of mammals spending time under trees are also major inputs of nutrients under trees (Belsky et al., 1989). Thus, our results supported the hypothesis of the positive influence of *A. tortilis ssp. raddiana* in terms of soil enrichment in arid ecosystems.

4.3. Effect of Acacia tree cover on cereals yields

In opposition to our main hypothesis that *Acacia* cover improves cereal productivity, we found that *A. tortilis ssp. raddiana* did not facilitate the growth of cereals under arid conditions. Although soil enrichment under tree canopies has been demonstrated in this study and others (Hagos and Smit, 2005), the grain yield did not differ significantly between the canopied plots and the uncanopied ones. Positive interactions between wooded vegetation and understory have already been reported in arid and semi-arid environments (Kho et al., 2001). However, there are conflicting opinions about the effect of canopy on grass species composition and yield. For example, Smit and Swart (1994) reported a high grass species replacement under canopy subhabitats. Yield increases are common under open and well-managed canopies of mature trees due to a combination of improvements in soil structure and fertility (Rao et al., 1998), and increases in soil water content resulting from reduced evaporation. Cannell et al. (1996) argued that agroforestry may increase productivity by capturing a larger proportion of the annual rainfall. These results may reflect a dynamics of net balance between negative and positive interactions, which may vary depending on small variations in climate, soil or topography (Pugnaire and Luque, 2001).

It is likely that the mechanisms underlying the positive effects of *Acacia* trees could be offset by other factors, such as shading and allelopathy. Unpublished data (Abdallah et al., 2010) showed that light transmission is only 35% below the Acacia trees. Also, we suggest two hypotheses for future investigations that could explain the absence of positive interaction observed between the tree and the cereals. First, there is a competition between *Acacia* trees and cereal seeds because woody species have a competitive advantage over herbaceous species, firstly, as superior interceptors of light and, secondly, due to more efficient root systems to pump soil water and nutrients. In this context, some authors (Rao et al., 1998) demonstrated that the generally positive influence of scattered trees on crops does not offset the large competitive effect of trees on crops for water and nutrients (Ong and Leakey, 1999). Khalique and Sheikh (1985) found that the yields in wheat were relatively low under trees, primarily due to shade and competition for nutrients and water. The extension of shade under pruned trees during the growth period seems to be detrimental to the species that require high solar intensity for their development. Moreover, many studies reported that under *Acacia*, the vegetative development of plants growing in the shade of these trees was 25–35 days longer than in the open areas (Ovalle and Avendano, 1987).

In contrast to our observations, several studies in savannahs suggested that tree shade increased understory herbaceous productivity because of the reduction of temperature and evapotranspiration (Belsky et al., 1989). Foster (1999) suggested that small seedlings are more sensitive to abiotic stress and therefore profit from the presence of a neighbour, while negative neighbour effects predominate at later stages. Puri et al. (1993) demonstrated that the presence of trees decreased the growth and productivity of *T. aestivum* and suggested that the greater the distance between cereal and trees, the less negative the effect of the trees on the cereals.

Second, a possible allelopathic effect of *Acacia* trees has also been recognized. In fact, competition mediated by allelopathic factors has been thoroughly described in the literature, and can be especially important in semi-arid areas due to low activity of microorganisms, which favours the accumulation of allelochemicals. Other authors have shown a large inhibitory potential in the genus of *Acacia* (Mimosaceae) (Rafiqul-Hoque et al., 2003). Autotoxicity is also responsible for the inhibition of seed germination and/or delay of seedling growth exhibited by some annuals including corn, *Zea mays* (Martin et al., 1990) and wheat, *T. aestivum* (Jessop and Stewart, 1983), under successive cropping using conservation tillage systems. Research showed that *Acacia* trees are recognized as a versatile source of components with bioactive properties (Rafiqul-Hoque et al., 2003), suggesting a large inhibitory potential in *Acacia* species which dominate the dry south Saharan regions of Africa (Barnes et al., 1996). At our study site, Noumi et al. (2010) have demonstrated that *Acacia* trees can have an inhibitory effect (from its leaves) on the germination of *Acacia* seeds. Also, we hypothesise that *Acacia* can also inhibit the germination of cereal seeds, which could induce a decrease in cereal yield below the canopy tree.

We did not find any interaction between land form and either habitat or year, which suggests that the negative direct effect of *Acacia* trees on cereal yield was not due to competition for water. Alternatively, this suggests that the negative effect of trees was either competition for light or allelopathy.

4.4. Conclusions

This study evaluated the possible impact of *Acacia* trees at varying canopy densities on soil properties and yield of three cereals grown under the tree canopy. We did not observe a net positive effect of trees on cereal yield, likely because the positive nutrient effects were balanced by the negative effect for light or by allelopathic interferences. For future investigations, it would be possible to collect the leaf litter from under trees and transfer it onto adjacent (and uncanopied) areas to separate likely allelopathic effects from competition for light (Callaway et al.1991).

Cereal management may be an issue. It is possible that cereal planting times and management have had an influence on the lack of yield response. If cereals are planted earlier (maybe through seed priming with water) then maybe they will use more of the N flush and grow better. If weed management is poor, this will also reduce the response. Moreover, as farmers have traditionally cropped cereals under the trees for many years, offtake of organic matter and nutrients in grain and stems may have been relatively high for a long time, meaning their effect on yield is now small.

Therefore, the results of this study are important in improving agroforestry. *A. tortilis ssp. raddiana* forms an important traditional agroforestry system in the Bled Talah region, characterised by precarious climate, although this species is not always socially accepted. In fact, there is a general belief among farmers that when trees are grown in combination with agricultural crops, the latter are adversely affected. At least, we showed that the net effects are not negative.

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