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The influence of Saharan agro-pastoralism on the structure and dynamics of acacia stands

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1 Running title: Saharan acacia stands and agro-pastoralism

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16 Summary

17

18 Trees play a crucial role in drylands, where they are often considered as keystone species for
19 ecosystems and for local livelihoods. In particular in the Saharan region, *Vachellia tortilis*
20 subsp. *raddiana* (ex. *Acacia tortilis* subsp. *raddiana*) are multi-purpose acacia trees for people
21 and contribute to the overall ecosystem functioning. Despite progress in research, acacia stands
22 in this region are poorly documented and little is known on their interactions with human
23 Saharan populations. On the basis of a multidisciplinary approach, the aim of this study was to
24 assess the structure and dynamics of Saharan acacia stands in south-western Morocco and the
25 influence of human activities and practices. Interviews and participant observations were
26 performed in two villages and individual acacia trees were measured in contrasting topography,
27 microhabitat and land use situations. The acacia stands were located in cultivated and browsed
28 areas where trees were used and shaped in the framework of human subsistence activities. In
29 this context, the low-density acacia stands (4.8 trees/ha) showed high regeneration (47.8%) and
30 recruitment rates, and low mortality (3.3%). Land use had more effect on stand structures than
31 topography or microhabitat. Tree regeneration and density were especially high in cultivated
32 areas. Most trees showed traces of pruning (60.3% of them) and debarking (33.9%), but with
33 no correlation with tree mortality. Environmental and anthropogenic factors jointly contributed
34 to the structure and dynamics of acacia stands, and no threat to their sustainability was observed.

35 Even though further investigation would be required to better distinguish environmental and
36 anthropogenic factors and to draw long-term conclusions, our results suggest that Saharan agro-
37 pastoralism activities are not necessarily incompatible with acacia tree conservation, contrary
38 to the commonly admitted postulate in Morocco.

39

40

41 Keywords

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43 *Vachellia tortilis* subsp. *raddiana*; acacia; drylands; local practices; agro-pastoral systems; tree
44 measurement; Morocco.

45

46

47 1. Introduction

48

49 Drylands – defined as areas with an aridity index lower than 0.65 – cover about 41% of the
50 Earth’s land surface and harbour 38 % of the global human population (MEA, 2005). Drylands
51 are environmentally and socially vulnerable, in particular in the face of desertification, that is
52 irreversible land degradation resulting from multiple climatic and anthropogenic factors (MEA,
53 2005). Despite early studies that highlighted worrying rates of desertification and identified
54 humans as the main cause (Lamprey, 1975), recent research has cast doubt on these conclusions
55 (Helldén and Tottrup, 2008). A better understanding of climatic variability, socio-economic
56 processes and political dimensions, associated with a shift in rangeland ecology paradigms,
57 have provided a basis for highlighting the non-uniformity of desertification and for more
58 nuanced conclusions on the role of human activities in the face of climatic variations (Herrmann
59 and Hutchinson, 2005). Yet desertification remains subject to scientific debate mainly because
60 finding accurate indicators of long-term changes – such as “slow” variables (Carpenter and
61 Turner, 2001) – is challenging. Considering the crucial ecological role of trees in dryland
62 ecosystems (Belsky et al., 1989), monitoring woodlands in drylands may constitute accurate
63 “slow” indications of potential degradation and desertification.

64 *Vachellia tortilis* (Forssk.) Galasso & Banfi subsp. *raddiana* (Savi) Kyal. & Boatwr. – ex
65 *Acacia tortilis* (Forssk.) Hayne subsp. *raddiana* (Savi) Brenan (Kyalangalilwa et al., 2013);
66 further noted *V. raddiana* or acacia tree in this paper – is the most widespread native acacia tree
67 in the Saharan region. Considered as a keystone species (Munzbergova and Ward, 2002; Noumi
68 et al., 2012), *V. raddiana* improves soil fertility, decreases potential evapo-transpiration and
69 consequently affects the establishment, development and survival of other plants (Abdallah et
70 al., 2008; Noumi and Chaieb, 2012). In addition, *V. raddiana* is a precious source of forage,
71 fuel wood and other materials (Grouzis and Le Floc’h, 2003). Hence, conserving *V. raddiana*
72 is a crucial challenge in the Saharan region, both for its role in terms of ecosystem conservation
73 and for the preservation of local livelihoods. Nevertheless, the conservation of *V. raddiana* still
74 remains uncertain as the literature has reported contrasting conclusions. On the one hand, *V.*
75 *raddiana* stands showed positive trends in Israel (Lahav-Ginott et al., 2001), in Algeria
76 (Sahraoui et al., 1996) and in Tunisia (Noumi et al., 2010b). On the other hand, negative trends
77 were reported in Egypt (Andersen and Krzywinski, 2007), in Israel (Ward and Rohner, 1997)
78 and in Tunisia (Noumi and Chaieb, 2012). These contrasting dynamics are associated with
79 contrasted local conditions in terms of rainfall regime (Sahraoui et al., 1996), runoff and water
80 flux (BenDavid-Novak and Schick, 1997; Ward and Rohner, 1997; Wiegand et al., 2000b),

81 seed predation by insects (Derbel et al., 2007), browsing intensity (Noumi et al., 2010b) or
82 anthropogenic exploitation (Andersen and Krzywinski, 2007). Given such local variations,
83 extending the carrying out of local studies is crucial to fill the knowledge gap on the dynamics
84 of *V. raddiana* at regional scale and to better assess conservation priorities.

85 In Morocco, no study has investigated the structure and dynamics of *V. raddiana* stands.
86 Furthermore, most Moroccan *V. raddiana* stands are located outside protected areas and are
87 embedded in local agro-pastoral and pastoral systems. Except for some descriptions of local
88 practices for *V. raddiana* in Egypt (Andersen et al., 2014; Hobbs et al., 2014), no study has
89 addressed the effects of local practices, uses or management on the structure and dynamics of
90 *V. raddiana* stands. Such studies may help to achieve a better understanding of coupled Human-
91 Environment systems in drylands (Reynolds et al., 2007) in the interests of sounder and more
92 efficient conservation methods.

93 The aim of the present study was (1) to assess the structure and dynamics of *V. raddiana* stands,
94 and (2) to identify human activities and related practices and their influence on tree stands. We
95 hypothesized that, in complement to environmental variables, human activities and practices
96 may substantially influence the structure and the dynamics of *V. raddiana* stands. To test this
97 prediction, we adopted a multidisciplinary approach in an agro-pastoral landscape and in two
98 neighbouring villages in south-western Morocco. We combined (1) socio-anthropological
99 investigations in order to identify and characterize human activities and practices related to *V.*
100 *raddiana* trees, and (2) ecological measurements to assess the structure and dynamics of *V.*
101 *raddiana* stands subjected to human practices.

102

103 2. Materials and methods

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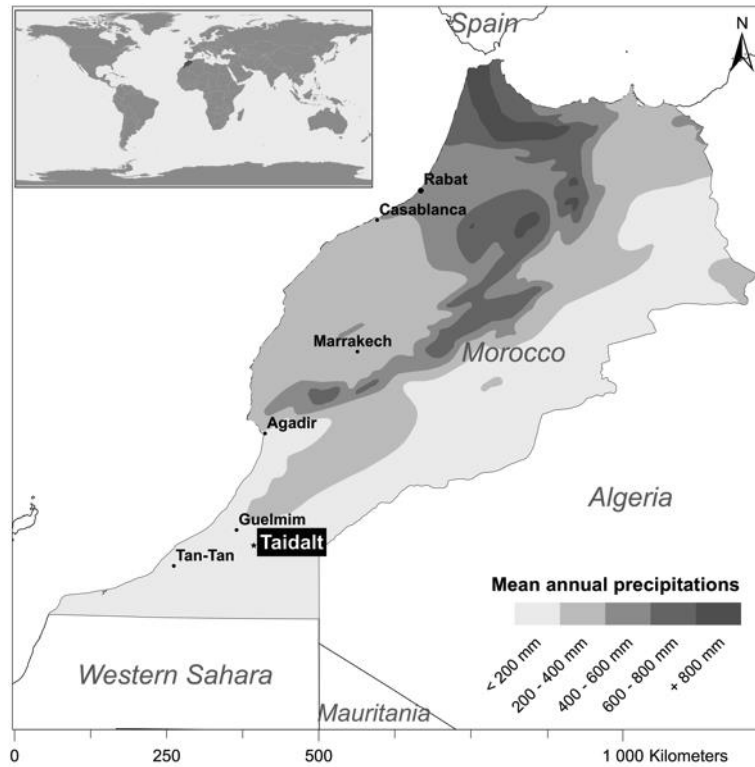
105 2.1 STUDY SITE

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107 This study took place in south-western Morocco (Fig. 1) in the north-western Saharan
108 biogeographical zone (Le Hou  rou, 1990). With mean annual rainfall of 112 mm and average
109 temperature of 19.6  C, the climate is arid with mild winters, due the proximity of the Atlantic
110 Ocean. In this area, three geomorphological formations dominate (Monteil, 1948): (1) rocky
111 terraces superficially covered with sand and gravel and criss-crossed by sandy runnels; (2) a
112 plain with deep alluvial soils and local sand accumulations from wind erosion, transected by
113 dry riverbeds; and (3) high-sloped rocky inselbergs forming part of the Anti-Atlas Mountains.
114 The vegetation is characteristic of the Saharan eco-region with *V. raddiana* as the dominant

115 tree species and *Hammada scoparia* (Pomel) Iljin as the dominant shrub, locally associated
116 with *Panicum turgidum* Forssk. in sandy riverbeds, *Convolvulus trabutianus* Schweinf. &
117 Muschler in terraces and *Ziziphus lotus* (L.) Lam in the plain (Msanda et al., 2002). Acacia trees
118 only colonize the plain and the terrace runnels.

119



120

121 Figure 1: Study site location (Taidalt village) in south-western Morocco, province of
122 Guelmim.

123

124 Two types of human subsistence activities predominate in the acacia woodlands. Firstly, plains
125 and major riverbeds are occasionally used for the cultivation of rain-fed cereals (maize, wheat
126 and barley) (Monteil, 1948). Farmers cultivate flooded areas after episodic rains. Secondly,
127 there are semi-nomadic and settled livestock farming units of goats, sheep and dromedaries, for
128 which acacia woodlands constitute a key rangeland component. In contrast to certain pastoral
129 systems of the Atlas Mountains of Morocco (Genin and Simenel, 2011), no specific rules aimed
130 at forbidding the herds' access to parts of the rangeland for a given period in order to preserve
131 resources were observed. The only grazing restriction concerns sown fields, and ends after
132 harvesting. Acacia woodlands are thus common rangelands, occasionally used for cereal
133 cultivation in suitable areas. Neighbouring villagers and semi-nomads also harvest fuel wood,
134 raw materials or medicines.

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2.2 RESEARCH METHODS

Seven one-month stays at different seasons of the first author in the El Borj and Taidalt villages from February 2013 to June 2014 enabled the identification of (1) human activities and practices related to acacia stands and (2) the place and schedule of these activities. Information was obtained from semi-nomads and settlers through semi-structured and informal interviews, participative observation and transects. Interviews focused on local uses and practices related to the *V. raddiana* tree. In particular, farmers were asked about the role of *V. raddiana* in crop fields and how they were managing trees. Herders and shepherds were questioned on the way they used and integrated *V. raddiana* within the framework of their pastoral activities. In addition to interviews, a total of 25 days between March 2013 and June 2014 were dedicated to participative observation, with a diverse panel of farmers, charcoal producers and herders. Livestock browsing is a structuring activity in arid environments, both for human societies and ecosystems. Nevertheless, the unpredictability and stochasticity of pastoral systems in drylands – including opportunistic behaviour, mobility, livestock variations, etc. (Niamir-Fuller, 1998) – challenge quantitative assessment from snapshot studies and the relevance of certain indicators such as the pastoral pressure. Furthermore, because of the absence of any unbrowsed area in the study site, assessing the impact of browsing on the vegetation without long-term experimental procedures was impossible. Thus our investigations focused on understanding general spatio-temporal patterns of livestock management and on identifying the nature of human practices related to pastoral activities. Interviews with the local forester at the beginning and at the end of the research also helped to confirm information obtained from villagers and observations. A general land use map of the study zone was compiled, based on geomorphology and main human activity (Fig. 2). A set of measurable indicators of the influence of human practices on *V. raddiana* trees, at the individual and stand scales, was determined (Table 1).

162 Table 1: Human activities and practices influencing *V. raddiana* stands and associated
 163 measurable indicators and indexes

Activities	Related practices	Purposes	Measurable indicator	Corresponding index influenced by the practice
Agriculture	Pruning and trimming	Shaping trees for shade	Number of visible scars	<i>PI</i> (pruning intensity)
	Tree removal	Controlling tree density inside fields	Tree density	<i>R</i> (distance to the nearest tree) <i>λ</i> (calculated tree density)
Livestock farming	Leaves hanging	Feeding animals	State of the tree foliage	<i>GI</i> (Greenness index)
	Pods hanging	Feeding animals	Pods number	<i>TRR</i> (Total regeneration rate) <i>ERR</i> (Established regeneration rate)
	Debarking	Feeding animals	Tree bark state	<i>DI</i> (debarking intensity) <i>DP</i> (debarking probability)
Wood harvesting	Pruning and trimming	Firewood and charcoal production	Number of visible scars	<i>PI</i>
	Felling entire tree	Charcoal production	Number of visible stumps	Count of the number of visible stumps
Medication	Leaves harvest	Medicine preparation	State of the tree foliage	<i>GI</i>
	Gum exudates collect	Medicine and tea preparation	No measurable impact on trees	-
	Pods hanging	Medicine preparation	Pods number	<i>TRR</i> <i>ERR</i>
	Debarking	Medicine preparation	Tree bark state	<i>DI</i> <i>DP</i>

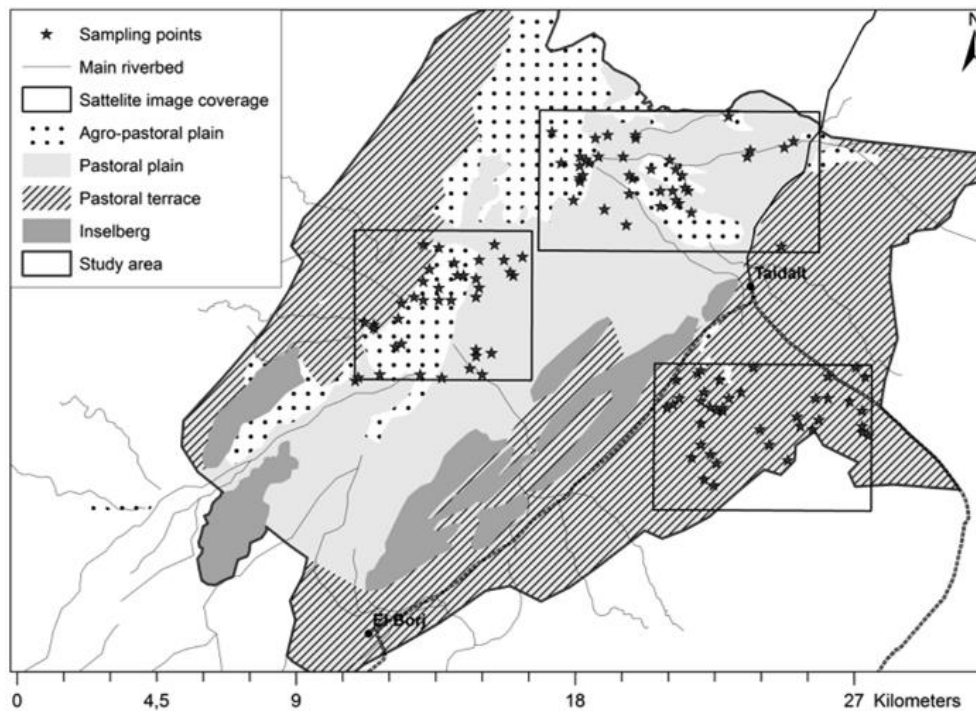
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2.3 SAMPLING DESIGN

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167 The delimitation of *V. raddiana* sparse stands required the preliminary mapping of tree density
 168 from three high-resolution Digital Globe satellite images, extracted from Google Earth and
 169 dated February 2011. Two images (covering 62 km²) covered the plain, and the third one (22
 170 km²) the terraces. The detection of individual tree canopies was performed under the ArcMap
 171 10.0 software, resulting in three tree density maps used to implement the sampling design (Fig.
 172 2). A total of 120 sampling points were randomly computed in order to take into account the
 173 population heterogeneity and to have the same number of points on each map and in each
 174 density class. The sample was thus stratified according to topography and tree density, and
 175 represented contrasted land use modalities and microhabitats. It consequently allowed testing
 176 the effect of environmental (topography and microhabitat) and of anthropogenic (land use)
 177 factors on the structure and dynamics of acacia stands.



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Figure 2: Land use modalities and sampling design distribution in the study area.

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2.4 TREE INVENTORY AND MEASUREMENT

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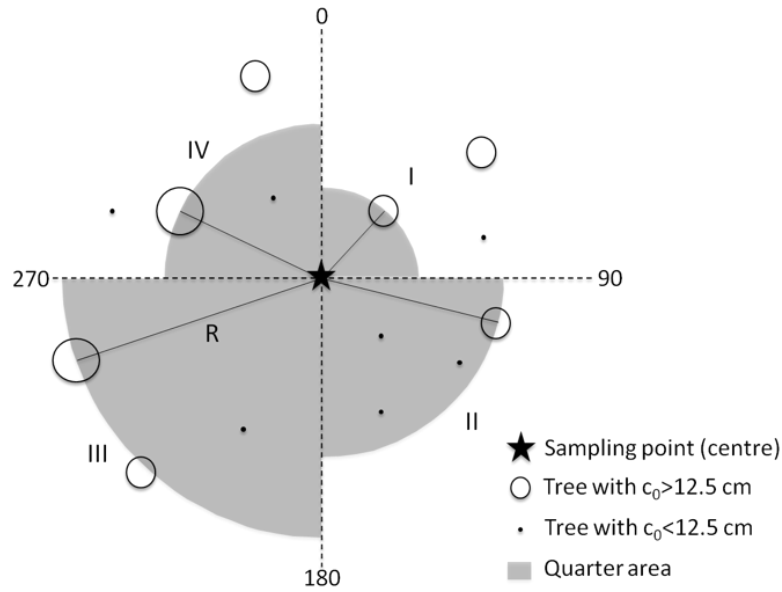
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Sampling points were identified in the field with a Garmin 62 GPS. The Point-Centred Quarter Method (PCQM) was chosen for its accuracy regardless of stem density heterogeneity (Sparks et al., 2002) and for its feasibility for a single operator. PCQM consists in the delimitation of four quarters (here delimited according to the cardinal points) and in the measurement in each quarter of the nearest tree from the centre (Fig. 3).



190

191 Figure 3: PCQM-plot design. Distances of the nearest tree from the centre (R) define quarter
 192 area. One tree was measured per quarter; understory composition, regeneration and stumps
 193 counts concern the whole grey area.

194

195 The nearest tree (with a circumference at ground level $c_0 > 12.5$ cm) was located and its distance
 196 R from the centre was measured with a tape for $R < 30$ m or was calculated with the GPS for
 197 $R > 30$ m. The tree species was identified and we measured the total height (H), the
 198 circumference at ground level (c_0) of every tree stem with $c_0 > 12.5$ cm, two perpendicular
 199 canopy diameters (D_{max} and D_{min}), and the first green leaf height (h). The debarking intensity
 200 (DI) was estimated as the percentage of trunk debarked and the pruning intensity (PI) through
 201 a count of visible scars. Tree vitality was subjectively assessed through a greenness index (GI ,
 202 0: no green leaves; 1: green leaves covering less than 50% of the total canopy; 2: green leaves
 203 covering between 50 and 90% of the canopy; 3: dense and totally green canopy) (Andersen &
 204 Krzywinski 2007). If the nearest tree was more than 100 m away from the centre, the quarter
 205 was considered as vacant, *i.e.* containing no tree. Inside the quarter area, visible stumps were
 206 counted and the three dominant shrub species were noted. *V. raddiana* regeneration was
 207 counted by distinguishing seedlings ($10 \text{ cm} < H < 50 \text{ cm}$ and $c_0 < 12.5 \text{ cm}$) and saplings ($H > 50 \text{ cm}$
 208 and $c_0 < 12.5 \text{ cm}$). Topography was coded as plain or terrace. Land use was either only pastoral
 209 or agro-pastoral (in areas occasionally used for cereal cultivation). Finally, topography and land
 210 use were mixed into three land use modalities: (pastoral) terrace, agro-pastoral plain and
 211 pastoral plain (no cereal cultivation was practised on terrace). Tree microhabitat was

212 determined as floodplain, main channel, secondary channel or interfluve (Stavi et al., 2014).
 213 Table 2 shows the number of quarters per land use and microhabitat.

214

215 Table 2: Tree species in the 468 quarters and their distribution in land use modalities and
 216 microhabitats

	<i>Vachellia tortilis</i> subsp. <i>raddiana</i>	<i>Vachellia</i> <i>flava</i>	<i>Argana</i> <i>spinosa</i>	<i>Ziziphus</i> <i>lotus</i>	Vacant	Total
Terrace	145	0	8	0	19	172
Main channel	15	-	6	-	2	23
Secondary channel	65	-	-	-	-	65
Floodplain	65	-	2	-	2	69
Interfluve	-	-	-	-	15	15
Pastoral plain	148	0	1	20	34	203
Main channel	35	-	1	4	9	49
Secondary channel	9	-	-	1	-	10
Floodplain	104	-	-	15	25	144
Interfluve	-	-	-	-	-	-
Agricultural plain	67	1	1	15	9	93
Main channel	2	-	-	4	-	6
Secondary channel	2	-	1	2	-	5
Floodplain	63	1	-	29	9	102
Interfluve	-	-	-	-	-	-
Total	360	1	10	35	62	468

217

218 2.5 VARIABLES AND STATISTICS

219

220 Tree basal area (BA) was calculated as $BA = \sum c_0 / (4\pi)$. Total trunk diameter (d_0) was deduced
 221 from BA as $d_0 = \sqrt{4BA/\pi}$. Canopy was assumed to be an ellipse for the calculation of canopy
 222 area as $CA = \pi \cdot D_{max} \cdot D_{min} / 4$. A shape index ($SI = H/d_0$) was defined to characterize the general
 223 shape of *V. raddiana*. Because of the presence of vacant quarters, the Warde and Petranksa
 224 (1981) method was used for tree density calculation. Tree density was defined as $\lambda = CF/R'^2$
 225 with CF the Warde and Petranksa correction factor and $R' = \sum_{l=1}^{4n-n_0} R / (4n-n_0)$ with $4n$ the total
 226 quarter number, R the distance from the sampling point to the nearest tree, and n_0 the vacant
 227 quarter number. The relative density for a species i was calculated as $\sum n_i / (4n-n_0)$ with n_i the
 228 number of quarters with the species i . A Principal Components Analysis (PCA) was performed
 229 from quantitative variables (*i.e.* R , d_0 , H , h , CA , SI , DI , GI and PI) in order to study tree
 230 heterogeneity and the contributions of variables.

231 Total regeneration was calculated by summing seedling and sapling numbers. Total
 232 Regeneration Rate (TRR) was defined as the ratio between total regeneration and the number
 233 of adult trees measured. Established regeneration – and corresponding Established

234 Regeneration Rate (*ERR*) – was calculated from saplings. The debarking probability (*DP*) was
235 defined as the percentage of debarked trees. Mortality was assessed from the number of visible
236 stumps and dry trees (*i.e.* greenness index = 0).

237 Non-parametric Kruskal-Wallis analysis of variance enabled testing of the distribution
238 difference among groups. When the null-hypothesis was rejected, the non-parametric Dunn test
239 was used to identify the stochastic difference between groups. When hypotheses of normal
240 distribution (Shapiro test) and homoscedasticity (Bartlett test) were verified, ANOVA was used
241 instead of Kruskal-Wallis. Correlations were tested with the Spearman test for quantitative
242 variables. The statistical analysis was computed with the R software [[http://www.R-](http://www.R-project.org/)
243 [project.org/](http://www.R-project.org/)]. The null-hypothesis was rejected at a significance level of 5 %.

244

245 3. Results

246

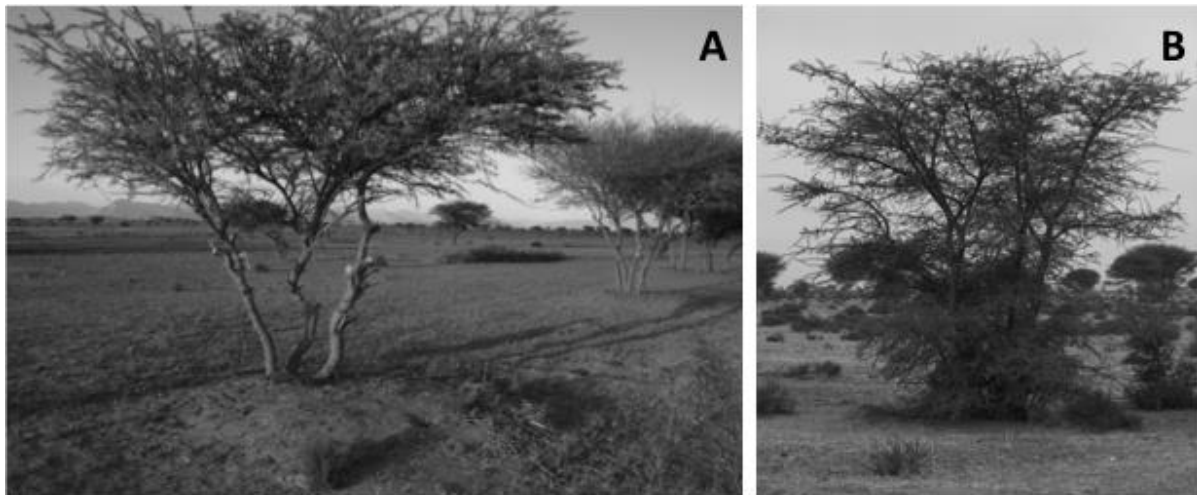
247 3.1 ACACIA STANDS AND HUMAN ACTIVITIES

248

249 3.1.1 Acacia trees and agricultural activities

250 Cultivation in the agro-pastoral plain depended on the date of the flood episode and the amount
251 of rainfall. In the study area, on a potential arable area of 1 400 ha, the effectively cultivated
252 area was 52.2 ha in 2013 and 173.9 ha in 2014. Cultivation work starts just after the flood
253 episode, between one or two weeks after the rainfall. During the same day, each farmer hand-
254 sows grains, and then disks his field with a tractor. Tractors are owned by wealthy farmers and
255 are rented to others. All farmers use mechanized disking, and animal-drawn tillage is no longer
256 practised in this area. In both years, the harvest was taken in by hand in May and June, but for
257 more productive years, a combine harvester may be rented in the closest city.

258 Farmers do not appreciate small acacia trees or other shrubs in their fields, because they
259 represent an obstacle for machines, but they do not systematically remove acacia saplings: “As
260 we don’t farm every year, acacia trees grow. We have not farmed here for three years now, and
261 look how many [acacia trees] have grown. It’s good to farm this year: if we don’t, the whole
262 area will be full of acacia trees” (Taidalt farmer, June 2013). In contrast, they appreciate large
263 acacia trees, mainly for their shade or as windbreaks. To obtain shade, people “clean” trees (*i.e.*
264 they trim lowest branches) to force them to “rise” (*i.e.* to develop a distinct canopy) (Fig. 4A).
265 Without any human intervention, farmers consider acacia tree grows as a windbreak (Fig. 4B).
266 Farmers consequently manage tree regeneration during cultivation periods in selecting saplings
267 according to their shape and their location.



268

269 Figure 4: Contrasting management practices of *V. raddiana* trees in the agro-pastoral plain. A:
 270 aligned pruned tree dedicated to shade and frontier materialization; B: un-pruned tree acting
 271 as a windbreak.

272

273 3.1.2 Acacia trees and pastoral activities

274 Like the rest of the study area and despite occasional cultivation, the agro-pastoral plain is
 275 essentially a rangeland. *V. raddiana* trees are thus primarily conserved in the agro-pastoral plain
 276 for their pastoral value: “If I cut an acacia tree today and a camel or a goat comes tomorrow,
 277 what will he [she] eat?” (Shepherd, February 2014). Both sedentary and semi-nomadic herds
 278 browse the area. Sedentary herds for a household do not exceed 20 animals. When grasses and
 279 herbs are available, herds are grouped – due to their small size – and given to a paid shepherd
 280 who herds them around the village (to a radius of about 10 km). In 2013, Taidalt villagers
 281 employed three shepherds. One of them, for example, was employed between April and July
 282 2013 by 16 villagers to herd a total of 138 goats and 44 sheep. Semi-nomadic herds of goats
 283 and sheep are bigger (from 150 heads) and may include dromedaries. Their pastoral area ranges
 284 from the southern border with Mauritania (more than 1 000 km from the study site) to less
 285 clearly defined northern limits. They usually do not go further than 100 km north, except in the
 286 case of severe drought. In 2013 and 2014, they were particularly numerous in the study area
 287 between March and August, where they settled and grazed, mostly in the plain.

288 Acacia trees are highly sought by livestock for their mature pods in April-May (period called
 289 *tawadi*) and leaves in August (*smeim*). They therefore constitute a highly valued standing
 290 source of forage in a context of general uncertainty, especially in periods of shortage: “If there
 291 is an abundance of herbs, during a wet year, goats won’t eat acacia pods between May and
 292 August. They will eat only few of them. So, pods stay on the ground and goats will eat them in

293 August or September, when herbs are dry” (Herder, February 2014). Herders and shepherds
294 may consequently hang pods and leaves from acacia trees to feed animals. For instance, the
295 shepherd employed in 2013 by settlers in Taidalt went for two days to an area where he was
296 told there were a lot of acacia pods. On this occasion, an iron rod was used to hang pods from
297 acacia trees. Herders used to debark trees in the case of severe drought, especially to feed
298 camels. But all interviewed settlers and semi-nomads affirmed they no longer practised
299 debarking as they preferred buying state-subsidized grain as food complement. This was
300 confirmed by our observations and by the local forester.

301

302 3.1.3 *V. raddiana* trees exploitation

303 Local foresters do not consider the study site as an area of commercial charcoal production.
304 During the survey, only one charcoal burner, in Taidalt village, was identified and observed in
305 his activities. The charcoal burner either prunes or cuts entire living trees with a small axe.
306 Wood is then gathered in a 2x1 m coalhole with donkey-drawn cart. After a three-hour
307 carbonization process, charcoals cool down for eight hours and are gathered in two to three
308 large bags to be sold in Taidalt village (from 110 to 130 MAD/bag). Thus, up to 15 bags a week
309 could be produced. The charcoal producer was active only during periods of unemployment, so
310 the charcoaling activity varied from year to year and over the course of a year.

311 In addition to commercial charcoal, semi-nomads harvest domestic fuel wood. All informants
312 assert they only prune dry branches, perceived as sufficient to meet domestic needs. This was
313 confirmed by the local forester: “Here in the province, the charcoal production does not
314 represent a big issue. People only produce charcoal for self-consumption. And they mostly use
315 gas. And they mostly use dry and dead branches” (Local forester of Guelmim province,
316 February 2014).

317 Finally, *V. raddiana* is a source of medicines for people who use its gum, leaves and pods in
318 the local pharmacopeia. Gum is collected exclusively from exudates during summer. Given the
319 northern location of the study site, people considered that *V. raddiana* does not produce a lot
320 of gum there.

321 Altogether, these uses and practices may influence, together with environmental factors, several
322 measurable tree and stand parameters (Table 1).

323

3.2 STRUCTURE OF ACACIA STANDS

3.2.1 Distribution and individual variability

V. raddiana was the dominant tree species with a relative density of 79.6%, associated with *Ziziphus lotus* in sandy plain (7.5%) and *Argania spinosa* (L.) Skeels in terrace (2.1%). Vacant quarters occupied 13.2% of the sample (Table 2). *Hammada scoparia* (found in 94% of the quarters) and *Launaea arborescens* (Batt.) Murb. (46%) dominated the shrub layer. Some species were specific to particular habitats, e.g. *Stipagrostis pungens* (Desf.) de Winter on sandy soils, *Retama raetam* (Forssk.) Webb in main riverbeds or *Traganopsis glomerata* Maire & Wilczek on rocky terrace soils. Most quarters were located in floodplain microhabitat (Fig. 5) and 77.3% of them included a *V. raddiana* tree. Secondary channels had the highest probability of including an acacia tree (96.2%) while no measurable tree was found in interfluves.

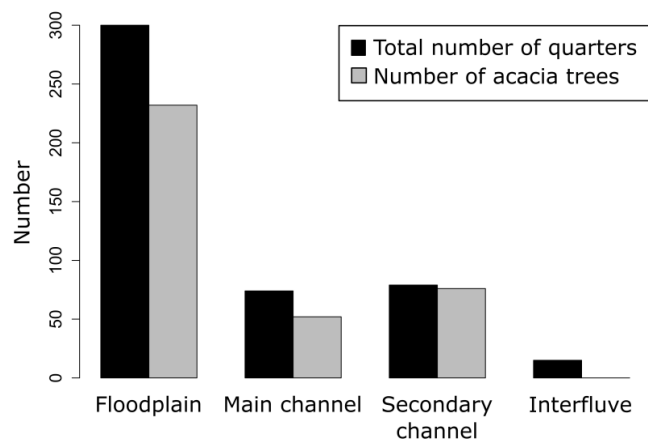
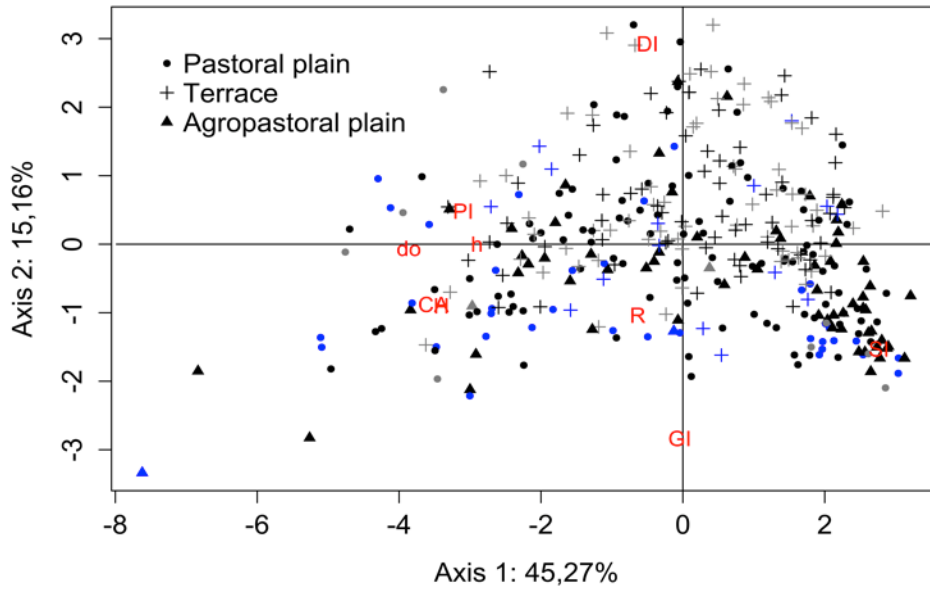


Figure 5: Numbers of quarters and acacia trees by microhabitat.

The two-dimensional projection of *V. raddiana* individuals explained about 60% of the total variance of the PCA (Fig. 6). Size parameters (*CA*, *do*, *H*) contributed to the first axis and explained 45.27% of the variance. The second axis explained 15.16% of the variance and was associated with greenness index and debarking intensity. Individuals from the three microhabitats and from the three land use modalities were mixed in the PCA plan (Fig. 6). *V. raddiana* size was mainly influenced by land use and microhabitat; topography had less effect (Table 3). Dunn tests additionally distinguished agro-pastoral plain trees from terrace and pastoral plain trees. Tree vitality and exploitation were affected by land use, microhabitat and topography (Table 3). Dunn tests revealed significant differences in vitality and exploitation between the three land use modalities, the three microhabitats and the two topographic contexts.



350

351 Figure 6: Acacia trees and variables projection in the PCA two-dimensional plan by land use
 352 modalities (symbols) and microhabitats (floodplain in black, main channel in grey, secondary
 353 channel in blue). Considered variables (named in red) are: canopy area (*CA*), trunk diameter
 354 (*do*), tree height (*H*), first leaf height (*h*), shape index (*SI*), distance from the centre (*R*).

355

356 Table 3: Effects of land use, microhabitat and topography on *V. raddiana* size variables,
 357 greenness index, debarking and pruning intensity (Kruskal-Wallis tests p-value)

		Land use	Microhabitat	Topography
Size variables	<i>do</i>	0.009**	0.078	0.864
	<i>CA</i>	0.003**	0.023*	0.096
	<i>H</i>	0.009**	0.023*	0.042*
	<i>h</i>	0.489	0.793	0.499
	<i>SI</i>	<0.001***	0.204	<0.001***
Vitality variable	<i>GI</i>	<0.001***	<0.001***	<0.001***
Exploitation variables	<i>DI</i>	<0.001***	0.005**	<0.001***
	<i>PI</i>	0.002**	0.130	0.090

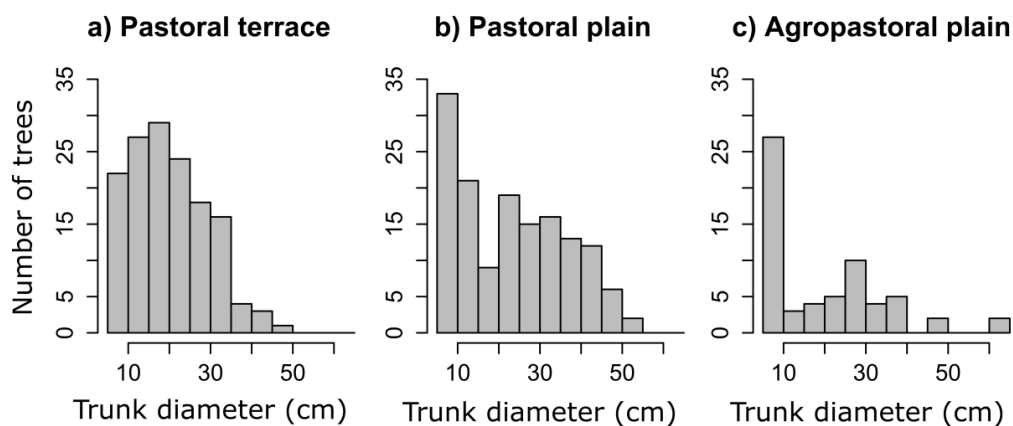
358 * Significant effect at $p < 0.05$; ** significant effect at $p < 0.01$; *** significant effect at $p < 0.001$.

359

360 3.2.2 Land use effect on the structure of acacia stands

361 *V. raddiana* were small trees with a mean height of 2.9 m (± 1.3 SD) and a maximum height of
 362 9.0 m. Small trees in terms of trunk diameter were predominant in pastoral and agro-pastoral
 363 plain (Fig. 7). In terrace, there were fewer 5-10 cm and 10-15 cm trunk diameter trees than 15-
 364 20 cm trees. The agro-pastoral plain had the highest ratio of both small trees and the largest
 365 trees. Individual parameters varied by land use (Table 4). In terrace and agro-pastoral plain,

366 tree heights (Dunn test; $p=0.45$) and canopy areas ($p=0.21$) were similar, and differed from
 367 those of the pastoral plain (all $p<0.01$). Tree diameter differentiated pastoral plain and terrace
 368 trees ($p=0.09$) from agro-pastoral plain trees (all $p<0.03$). Greenness index was similar in
 369 pastoral and agro-pastoral plain ($p=0.28$) when compared to terrace (all $p<0.001$). The shape
 370 index was different between the three land use modalities (all $p<0.03$).
 371 The mean distances to the nearest tree (R) were 38.6 m (± 22.5 SD) in terrace, 41.3 m (± 23.9
 372 SD) in pastoral plain and 39.2 (± 22.8 SD) in agro-pastoral plain. Corresponding tree densities
 373 per hectare were 5.2 in terrace, 4.0 in pastoral plain and 6.1 in agro-pastoral plain. The distance
 374 R was influenced by land use (ANOVA; $F\text{-value}=3.388$; $p=0.035$), but differences were
 375 significant only between pastoral and agro-pastoral plains (Wilcoxon test; $p=0.02$). The
 376 microhabitat also influenced the distance R (Kruskal-Wallis test; $p<0.001$) with mean values of
 377 44.6 (± 29.3 SD) in floodplain, of 56.0 (± 30.0 SD) in main channel and of 39.0 (± 20.2 SD) in
 378 secondary channel. The differences were significant between all pairs (Dunn tests; all $p<0.001$),
 379 except between floodplain and secondary channel ($p=0.20$).
 380



381
 382 Figure 7: *V. raddiana* tree size distribution by land use (for trees with $d_0 > 5$ cm).
 383

384 3.3 DYNAMICS OF ACACIA STANDS

385 386 3.3.1 *V. raddiana* regeneration

387 Total regeneration was represented by 377 individuals including 205 seedlings and 172
 388 saplings. Regeneration concerned 24% of terrace, 20% of pastoral plain and 49% of agricultural
 389 plain quarters; and 28% of floodplain, 23 % of main channel, 30% of secondary channel and
 390 20% of interfluvial quarters. Regeneration density was highly heterogeneous with 4.6
 391 individuals/ha (± 17.2 SD) in terrace, 4.3 (± 20.1 SD) in pastoral plain and 28.7 (± 65.5 SD) in

392 agro-pastoral plain. Land use significantly influenced regeneration density (Kruskal-Wallis
 393 test; $p < 0.001$); Dunn test contrasted agro-pastoral plain with pastoral plain and terrace.
 394 Conversely, no microhabitat effect on the regeneration density was found (Kruskal-Wallis tests;
 395 $p = 0.50$). The lowest regeneration rate was in terrace while agro-pastoral plain had the highest
 396 score (Table 4).

397

398 Table 4: Main *V. raddiana* stand parameters by land use (mean values are given with
 399 standard-deviation and Kruskal-Wallis tests p-value)

		Pastoral terrace	Pastoral plain	Agro-pastoral plain	p-value
Size variables	<i>H</i> (m)	2.7 ± 0.9	3.2 ± 1.3	3.0 ± 1.7	$p < 0.01$
	<i>d_o</i> (cm)	19.8 ± 9.2	23.0 ± 13.3	18.7 ± 14.5	$p < 0.01$
	<i>SI</i>	0.15 ± 0.05	0.17 ± 0.07	0.20 ± 0.07	$p < 0.001$
	<i>CA</i> (m ²)	16.3 ± 12.3	26.8 ± 24.3	24.0 ± 33.1	$p < 0.01$
Total regeneration	count	73	69	235	
	<i>TRR</i>	50.3%	46.6%	350.7%	
Established regeneration	count	23	31	118	
	<i>ERR</i>	15.9%	20.9%	176.1%	
Mortality	stumps count	4	7	0	
	dead trees	1	0	0	
	Mortality rate	3.4%	4.7%	0%	
	Mean <i>GI</i>	1.88 ± 0.55	2.25 ± 0.69	2.31 ± 0.58	$p < 0.001$
Greenness index	0	0.7%	0	0	
	1	20.0%	14.2%	6.0%	
	2	70.3%	46.6%	56.7%	
	3	9.0%	39.1%	37.3%	

400

401 3.3.2 *V. raddiana* mortality and human exploitation

402 Eleven visible stumps were noted in five quarters (three in terrace and two in pastoral plain)
 403 and one dry tree was found, leading to low mortality rates (Table 4). Most wood exploitation
 404 was done by pruning and trimming: 60.3% of *V. raddiana* trees were pruned, with an average
 405 of 5.4 (± 7.0 SD) scars per tree. The pruning intensity was influenced by land use (Kruskal-
 406 Wallis test; $p < 0.01$) but this effect disappeared when corrected by tree size.

407 The main identified cause of debarking was donkeys. Debarking concerned 122 (33.9%) *V.*
 408 *raddiana* trees (42.1% of terrace, 35.1% of pastoral plain and 13.4% of agro-pastoral plain
 409 trees). Debarking probability was dependent on tree size (Kruskal-Wallis test; $p < 0.001$).
 410 Debarking intensity (*DI*) was positively correlated with trunk diameter (Spearman test;
 411 $p < 0.001$; $\rho = 0.26$). Debarking concerned between 31.8 and 55.6% of trees with $d_o > 15$ cm,
 412 11.0% of the 5-10 cm trees, and 17.6% of the 10-15 cm trees. Land use had no effect on *DI*
 413 after tree size correction (Kruskal-Wallis tests; all $p > 0.15$), except for the trees with $d_o < 10$ cm

414 ($p < 0.01$), which showed higher *DI* in terrace than in pastoral and agro-pastoral plains (Dunn
415 test; $p < 0.001$).

416

417 3.3.3 *V. raddiana* vitality

418 Most *V. raddiana* trees had a greenness index of “2” (Table 4). Pastoral and agro-pastoral plains
419 showed a higher percentage of trees with a greenness index of “3” and a lower percentage of
420 trees with a greenness index of “1” than terrace (Table 4). Greenness index was not correlated
421 with trunk diameter (Spearman test; $p = 0.54$) or canopy area ($p = 0.06$) and was negatively
422 correlated with debarking intensity ($p < 0.001$; $\rho = -0.21$). Land use influenced greenness index
423 (Kruskal-Wallis test; $p < 0.001$); Dunn tests contrasted terrace with agro-pastoral and pastoral
424 plains. The effect of land use on greenness index was significant even after excluding trees with
425 $d_o < 10$ cm (Kruskal-Wallis test; $p < 0.001$), and showed the same discrepancy between terrace
426 and pastoral and agro-pastoral plains. Greenness index correlated with debarking intensity in
427 agro-pastoral (Spearman test; $p < 0.001$) and pastoral ($p < 0.01$) plain but not in terrace ($p = 0.82$).
428 Thus, greenness index depended on both topography and debarking.

429

430 4. Discussion

431

432 4.1 FUNCTIONS AND STRUCTURE OF *V. RADDIANA* STANDS

433

434 4.1.1 Socio-ecological roles of *V. raddiana*

435 In the study site, *V. raddiana* trees are spatially and functionally embedded within a complex
436 human subsistence system, which confirms that acacia trees are of major importance for
437 Sahrawi agro-pastoralists (Volpato and Puri, 2014). Farmers use mature man-shaped acacia
438 trees in their fields as shelters against the harshness of the climate (sun and winds), despite their
439 drawbacks in terms of machine accessibility and cereal productivity (Noumi et al., 2011). Trees
440 are also useful for land-ownership identification (Figure 2A) and as an aid to orientation
441 through the plain. One educated villager also mentioned that *V. raddiana* slows down water
442 flow and soil erosion, which nevertheless is not a widespread justification among farmers.
443 However, farmers do not plant nor transplant acacia trees in their fields and the renewal of the
444 tree population seems to be ensured because grain cultivation is occasional. Farmers manage
445 natural regeneration by regulating tree density and by pruning young and mature trees. In doing
446 so, they may consequently influence tree spatial distribution, shape and selection but may not
447 drastically change the spatial patterns of acacia stands through the landscape.

448 For herders, *V. raddiana* tree is particularly crucial during the dry season because of (1) its
449 evergreen canopy and (2) its production of leaves and mature pods when forage is scarce
450 (Andersen et al., 2014). *V. raddiana* presents in this season a high palatability and nutritive
451 value, especially for crude protein requirements (Heneidy, 1996). It has also an indirect forage
452 value through the overall improvement of rangeland understory (Abdallah and Chaieb, 2010).
453 The importance of *V. raddiana* as a valuable resting area for shepherds and animals is also well
454 known (Munzbergova and Ward, 2002). Shepherds used to cut branches and remove bark
455 during severe droughts to feed their animals, especially dromedaries and young goats. The
456 access to state-subsidized food complements could have led to the disappearance of this
457 practice. During tree inventories, no severe canopy damage was observed, which confirmed
458 informant information. Today, state subsidies for animal husbandry in the case of drought could
459 have greatly contributed to the evolution of *V. raddiana* uses and thus may have favoured acacia
460 conservation in these regions. Further socio-economic and historical studies on husbandry may
461 be necessary to confirm this assumption, notably because the access to markets may also have
462 played an important role.

463 Finally, the *V. raddiana* tree is harvested for firewood, charcoal and medicinal products, which
464 in certain regions constitutes a major obstacle to its conservation (Andersen and Krzywinski,
465 2007). At the study site, no local regulation legislation is in force while commercial charcoal
466 production is considered as a critical threat by informants. Moroccan forestry legislation forbids
467 wood harvesting, but the implementation of this legislation is however hampered by staff
468 shortages. The weakness of local and governmental institutions regarding tree harvest control
469 and regulation may contribute to the vulnerability of acacia stands and better enforcement is
470 required.

471

472 4.1.2 The heterogeneity of acacia stands

473 *V. raddiana* are small trees forming irregular and scattered stands (Noumi and Chaieb, 2012;
474 Ward and Rohner, 1997). Our measurements of tree height and canopy area were similar to
475 those found in other studies (Lahav-Ginott et al., 2001; Noumi et al., 2010b). In Tunisia, tree
476 density was five trees/ha (Noumi and Chaieb, 2012) and it ranged from 0.4 to 16 trees/ha in the
477 Negev Desert (Andersen and Krzywinski, 2007; BenDavid-Novak and Schick, 1997). Our
478 results indicate comparable densities, influenced by microhabitat and human activities. The
479 microhabitat effect was investigated by Stavi et al. (2014) who suggested that intensive floods,
480 in uprooting trees, may limit tree density in certain microhabitats, such as main channels.
481 Additionally, water and local variation in the runoff regime may have a considerable impact on

482 the distribution and density of *V. raddiana* stands (Lahav-Ginott et al., 2001). But other
483 environmental factors may play a role (*e.g.* soil fertility) and further study would be necessary
484 to address the origin of the microhabitat effect.

485 Tree inventory revealed a decreasing tree size distribution pattern, indicating a positive trend
486 in *V. raddiana* dynamics. In contrast, the literature more often offered negative perspectives
487 (Noumi and Chaieb, 2012; Ward and Rohner, 1997), except the work of Lahav-Ginott et al.
488 (2001). Our results indicated a weak effect of topography or microhabitat on acacia tree size,
489 in contrast to land use. In the agro-pastoral plain, *V. raddiana* stands contained the biggest trees
490 and showed especially high recruitment rates. In addition, topography had also an effect on
491 recruitment, with lower values in pastoral terrace than in pastoral plain. Thus, at the stand scale,
492 *V. raddiana* structure was influenced by environmental (*i.e.* topography and microhabitat) and
493 anthropogenic (*i.e.* land use) factors. While the agro-pastoral use of the landscape was
494 positively correlated with tree recruitment and density, further study would be required to
495 distinguish the respective roles of environmental and anthropogenic factors.

496

497 4.2 HUMAN INFLUENCE ON ACACIA STAND DYNAMICS

498

499 4.2.1 *V. raddiana* regeneration

500 With high regeneration density and low mortality rate, our results underlined a regenerative
501 dynamic, especially in the agro-pastoral plain. Tree regeneration in drylands strongly depends
502 on water availability (Larwanou and Saadou, 2005). The germination of *V. raddiana* seeds
503 additionally requires high temperatures (Danthu et al., 2003). Thus, both temporality and
504 intensity of rainfall have to be considered. *V. raddiana* regeneration may also be strongly
505 affected by an alteration of water surface flows (BenDavid-Novak and Schick, 1997; Ward and
506 Rohner, 1997). One may assume that farmers cultivate areas that offer the best water conditions
507 and thus that agro-pastoral plains may have better water status than pastoral lands. In addition,
508 farmers maintain traditional dams and flatten cultivated areas in order to maximize runoff
509 harvesting and the surface area flooded and also to minimize the flow velocity. In addition,
510 tractor disking may contribute to breaking the soil pellicle and increases soil water infiltration,
511 notwithstanding its possible detrimental effects on soil water storage and hydraulic conductivity
512 (McGarry et al., 2000). Overall, land planning for agriculture and farming practices may
513 contribute (1) to burying and protecting seeds, and (2) to creating a favourable microhabitat for
514 germination (Noumi et al., 2010a). Hence, scattered agricultural activities under these extreme
515 conditions may promote acacia regeneration.

516 Secondly, moderate browsing is recognized as contributing to the regeneration of *V. raddiana*
517 (Rohner and Ward, 1999), through seed dispersal (Miller, 1996), enhanced germination
518 (Danthu et al., 2003) and trampling (Noumi et al., 2010b). Unfortunately, the influence of
519 browsing is difficult to assess in a field snapshot for mobile and open-access systems (Andersen
520 and Krzywinski, 2007), which prevented us from studying the direct effect of browsing.
521 Nevertheless, our results showed that *V. raddiana* regeneration, establishment and survival
522 were effective under the observed agro-pastoral practices. This suggests a sustainable use of *V.*
523 *raddiana* trees within the framework of the current agro-pastoral system. To go further in the
524 understanding of acacia regenerative dynamics in this area, it would be necessary to investigate
525 (1) the effect of domestic herds on seed dispersal, germination and seedling survival and (2) the
526 effect and intensity of seed predation by insects (Derbel et al., 2007), which is a major issue for
527 *V. raddiana* regeneration elsewhere (Noumi et al., 2010a).

528

529 4.2.2 *V. raddiana* mortality and human exploitation

530 High *V. raddiana* mortality (up to 16.8%) was reported in the Negev Desert (Stavi et al., 2014).
531 Considering our contrasting results, *V. raddiana* mortality may be a problem specific to that
532 area. Mortality may be related to climate change (Stavi et al., 2014), road construction (Ward
533 and Rohner, 1997) or charcoal production (Andersen and Krzywinski, 2007). In our case,
534 charcoal production (assessed from visible stumps) induced most tree death but remained weak.
535 The low mortality rates, following three successive dry years, highlight the high tolerance of *V.*
536 *raddiana* to drought (Andersen et al., 2014). Informant information corroborates that acacia
537 trees rarely die from drought, but this would require further specific studies to be better
538 understood.

539 Debarking affected one third of acacia trees. All informants (from local people to foresters)
540 suggested that debarking trees to feed animals is no longer practised and that current debarking
541 was mainly caused by donkeys. Consistently with MacGregor and O'Connor (2004), we found
542 that debarking was correlated with tree size and was unlikely to cause tree death. Only partial
543 debarking was observed, which may not be sufficient to kill trees (Moncrieff et al., 2008).
544 Debarking had however an impact on canopy greenness in plain, in contrast to terrace. In
545 assuming that water availability is the main limiting factor for acacia tree vitality (Wiegand et
546 al., 2000a), the effect of debarking may be visible when water becomes less constraining.
547 Debarking may thus affect tree growth (Scogings and Macanda, 2005) and increase water stress,
548 contributing to tree vulnerability in the face of severe drought. Furthermore, small trees were
549 more often debarked in terrace than in plain. Because of lower vitality and higher water scarcity,

550 an acacia tree in terrace may be older than a same-sized acacia in plain (Martin and Moss,
551 1997). Small terrace trees may consequently have been longer exposed to bark predators (either
552 people or animals) than plain trees. The access to the trunk may also influence debarking.
553 Because of their higher vitality in plain, small *V. raddiana* trees had higher canopy density and
554 a bushier configuration there (pers. obs.). Small terrace tree trunks may thus be more accessible.
555 Finally, debarking depends on the animals' preferences and forage availability (Scogings and
556 Macanda, 2005), which may be lower in terrace.

557

558 4.3 PERSPECTIVES FOR RESEARCH ON SAHARAN ACACIA TREES

559

560 4.3.1 Acacia trees and people: a currently sustainable cohabitation?

561 Assessing the effect of human practices on tree ecology remains a challenge as measurable tree
562 parameters are also influenced by numerous other environmental factors (*e.g.* greenness index
563 depends on human exploitation and on drought harshness levels, tree density depends on tree
564 removal and selection by people and on abiotic factors, etc.). This study however showed that
565 altogether, the socio-ecological roles of *V. raddiana* encourage Sahrawi agro-pastoralists to
566 conserve, protect and shape trees. The management practices of acacia trees in the agro-pastoral
567 plain, together with environmental factors, resulted in relatively dense and, at the time of the
568 study, regenerating tree stands. In addition, current wood exploitation did not represent a threat
569 to the sustainability of *V. raddiana* trees, despite the powerlessness of the regulatory authorities.
570 Clearly, snapshot studies constitute a starting point to the understanding of drylands, because
571 of the high stochasticity and the low predictability of environmental factors and of tree stands
572 dynamics (Wiegand et al., 2000b). Moreover, as those dynamics commonly differ between
573 local sites (Lahav-Ginott et al., 2001), other locations should be investigated by further
574 research. For instance, the southern Draa Hamada, an area regionally known as a place of high
575 charcoal production, may show dissimilar dynamics. However, restricted access, for reasons of
576 safety and political instability, hampers such research. Thus, further long-term and multi-site
577 studies are required to assess the sustainability of *V. raddiana* stands in the Saharan region. In
578 addition, such studies should pay particular attention to the mixed effects of human and
579 environmental factors on tree stands dynamics.

580

581 4.3.2 The rural forest paradigm to better address dryland forest management?

582 In underlining the simultaneous influence of anthropogenic and environmental factors on *V.*
583 *raddiana* trees and the importance of this species for local activities, our results suggest that *V.*

584 *raddiana* stands could be considered as rural forests (*sensu* Genin et al., 2013). Firstly, *V.*
585 *raddiana* ensures livelihood-sustaining functions through its multipurpose role for people
586 (sheltering function, wood and forage provision, medicines, cultural). Secondly, *V. raddiana*
587 trees are managed in a multipurpose perspective, especially by farmers who shape them and
588 manage selection and regeneration. Thirdly, *V. raddiana* constitutes a secure and predictable
589 resource for herders, *i.e.* a living capital to better cope with drought and uncertainty. Finally, as
590 in the case of rural forests (Genin et al., 2013; Michon et al., 2007), *V. raddiana* stands are (1)
591 managed, shaped and transformed by Saharan rural societies; (2) fully integrated within farming
592 and pastoral systems; and (3) structure-building components of rural landscapes and production
593 systems.

594 The framework of analysis of the rural forest paradigm may contribute to better distinguishing
595 the respective influence of human and environmental factors on tree stands structure and
596 dynamics in drylands. This is particularly crucial in order to bring desertification and dryland
597 degradation under control and as a basis for determining appropriate conservation policies. One
598 of the current challenges in monitoring desertification and its causes is to use accurate indicators
599 of long-term trends, such as slow variables (Carpenter and Turner, 2001). In contrast with
600 annual plants, trees have a slow response to short-term climatic variations and may constitute
601 an indicator of dryland ecosystem state and degradation. Notably, as ecological keystone
602 species (Munzbergova and Ward, 2002; Noumi et al., 2012), *V. raddiana* trees may be a good
603 *proxy* to assess overall ecosystem sustainability (Grouzis and Le Floc'h, 2003). Furthermore,
604 *V. raddiana* stand monitoring may provide a basis for assessing patterns of change in climatic
605 or human exploitation. Rural forest paradigm and associated integrated approaches (as
606 suggested Reynolds et al., 2007) may thus improve our understanding of desertification
607 processes and may help in implementing effective measures to deal with this environmental
608 and social issue.

609

610 5. Conclusion

611

612 The aim of this work was to assess the structure and dynamics of Saharan acacia stands and to
613 better understand the influence of human activities. Our results emphasized the practices of
614 Sahrawi farmers and herders who shape individual trees and their influence on *V. raddiana*
615 stand structure and dynamics. In exchange, *V. raddiana* provides a broad range of provisioning
616 ecosystem services that may influence local subsistence strategies. Far from being a binary
617 exploitation / degradation relationship, current Saharan agro-pastoralism cannot be described

618 as an unsustainable use of *V. raddiana* trees. On the contrary, acacia stands were in a positive
619 regenerative dynamic, in spite of browsing and cultivation. While national forest management
620 and conservation plans in Morocco are based on the regulation, or even exclusion, of human
621 activities because of their deleterious effects (Aubert, 2013), our results plead against this
622 widespread approach. Further studies would be required to better understand the complex
623 nature of the relationships between *V. raddiana* and the Sahrawi society on the one hand, and
624 to better distinguish the respective impact of anthropogenic and environmental factors on the
625 other hand. In a context of forthcoming harsher climatic conditions, such studies are crucial to
626 provide better information on socio-ecosystem issues and challenges regarding *V. raddiana* and
627 to plan efficient conservation policies that will satisfy both ecological and socio-economic
628 priorities.

629

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631

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639

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