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# 1 Microclimate in Mediterranean pine forests: What is the influence of the shrub layer?

2

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17

## 18 **Abstract**

19 Forest cover creates a specific microclimate by buffering most environmental variables. If the  
20 influence of the overstory on microclimatic variables has been well studied, the role of the  
21 understory has received less attention. In this study we investigated how the shrub layer  
22 modifies solar radiation, air temperature (T), relative air humidity (RH), vapor pressure deficit  
23 (VPD) and soil moisture under different thinning treatments in an Aleppo pine forest (*Pinus*  
24 *halepensis* Mill.). Microclimatic variables were measured along a vegetation cover gradient  
25 made up of three pine densities (dense, medium, low) and open conditions, with or without the  
26 presence of shrubs. The results were analyzed with a focus on the summer period which  
27 represents a major bottleneck for plant development in the Mediterranean area.

28 Average T and VPD values increased with decreasing vegetation cover (+1.38°C and +0.21  
29 kPa for the whole year) while RH decreased (-2.34%). Along the same gradient, daily amplitude  
30 of T, RH, VPD increased while the buffering capacity decreased. These patterns were more

31 pronounced during the summer period compared to the whole year and were primarily driven  
32 by overstory transmittance. However, the shrub layer played a significant role in the low pine  
33 cover treatment where it was developed and in open conditions. Soil water content in the forest  
34 area was higher under low pine cover without shrubs than it was in the other treatments, though  
35 differences were less marked during summer drought episodes. In open conditions, soil  
36 moisture was always significantly lower beneath the shrub canopy than outside it. Despite a  
37 reduction in soil moisture, shrubs may represent safe sites for woody seedling development in  
38 sparse pine forests and in treeless areas by buffering the microclimate during the summer  
39 period.

40

41 **Keywords:** Temperature, vapor pressure deficit, light, soil water content, thinning, Aleppo  
42 pine.

43

44 **Declaration of interest.**

45 The authors have no competing interests to declare

46

47 **Highlights**

48

- 49 • A buffering effect on T, VPD, RH was noted for the overstory and the understory
- 50 • This effect was more pronounced in summer due to a stronger shading effect
- 51 • Shrub influence on T, RH, VPD was higher in low pine cover and in open conditions
- 52 • Soil moisture was reduced in the presence of a developed shrub layer

53

## 54 1. Introduction

55

56 Mediterranean forests are primarily threatened by climate change and its associated  
57 disturbances, in particular more severe and prolonged drought episodes as well as recurrent heat  
58 waves (e.g. Peñuelas et al., 2017). These disturbances result in an increase in tree mortality,  
59 shifts in species distribution and higher fire risk (Allen et al, 2010; Carnicer et al., 2011; Pausas  
60 and Fernández-Muñoz, 2012). In this context, management methods mitigating these risks and  
61 improving forest resistance and resilience are urgently needed. The reduction of stand density  
62 by thinning is certainly one of the most studied adaptive management practices (Vila-Cabrera  
63 et al., 2018). Thinning increases light availability and reduces competition between trees. It also  
64 has a large influence on the water budget of the ecosystem (e.g. Aussenac and Granier, 1988).  
65 The reduction of tree density decreases rainfall interception, limits stand transpiration and can  
66 therefore delay soil water depletion (Cabon et al., 2018) and reduce tree drought stress (Bréda  
67 et al., 1995). Recent studies have shown that this alleviation of water stress can improve drought  
68 resistance and recovery, but these effects vary greatly between site conditions, species and  
69 thinning intensities (Giuggiola et al., 2013, 2016; Sohn et al., 2016). However, the effects of  
70 thinning on tree water alimentation may be dampened by several factors. For example, the  
71 transpiration of the remaining trees can increase (Bréda et al., 1995) and the development of  
72 the understory and ground vegetation, boosted by the light increase, can drain above and below  
73 ground resources (Aranda et al., 2012; Simonin et al., 2007), possibly cancelling or even  
74 reversing the effects of thinning on stand water consumption (del Campo et al., 2019).

75 Thinning, by reducing the tree cover, leads to the modification of microclimatic conditions  
76 (*sensu* Geiger et al., 2003) in which we include air temperature, air humidity, air water vapor  
77 pressure deficit (VPD), light availability and soil moisture. A main effect of tree cover is to  
78 moderate most of the meteorological variables and several previous studies have highlighted  
79 this buffering ability by comparing the microclimate within forest stands and in nearby open

80 areas (e.g. Renaud et al., 2011, von Arx et al., 2012, De Frenne et al., 2019). Below-canopy  
81 microclimates are generally characterized by lower annual and seasonal maximum  
82 temperatures, with higher minimum temperature and air humidity values (Gaudio et al., 2017;  
83 Renaud et al., 2011), although the magnitude of these effects varies with forest structure and  
84 site conditions. Buffering of daily microclimate variations has also been reported: air  
85 temperature increases less during the day and decreases less during the night, whereas the  
86 reverse trend was noted for relative air humidity (Aussenac, 2000; von Arx et al., 2012). Such  
87 fine-scale modifications of microclimate by forest cover have important implications for tree  
88 seedling and understory species establishment and diversity (e.g. De Frenne et al. 2015, Gavinet  
89 et al. 2016).

90 Several studies have explored the relationship between tree cover and microclimatic conditions  
91 in relation to overstory composition and structure (e.g. Heithecker and Halpern, 2007; Porté et  
92 al., 2004; von Arx et al., 2012). However, few have considered the influence of the understory  
93 vegetation on microclimatic conditions (Kovács et al., 2017; Giuggiola et al., 2018). In fact, the  
94 understory also influences light interception, water budget and variations in other microclimatic  
95 variables (Balandier et al., 2013; Giuggiola et al., 2018; Riegel et al., 1992). Moreover,  
96 understory composition and structure are affected by climate change and by the reduction of  
97 overstory cover (Bernhardt-Römermann et al., 2015, Coll et al., 2011; De Frenne et al., 2015).  
98 Lastly, the understory can be also impacted by certain management practices that involve  
99 reducing or removing the understory vegetation for economic purposes, such as biomass  
100 harvesting, or for fire risk limitation.

101 In this study, we explored the role of the understory vegetation on several microclimatic  
102 variables in a Mediterranean Aleppo pine (*Pinus halepensis* Mill.) forest and a nearby open  
103 area. We first thinned pine stands at different intensities to create a gradient of overstory cover  
104 conditions, and then conducted an understory removal experiment. The understory was  
105 composed of shrubs, which is very common in Mediterranean systems especially in open forests

106 and in open habitats (e.g. garrigues, matorrals). Many of the microclimatic variables fluctuate  
107 with time and influence plant processes differently, depending on the season (Ogle et al., 2012)  
108 and should therefore be studied at different time-scales. We monitored the main microclimatic  
109 variables: soil water content (SWC), air temperature (T), relative humidity (RH), vapor pressure  
110 deficit (VPD) and light availability.

111 In Mediterranean areas, summer period represents a major constraint for many processes  
112 affecting plant development and is clearly identified as a bottleneck for vegetation dynamics  
113 (e.g. Castro et al., 2005; Gómez-Aparicio et al. 2004, 2005). Furthermore, climate models for  
114 the next few decades forecast even drier and warmer climate during summer, that puts most  
115 ecosystem functions at risk (Cramer et al., 2018). We therefore specifically studied the  
116 fluctuations of microclimatic conditions during summer and compared them with those  
117 recorded during the whole year. More specifically, our questions were the following:

- 118 i) To what extent are variations in microclimatic variables affected by overstory and  
119 understory cover?
- 120 ii) How do interactions between the overstory and the understory influence  
121 microclimate?
- 122 iii) Are there any seasonal patterns in the effect sizes of below-canopy microclimate?  
123 In particular, we have investigated how the microclimate was modified during the  
124 summer period compared to the whole year.

125

## 126 **2. Material and methods**

127

### 128 2.1 Study site and experimental design

129

130 The study site is located in Southeastern France (43°4'N; 5°0'E) at about 30 km Northwest of  
131 the city of Marseille, on a flat area at an altitude of 130 m. Mean annual temperature is 14.5°C

132 and mean annual rainfall is 550 mm based on historical records (1961-2010) of the nearby  
133 weather station of Istres (Météo France). However, as it is often observed in the Mediterranean  
134 climate, rainfall fluctuations are pronounced: 2014 and 2015 were ‘wet’ years (705 and 619  
135 mm) whereas 2016 and 2017 were ‘dry years’ (382 and 318 mm). Differences in total rainfall  
136 during the summer period were even more pronounced between 2014-2015 (138 mm and 157  
137 mm) and 2016-2017 (17 mm and 35 mm). The soils developed on a calcarenite bedrock  
138 composed of sandy limestone material and fossil shells. Alteration of this bedrock has led to  
139 calcareous soils (mean depth 60 cm) with mostly sandy textures ( $52\% \pm 0.7$ ), followed by silt  
140 ( $34\% \pm 0.5$ ) and clay ( $14\% \pm 0.6$ ).

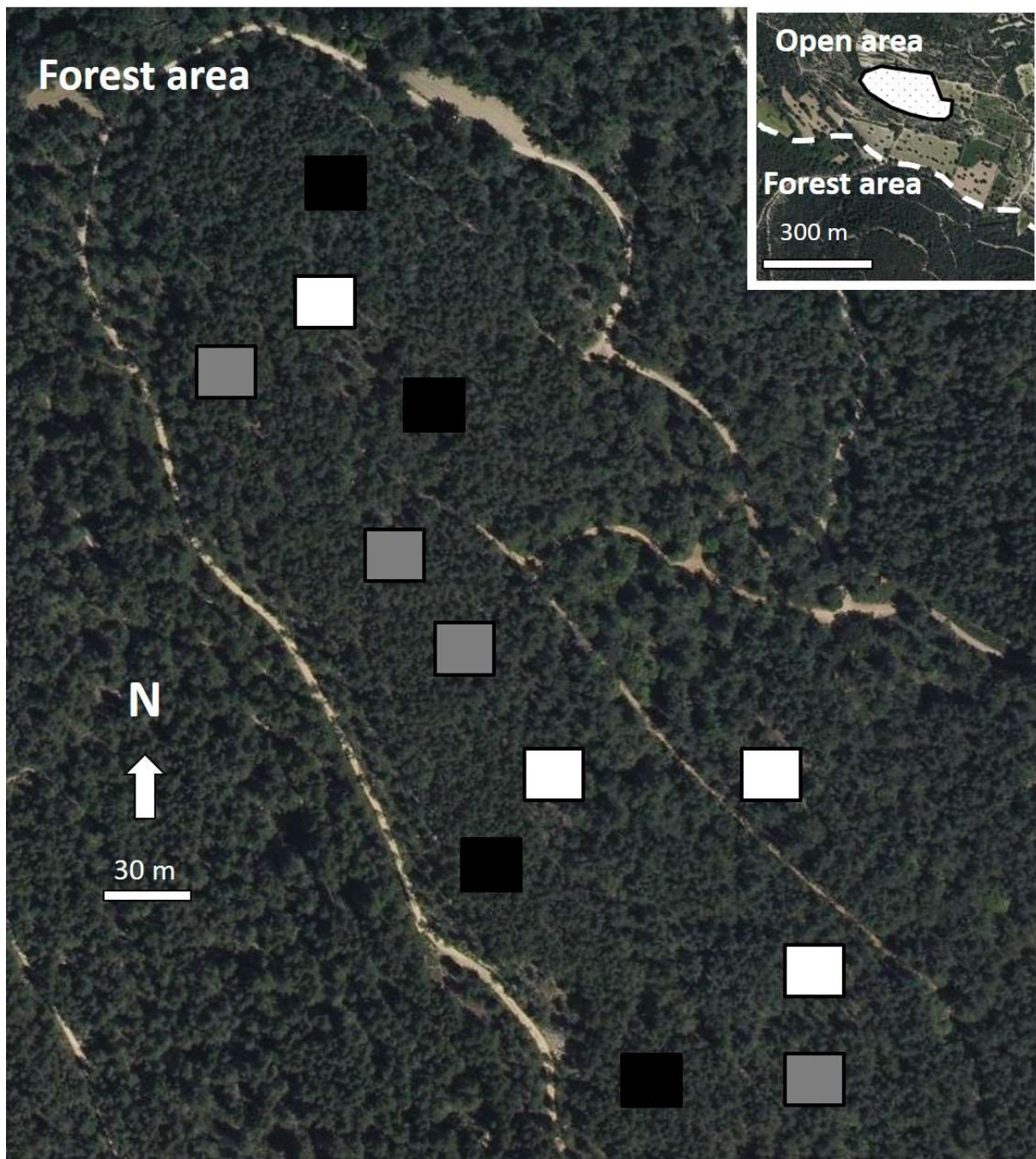
141 The site was covered by a 60-year-old *Pinus halepensis* forest that had naturally established on  
142 former agricultural fields. The tree layer was composed of Aleppo pine solely, with the  
143 evergreen holm oak (*Quercus ilex* L.) present in some places in the sub-canopy layer, the shrub  
144 layer was dominated by *Quercus coccifera* L., *Quercus ilex*, *Rosmarinus officinalis* L.,  
145 *Phyllirea angustifolia* L. and the herb layer was scant.

146 In 2007, we established twelve 25 m  $\times$  25 m plots (Fig. 1) in the pine forest and thinned eight  
147 randomly selected plots according to two intensities (4 plots per thinning intensity): heavy  
148 thinning removing 2/3 of the basal area and moderate thinning removing 1/3 of the basal area.  
149 Four plots were not thinned and left as control. This led to three levels of ‘pine cover  
150 treatments’: low cover (L) after heavy thinning, medium cover (M) after medium thinning and  
151 dense cover (D) in the unthinned control. In February 2016, half of the surface of the shrub  
152 layer that had developed was removed from each plot of the L and M treatments, while the  
153 other half was left untouched. Shrub removal was not performed in plots of the D treatment as  
154 the shrub cover was already very low. Shrub regrowth was then suppressed each year during  
155 the winter period in the shrub removal treatments. Stand characteristics of the overstory and the  
156 understory are summarized in Table 1 and pictures of the treatments are provided in the  
157 supplementary material.

158

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160



161

162 Figure 1. Location of the 12 plots (squares) in the forest area and the open treeless area (in the

163 insert). Treatments are as follows: low pine cover (L, after heavy thinning, white squares),

164 medium pine cover (M, after medium thinning, grey squares) and dense cover (D, no thinning

165 = control, black squares).

166



167

168 **Table 1.** Mean characteristics (mean  $\pm$  se) of the plots in 2016

Treatment	Pine density (/ha)	Basal area (m <sup>2</sup> /ha)	Pine circumference (cm)	Cover of the shrub layer (%)	Height of the shrub layer (cm)
Dense cover	1192 ( $\pm$ 111)	37 ( $\pm$ 0.9)	58.2 ( $\pm$ 1.3)	12.5 ( $\pm$ 2.9)	47.6 ( $\pm$ 7.6)
Medium cover	632 ( $\pm$ 47)	28 ( $\pm$ 1.5)	70.8 ( $\pm$ 1.8)	33.1 ( $\pm$ 2.9)	92.7 ( $\pm$ 5.4)
Low cover	236 ( $\pm$ 30)	17 ( $\pm$ 0.3)	91.4 ( $\pm$ 2.9)	46.8 ( $\pm$ 2.8)	107.0 ( $\pm$ 6.1)

169

170 In addition to the forest plots, we also selected a nearby open area (O, see Fig. 1) that was  
171 covered by a discontinuous shrub layer with the same species as in the forest area.

172 Hereafter we refer to the seven different treatments resulting from the canopy cover and the  
173 shrub treatments as follows: dense pine cover without shrubs (D), medium pine cover with  
174 (M+S) and without (M) shrubs, low pine cover with (L+S) and without (L) shrubs, open area  
175 with shrubs (O+S) and without shrubs (O).

176

## 177 2.2 Measurements of the microclimatic variables

### 178 2.2.1 Light transmittance of the pine cover

179 Light availability in the photosynthetically active radiation (PAR) domain was measured in the  
180 forest plots using 65 measurement points distributed along transects in the different plots and  
181 treatments, below pine canopy (D, M, L) and below pine + shrub canopy (M+S, L+S). At each  
182 measurement point, light availability ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) was recorded every minute for 24 hours by  
183 a solarimeter tube of 30 cm length (DPAR/LEC1C, Solems S.A., France) installed at 40 cm  
184 height. Data were recorded during two successive clear days of April 2017. Light was also  
185 measured simultaneously in the open area as a proxy of above tree canopy light availability  
186 (full light conditions) using two solarimeters. Light transmittance was computed as the ratio of  
187 below canopy light availability at each forest point to light availability in the open.

### 188 2.2.2 Light transmittance of the shrub cover

189 To accurately investigate the interception of light by the shrub layer in the forest area, we  
190 measured the light under shrubs using two different methods. Light availability above and  
191 below the shrub canopy was measured at 314 points distributed in the different plots with shrub  
192 manipulation (M+S, L+S, O+S) with a PAR ceptometer (AccuPAR LP 80, METER Group, Inc.  
193 USA). Because shrub transmittance may strongly vary within the day, we additionally  
194 measured shrub transmittance using continuous measurements over 24 hours on 17 additional  
195 points, using light sensors (SKP 215, Skye Instrument, UK, Supp. Fig. S1C) installed above  
196 and below the shrub canopy. At each measurement point, shrub cover was visually estimated  
197 in 5% classes using a 1 m<sup>2</sup> square grid. Light transmittance (below/above) of the shrub layer  
198 was established by computing the mean values for each 5% shrub cover class.

199 Finally, in the open area, light availability below shrub canopy was measured using a PAR  
200 ceptometer during a clear day in July. A total of 24 shrubs of the same species as those recorded  
201 in the forest area were selected and light was measured above and below the canopy at different  
202 time intervals during the day. The light transmittance was then computed for each shrub.

### 203 2.2.3 Air temperature and relative air humidity

204 We used 26 loggers (DS1923, iButton®, Maxim int., USA) in the forest plots to measure air  
205 temperature (T, ± 0.06°C) and relative air humidity (RH, ± 0.04%), distributed among the  
206 different treatments and 6 additional loggers distributed in the O and O+S treatments. The  
207 loggers were placed in a small meteorological shelter 30 cm above the ground, below the shrub  
208 canopy (M+S, L+S, O+S) and outside shrub influence (D, M, L, O). Data were collected from  
209 June 2016 to November 2018 at a one-hour time interval.

### 210 2.2.4 Soil water content

211 Soil volumetric water content (% SWC) was monitored from June 2016 to November 2018  
212 with a total of 42 soil moisture probes measuring the dielectric constant of the soil based on  
213 capacitance technology (EC-5, Decagon Device, UK) and distributed among the different  
214 treatments of the forest area. Only 8 of the 12 plots presenting the most similar soil conditions

215 were sampled (2 plots in the control treatment D, and 3 plots in each of the two thinning  
216 treatments, L and M). Probes were initially calibrated in the laboratory before being installed  
217 at 30 cm depth in the field. Data were collected every 4 hours with CR 800 data loggers  
218 (Campbell Scientific Ltd, France). For the open area, soil moisture was measured in 2014 and  
219 2015 using 6 EC-5 probes installed at 30 cm depth below the shrub canopy and 6 probes outside  
220 of the shrub canopy.

221

### 222 2.3 Data analysis

223

224 By analogy with the Beer-Lambert's law, light transmittance as a function of shrub cover was  
225 described by fitting an exponential negative regression model as follows :  $T = e^{-k \times \text{Shrub cover}}$ ,  
226 where T, the light transmittance (%) and k, the extinction coefficient, which depends on the  
227 shrub cover properties (Sonohat et al., 2014).

228 T, RH, SWC data series were quality-checked before analysis by checking maximum and  
229 minimum range limits, and variability over time, in order to detect any unusual behavior of the  
230 probes and data outliers which were discarded from later analyses. The T and RH data were  
231 used to produce the hourly VPD using the following formula:

232  $VPD \text{ (Pa)} = (1 - RH/100) \times 610.7 \times 10^{7.5T/(237.3+T)}$  where T, the temperature in °C.

233 The hourly data were used to compute daily maximum and minimum values for the summer  
234 period (from the summer of 2016, 2017 and 2018, respectively) and for the whole observational  
235 period (from October 2016 to October 2018) for each treatment. SWC mean daily values were  
236 also calculated for each treatment.

237 The buffering capacity was defined as the difference between the open area and the below  
238 canopy in daily maximum temperature ( $\Delta T_{\text{max}}$ ), relative air humidity ( $\Delta RH_{\text{max}}$ ) and vapor  
239 pressure deficit ( $\Delta VPD_{\text{max}}$ ).

240 Treatment effects on the different environmental variables were tested by one-way ANOVA  
241 followed by post-hoc Tukey's test. We used logarithm or power transformation to satisfy the  
242 assumptions of normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene's  
243 test). When these conditions were not met, we performed non-parametric Kruskal-Wallis test  
244 that was followed by multiple comparison test according to Siegel and Castellan (1988). In both  
245 cases, statistical differences were assumed at  $P < 0.05$ . All statistical analyses were performed  
246 using R (R core Team, 2017), for multiple comparisons related to the Kruskal-Wallis test, the  
247 'pgirmess' package was used.

248

249

250 **3. Results**

251

252 3.1 Light transmittance

253

254 There was a gradient of increasing light availability in the pine plots from dense cover to light  
255 cover without shrub (Fig. 2A). However, due to the high variability of light transmittance below  
256 forest vegetation cover, we did not detect significant differences among the treatments D, M,  
257 M+S and L+S, although values ranged from 0.08 for D up to 0.15 for L+S. In contrast, there  
258 was a clear difference between these later treatments and the L and O+S treatments, both of  
259 which showed higher light transmittance values (0.27 and 0.28 respectively).

260 In the forest area, despite high variability, we found a significant negative exponential  
261 relationship between light transmittance and shrub cover with an extinction coefficient  $k$  of  
262 0.019 (Fig. 2B).

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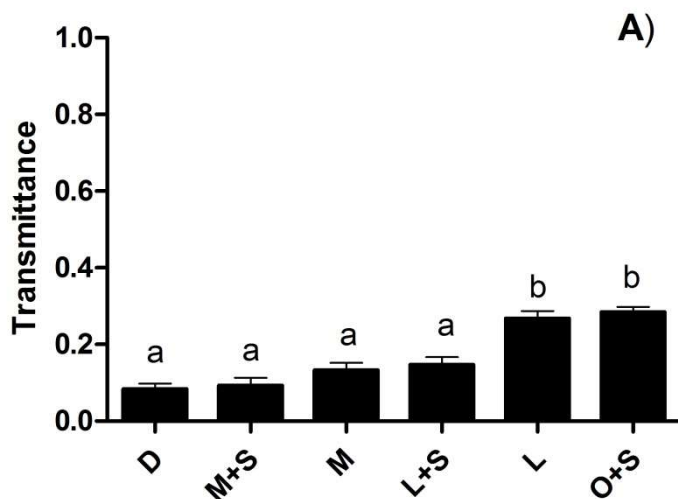
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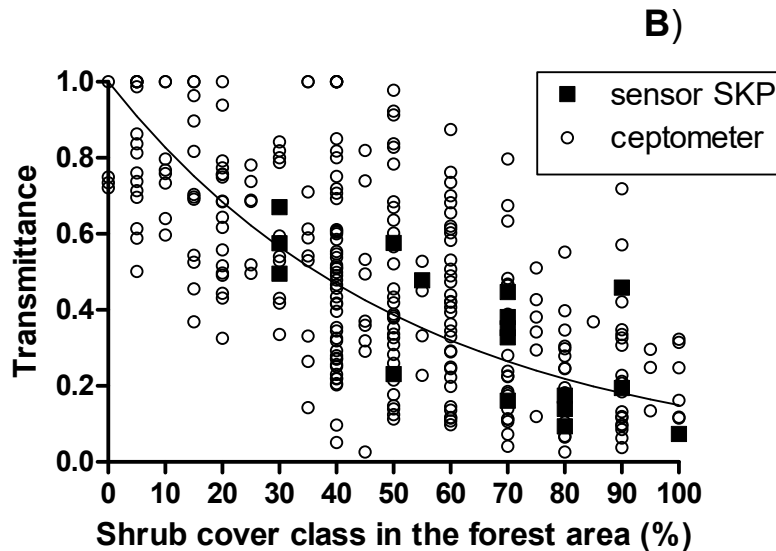
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288 **Figure 2.** A) Light transmittance (mean  $\pm$ SE) according to the treatments, computed as the ratio

289 of light availability below canopy compared to open conditions (O). D=dense cover,

290 M=medium cover, L=low cover, O=open, S=presence of the shrub layer. Letters indicate

291 statistically significant differences according to Tukey's post-hoc test ( $F= 30.2, P<0.001$ ). B)

292 Light transmittance according to shrub cover class in the forest area. The corresponding

293 regression curve is shown ( $y = \exp(-0.019 \times \text{cover class}), R^2=0.35, P<0.001$ ). The black squares

294 indicate the daily measurements based on SKP sensors, whereas the white circles indicate the

295 instantaneous ceptometer measurements.

296

297 3.2 Air temperature, relative humidity and VPD

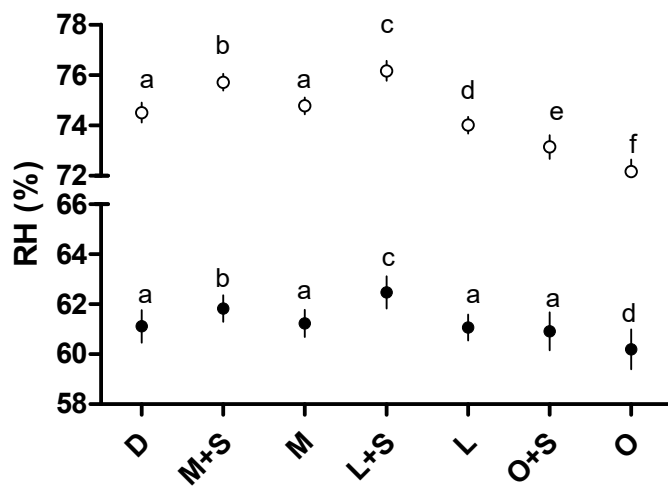
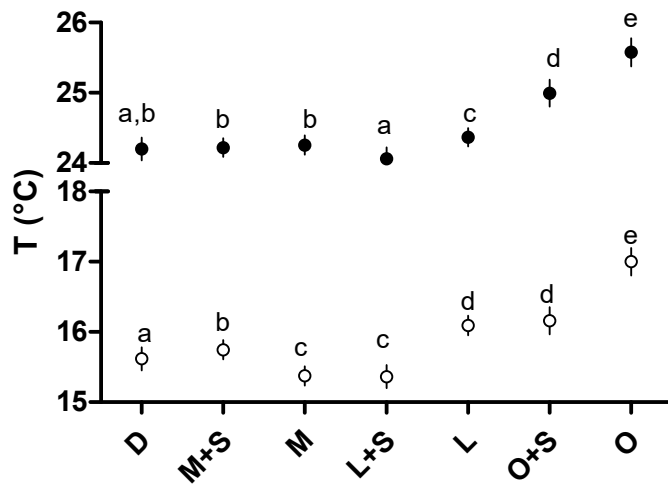
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299 Mean daily values of T and VPD followed similar trends among the different treatments (Fig.

300 3, Table S1): although the lowest values were recorded in the L+S treatment, they remained

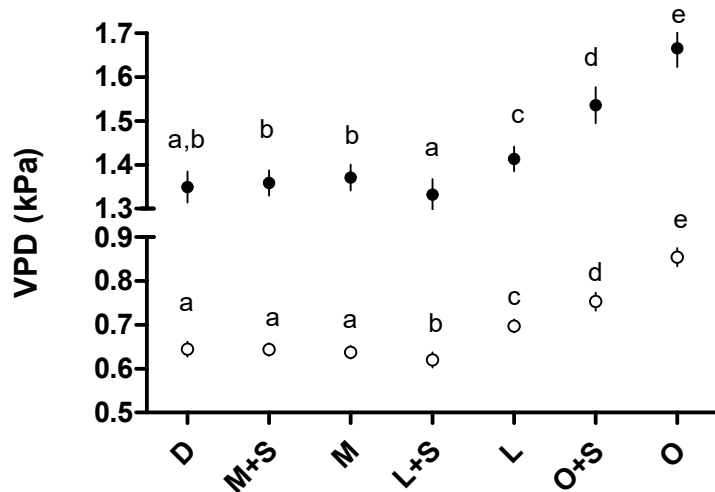
301 comparable among the treatments D, M, M+S and L+S. In contrast, a significant increase was

302 noted for the low cover treatment without shrub layer (L), for both the summer season and the  
 303 whole year. The influence of the shrub layer on the forest area was only noticeable in the L  
 304 treatment. The increase of T and VPD was marked in the O+S and O treatments, particularly  
 305 for the summer season. In contrast to these two factors, RH exhibited a regular decrease from  
 306 the L+S treatment to the O treatment. However, this decrease was less pronounced in the  
 307 summer season than during the year. Overall, L+S had the highest mean RH.



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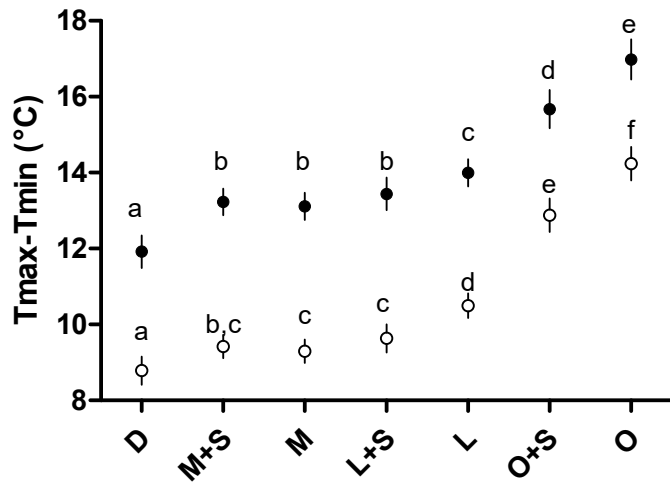
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312 **Figure 3.** Mean temperature (T), relative humidity (RH) and vapor pressure deficit (VPD)  
 313 hourly values (mean  $\pm$  5SE) by treatments. Letters indicate statistically significant differences  
 314 for the summer period (black points) and the whole year (white points).

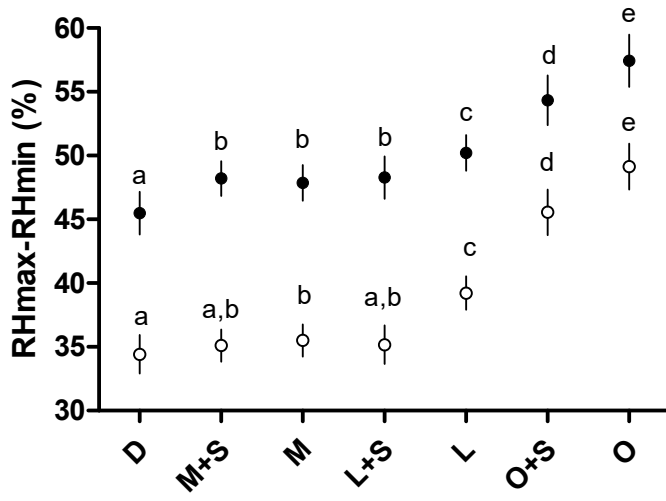
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316 The daily range for the three variables followed the same trend (Fig. 4, Table S1): they increased  
 317 along the decreasing vegetation cover gradient from dense pine cover (D) to open conditions  
 318 (O) and always showed higher values in summer than for the whole year. The influence of the  
 319 shrub layer was not significant in the medium cover treatment but was clearly marked for the  
 320 light cover and open treatments. Similar results were found for the maximal daily temperatures,  
 321 which ranged from 31.10°C in D to 34.96°C in O when averaged over the summer season and  
 322 from 20.64°C to 25.02°C for the whole year. Similarly, maximum daily VPD values were the  
 323 lowest in D (summer: 2.89 kPa, whole year: 1.43 kPa) and the highest in O (summer: 3.95 kPa,  
 324 whole year: 2.22 kPa).

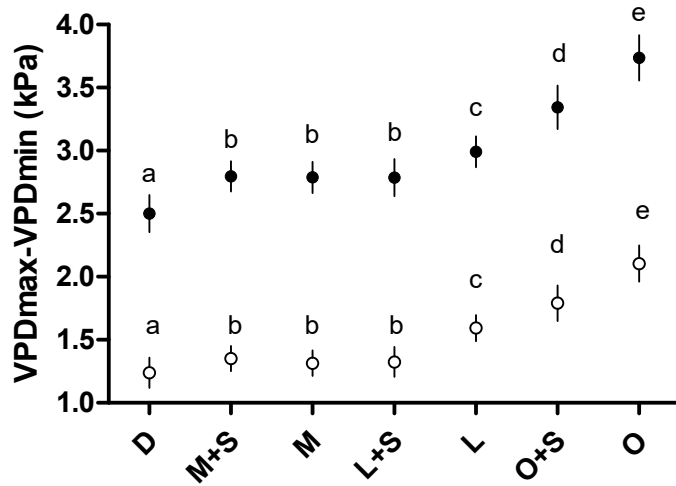




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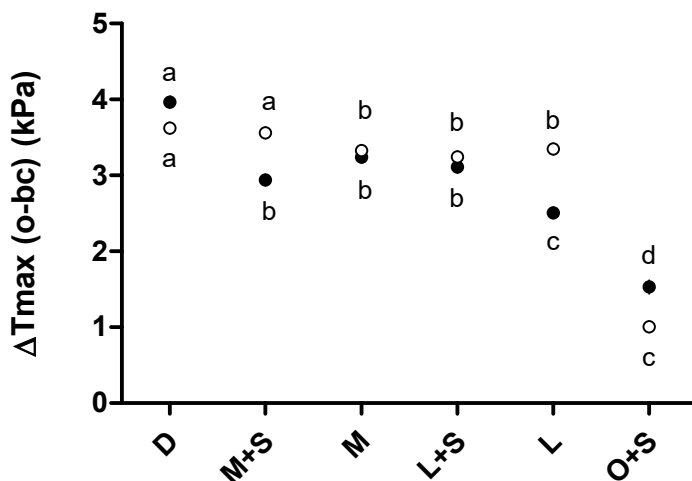
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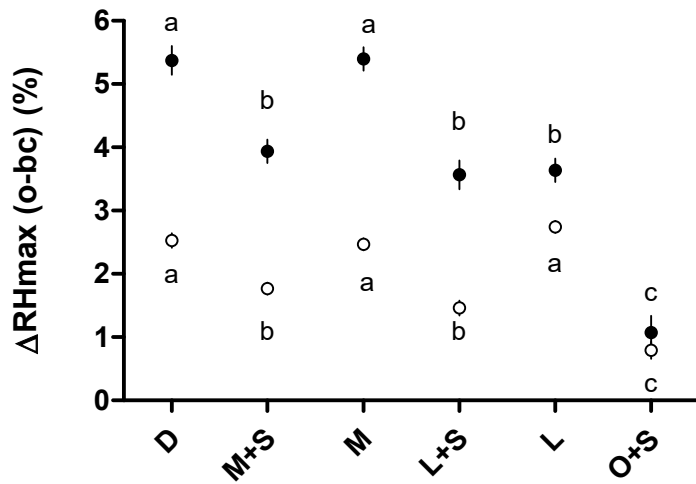
329 **Figure 4.** Temperature (T), relative humidity (RH) and vapour pressure deficit (VPD) mean  
 330 daily range values (mean  $\pm$  5SE). Letters indicate statistically significant differences for the  
 331 summer period (black points) and the whole year (white points)

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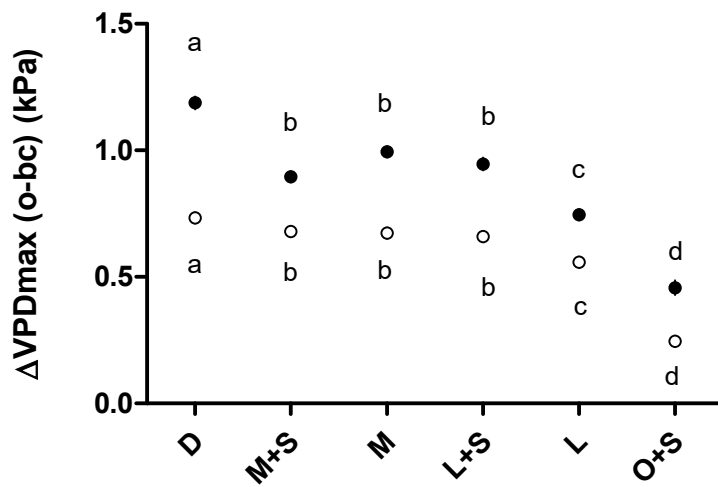
333 The buffering capacity, represented as the difference between open area and below canopy in  
 334 daily maximum temperature ( $\Delta T_{max}$ ), relative air humidity ( $\Delta RH_{max}$ ) and vapor pressure  
 335 deficit ( $\Delta VPD_{max}$ ), globally decreased along the vegetation gradient (from D to O) as shown  
 336 in Fig. 5 (see also Table S1). It must be noted that all values were positive even for  $RH_{max}$  due  
 337 to more frequent water condensation in the open favored by stronger daily temperature  
 338 differences. The buffering capacity was higher in summer compared to the whole year for RH  
 339 and VPD but not for T in the intermediate cover treatments. The buffering capacity was  
 340 consistently the highest in the dense cover treatment (respective values in summer for T, RH  
 341 and VPD: 3.96°C, 5.37%, 1.19 kPa) and the lowest in the O+S treatment (1.53°C, 1.07%, 0.46  
 342 kPa). During the summer season, the effect of the shrub layer on the forest area was pronounced  
 343 in the light cover treatment for T and VPD but not for RH. In contrast, its effect was not  
 344 significant in the medium cover treatment although  $\Delta RH_{max}$  was higher in M than in M+S.



345



346



347

348 **Figure 5.** Buffering capacity (mean ± SE) calculated as the difference in maximum daily  
 349 temperature ( $\Delta T_{max}$ ), relative humidity ( $\Delta RH_{max}$ ) and vapor pressure deficit ( $\Delta VPD_{max}$ )  
 350 between treatment O (o, open area) and below-canopy treatments (bc). Letters indicate  
 351 statistically significant differences for the summer period (black points) and the whole year  
 352 (white points).

353

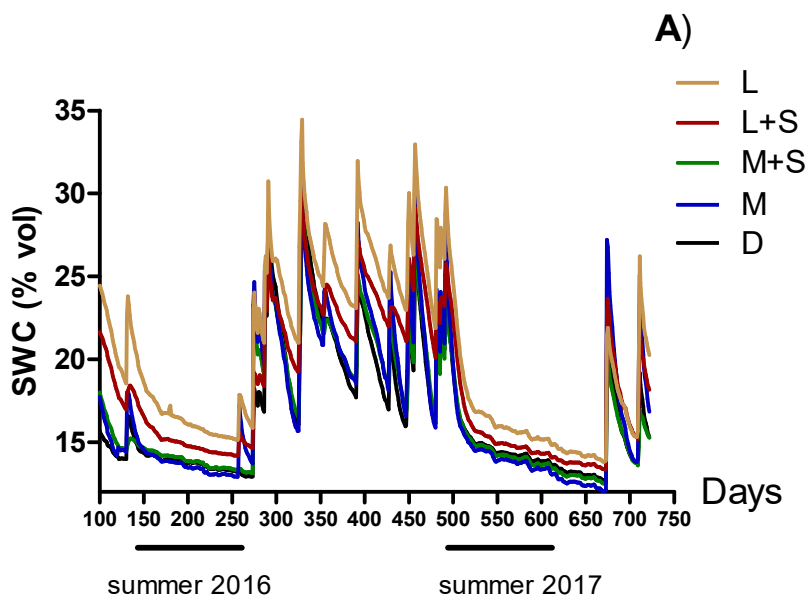
### 354 3.3 Soil water content

355

356 Variations in soil volumetric water content in both forest and open areas were characterized by  
 357 several peaks corresponding to rainfall events and a marked decrease during the summer season  
 358 (Fig. 6A and 6B). In the forest area (Fig. 6A), the L treatment consistently exhibited the highest

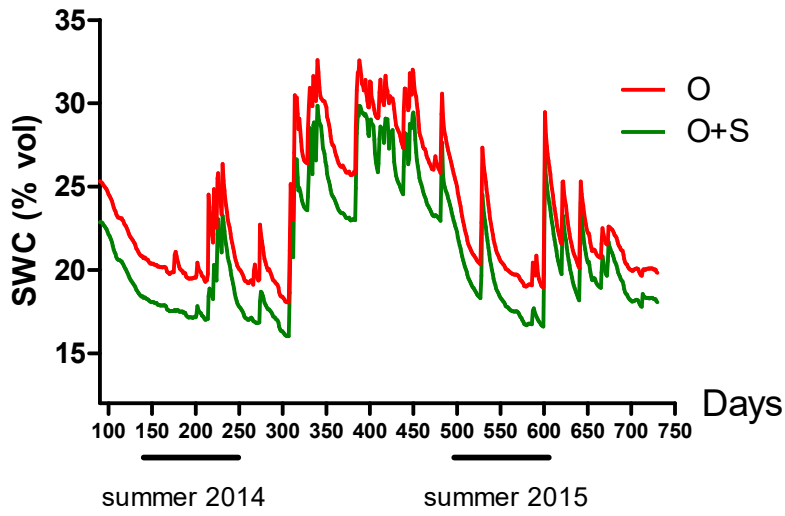
359 soil moisture throughout the year. However, the differences among the treatments were less  
360 pronounced in summer, particularly during the dry year 2017 (values ranging from 13.8% to  
361 16.2%), compared to the other seasons (18.9% to 22.6%, Fig. 6C). The shrub cover had a  
362 negative effect on soil moisture in the L treatment, both during the summer and the whole year.  
363 Similarly, in the open area, soil moisture values were always higher outside the shrub canopy  
364 than beneath the shrub canopy for the two years of measurement (Fig. 6B). As summers were  
365 wetter in 2014 and 2015 (years of SWC measurement in the open area), variations in soil  
366 moisture values were similar between the summer period (18.7% to 21.2%) and the other  
367 seasons (22.3% to 24.8%) (Fig. 6D).

368



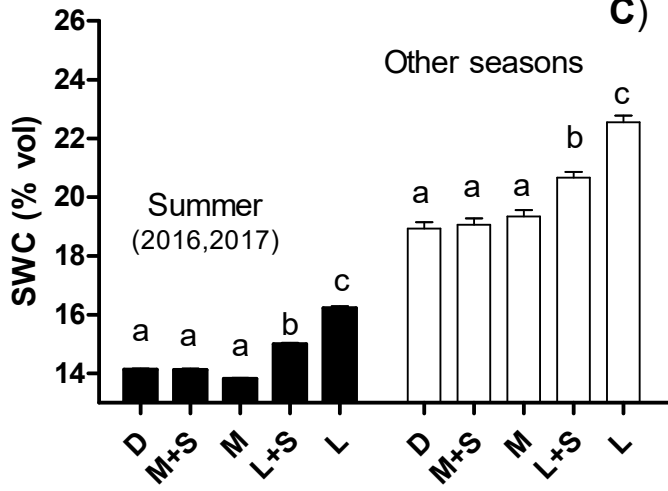
369

**B)**



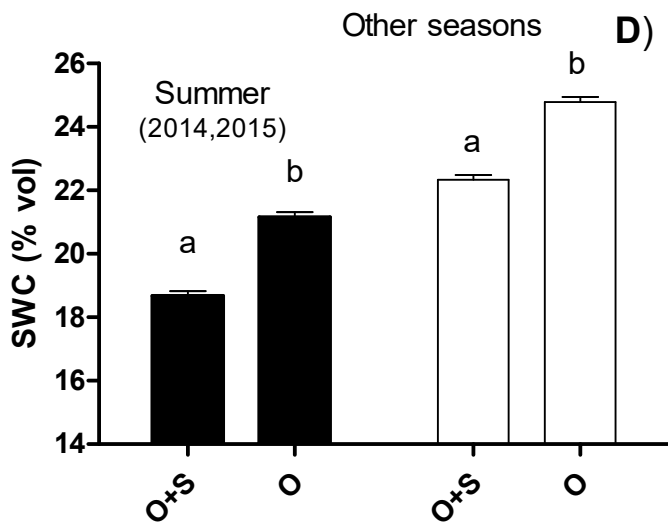
370

**C)**



371

**D)**



372

373

374

375 **Figure 6.** Variations in soil volumetric water content (SWC, at 30 cm depth) according to the  
376 treatments A) in the forest area (18 April 2016 to 18 April 2018), B) in the open area (18 April  
377 2014 to 18 April 2016). Mean SWC according to the treatments during summer and other  
378 seasons C) in the forest area and D) in the open area. Letters indicate significant differences  
379 among the treatments for a given period (summer/other seasons).

380

## 381 4. Discussion

382

### 383 4.1 Variation in microclimatic variables

384

385 Values of pine transmittance in the PAR domain are in the same range as those recorded in  
386 previous studies on Aleppo pine forests. Cooper et al. (2014) recorded in Israel a transmittance  
387 of 14-23% for a basal area between 14-16 m<sup>2</sup> ha<sup>-1</sup>, while in Spain, it ranged from 14.7% in  
388 dense closed pine stands (32 m<sup>2</sup> ha<sup>-1</sup>) to 36% in more open stands (12.4 m<sup>2</sup> ha<sup>-1</sup>) (Gavinet et al.,  
389 2015). The shrub transmittance was strongly correlated with its cover percentage following the  
390 formalism of the Beer-Lambert's law (Fig. 2B). The extinction coefficient (k) of 0.019 found  
391 in this study indicates moderate light interception compared to other species. For instance, in  
392 temperate forests, the transmittance of *Calluna vulgaris* (L.) Hull was found to be very high (k  
393 between 0.004 and 0.012) but it was considerably reduced by *Rubus fruticosus* L. (k=0.074)  
394 (Gaudio et al., 2011; Balandier et al., 2013). The influence of the understory vegetation on  
395 transmittance was only clearly marked in the light pine cover treatment and in the open  
396 treatment, whereas in the medium pine cover treatment the moderately developed understory  
397 only had a weak effect on light interception.

398 The increase in transmittance with decreasing pine cover mainly explains the gradient of  
399 increased T and VPD and decreased RH from closed canopies (D) to open conditions (O). The

400 effect of the shrub layer on the microclimate was also consistently significant and more  
401 pronounced in the light pine cover and open treatments. This is probably linked to a shading  
402 effect and the reduction of air movement, leading to higher humidity and a reduced temperature  
403 gradient (Kovács et al., 2017; Unterseher and Tal, 2006). In mixed oak stands, Clinton (2003)  
404 also found that the sclerophyllous evergreen shrub *Rhododendron maximum* L. significantly  
405 lowered air temperature; while Williams and Ward (2010) found that relative air humidity was  
406 positively related to the development of a thorny invasive shrub (*Berberis thunbergiide* DC.)  
407 in eastern USA. These gradients are more pronounced during the summer season than the whole  
408 year due to stronger solar radiation, which varies on average from 269 W/m<sup>2</sup> in summer to 168  
409 W/m<sup>2</sup> for the whole year in our study area.

410

#### 411 4.2 The effect of the vegetation cover on daily range and the buffering capacity

412

413 The daily ranges for T, RH and VPD (Fig. 4) increased along a decreasing vegetation gradient  
414 (from D to O). Shading provided by the overstory and understory vegetation cover, prevents  
415 the solar shortwave radiation from reaching the forest floor and warms up the near-surface air,  
416 resulting in lower T<sub>max</sub> and VPD<sub>max</sub> values, and higher RH<sub>min</sub> values. Furthermore,  
417 fluctuations are dampened in the presence of vegetation cover due to the reduction of the  
418 longwave radiative losses during the night (Rambo and North, 2009). Amplitudes are also  
419 higher during the summer season. This is mainly driven by the increase in solar radiation during  
420 the summer period which results in a stronger buffering effect of the vegetation layers, as has  
421 been reported in previous studies (Renaud and Rebetez, 2009; Renaud et al., 2011; von Arx et  
422 al., 2012).

423 The buffering capacity (Fig. 5) was more significant under dense cover than under sparse cover  
424 (Renaud and Rebetez, 2009; De Frenne et al., 2013; von Arx et al., 2013). This buffering  
425 capacity was also more intense during the dry summer period for VPD<sub>max</sub> compared to the

426 whole year. In contrast, in sparse evergreen temperate forests in Switzerland, von Arx et al.  
427 (2013) noted an absent or very low buffering capacity during the summer dry season on  $T_{max}$   
428 and  $VPD_{max}$ . They attributed this finding to more intense solar radiation during this period and  
429 less cooling by soil evaporation. The  $\Delta T_{max}$ , contrary to  $\Delta VPD_{max}$  and  $\Delta RH_{max}$ , showed  
430 similar values in summer and in the whole year, a result also reported in a previous study (von  
431 Arx et al., 2012). Certain factors could have played a role, such as lower soil moisture in  
432 summer resulting in an attenuation of the evaporative cooling effect (von Arx et al., 2012).

433 The effect of the shrub layer on buffering capacity was particularly marked where there was a  
434 well-developed shrub layer i.e. in the open and light pine cover treatments. This strong  
435 buffering capacity is mainly linked with the light interception of these two treatments. In fact,  
436 light dropped down from 100% to 28% under the shrub canopy in open conditions and from  
437 27% under light pine cover without shrub cover to 15% in the presence of shrubs. Taken  
438 together, we can conclude that the daily range of microclimatic variables and buffering capacity  
439 were primarily driven by overstory cover, as was also reported by Ehbrecht et al. (2019).  
440 However, under low overstory cover (L+S), microclimatic variables and buffering were mostly  
441 driven by the shrub layer where it was more developed. It must be noted that the buffering  
442 capacity of tree cover has not always been observed in the case of pine species. For instance,  
443 during the very hot summer of 2003, Renaud and Rebetez (2009) observed in Switzerland that  
444 the maximum daily air temperature was higher below the pine canopy, composed of Scots pine  
445 and Mugo pine, than in open conditions. They explained this finding by the higher transparency  
446 in the crowns at their site that was caused by high pine mortality rates. The role of thermal  
447 inertia of the air mass should be also considered in the process of buffering. Indeed, the air  
448 temperature in forest stands has been reported to decline more slowly in the afternoon on  
449 summer days than would be otherwise expected based on the decline in solar radiation (Gaudio  
450 et al., 2017). In contrast, our Aleppo pine stands were healthy, with dense crowns that  
451 intercepted about 70% of incoming light.



452

### 453 4.3 Variations of soil moisture

454 Reducing pine densities (L) increased soil water availability in summer and for the whole year,  
455 as reported in other studies (e.g. Bréda et al., 1995; Aussenac, 2000; Giuggiola et al., 2016).

456 In this study, we observed a clear effect of the shrub layer in the light pine cover and open  
457 conditions. In both cases, reduced soil moisture beneath shrub canopy was noted. For the forest  
458 area, this finding is in line with previous studies. In an understory removal experiment in a  
459 Scots pine forest at a dry site in Switzerland, Giuggiola et al. (2018) observed an increase in  
460 soil water content at 5 and 30 cm depth. A similar result was found by Zahner (1958) in a mixed  
461 *Pinus taeda* - *Pinus echinata* stand in a dry site in USA. However, such an effect is debated in  
462 Mediterranean conditions. Under heavy radiation, soil evaporation represents a significant part  
463 of the water losses of the ecosystem. In a semi-arid, low density (300 stems ha<sup>-1</sup>, LAI=1.5)  
464 Aleppo pine forest in Israel, Raz-Yaseef et al. (2010) found that soil evaporation could represent  
465 36% of the annual precipitation. In a Mediterranean cork oak (*Q. suber*) stand invaded by *Cistus*  
466 *ladanifer*, Caldeira et al. (2015) found that shrub presence increased soil moisture in the upper  
467 40 cm but decreased it below this point, resulting in an overall reduction in water availability  
468 for the oak trees.

469 In fact, the influence of the shrub layer on the soil moisture depends on several factors. On the  
470 one hand, water loss by soil evaporation is reduced due to the shading provided by the shrubby  
471 vegetation. In some cases, higher water availability below the shrub layer can also be linked to  
472 hydraulic lift (Prieto et al., 2011) or modified soil properties such as porosity, organic matter or  
473 texture (Pugnaire et al., 2004). On the other hand, the shrub layer has a detrimental effect on  
474 the water budget by transpiration (Simonin et al., 2007; Rascher et al. 2011; Caldeira et al.  
475 2015) and by intercepting a substantial amount of the rainfall. For instance, Llorens and  
476 Domingo (2007) in a literature review, reported a mean relative throughfall of about 49% for  
477 shrubs and bushes with large variation depending on species and environmental conditions. In

478 our study, the balance between these different processes results in a negative effect on soil  
479 moisture which is particularly prominent in open conditions but is not noticeable under  
480 moderate and dense pine covers. However, some studies have reported an absence of soil  
481 moisture variation between shrubs and nearby open areas (e.g. Gómez-Aparicio et al., 2004)  
482 while others have noted higher soil water content beneath the shrub canopy (e.g. Allegrezza et  
483 al., 2016). The impact of the shrub canopy on soil moisture may also differ depending on total  
484 soil depth (Caldeira et al., 2015) and therefore the water reservoir size. This suggests that the  
485 effect of shrubs on the water budget depends on multiple factors such as the species considered,  
486 and the climatic and edaphic conditions (Butterfield et al., 2016). It must also be emphasized  
487 that during the drought episode of 2017 (46 mm for the period June-October), the soil water  
488 content was very low and varied little among treatments in the forest area, suggesting that the  
489 influence of the shrubby understory cover is downplayed during such extreme episodes.

490

## 491 **5. Conclusions**

492 Very few studies have manipulated the vegetation layer to investigate the role of the understory  
493 in regulating forest microclimate. Our experiment reveals the buffering effect of both the  
494 overstory and understory on temperature, air humidity and VPD in Mediterranean pine  
495 woodlands. This effect is more clearly expressed during the summer period in link with the  
496 dominant role of light interception (reduction of the radiative forcing). The influence exerted  
497 by the pine overstory on microclimatic variables and their fluctuations is of primary  
498 importance. It is only when the tree cover is strongly reduced that the role of the shrub layer is  
499 more pronounced and could substitute the overstory which is the primary regulator of  
500 microclimatic conditions. These results have management implications for the development of  
501 adult trees and woody seedlings. In highly thinned stands (below 20 m<sup>2</sup> ha<sup>-1</sup>), a well-developed  
502 shrub layer can lead to a reduction in soil moisture during the growing season, increasing water  
503 stress and thus limiting tree growth. As a consequence, a reduction of the shrub layer can be an

504 option to limit these negative effects on growth. In contrast, the positive effect of shrubs on  
505 seedling development has been emphasized by many previous studies, particularly in opened  
506 Mediterranean environments (e.g. Gómez-Aparicio et al., 2004, 2005; Heydari et al., 2017).  
507 Our results have shown that this positive effect is due to the amelioration of the aerial  
508 microclimate, in particular a strong reduction of T, VPD and radiation, although the soil  
509 moisture is reduced under the shrub cover. However, this effect also depends on seedling stress-  
510 tolerance and ecophysiological strategy (Gavinet et al., 2016) such as sensitivity to air (VPD)  
511 and soil droughts (Saccone et al., 2009).

512

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514

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520

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685 **Supplementary Material**

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688 Photos of the treatments: A) treatment M and M+S, the shrub layer was removed on the left  
689 part, only young planted seedlings with their protectors were retained B) treatment L (right)

690 and L+S (left). C) Measurement of light beneath the shrub layer with sensor SKP 215. D)

691 Meteorological shelter for iButton logger.

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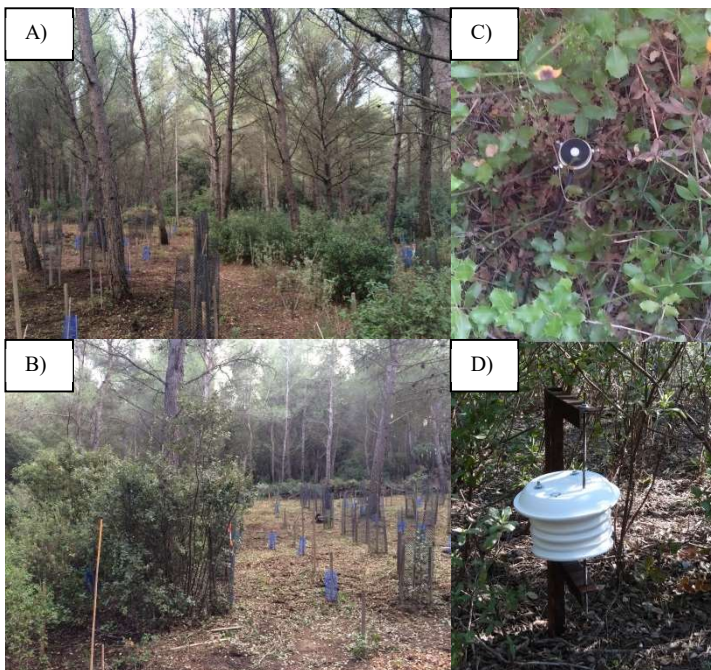
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710 **Table S1.** Statistics for the different microclimatic variables for the summer period and the  
 711 whole year.  
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	<b>Summer</b>		<b>Whole year</b>	
	<u>F-value</u>	<u>P-value</u>	<u>F-value</u>	<u>P-value</u>
<b>Mean T</b>	146.01	<0.001	262.92	<0.001
<b>Mean RH</b>	18.46	<0.001	261.23	<0.001
<b>Mean VPD</b>	163.30	<0.001	476.50	<0.001
<b>Tmax-Tmin</b>	319.64	<0.001	666.54	<0.001
<b>RHmax-RHmin</b>	125.19	<0.001	341.11	<0.001
<b>VPDmax-VPDmin</b>	157.87	<0.001	157.87	<0.001
<b><math>\Delta</math>Tmax (o-bc)</b>	94.19	<0.001	297.92	<0.001
<b><math>\Delta</math>RHmax (o-bc)</b>	48.33	<0.001	42.50	<0.001
<b><math>\Delta</math>VPDmax (o-bc)</b>	80.69	<0.001	201.92	<0.001

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