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1 **Title**

2 Olive agroforestry can improve land productivity even under low water availability in the
3 South Mediterranean

4

5

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16

17 **Abstract**

18 Agroforestry systems can be an effective means of stabilizing or even enhancing crop yields
19 under climate change. Although trees compete with crops for soil resources in
20 agroforestry, they can also improve crops' growing conditions, especially, by providing shade
21 under drought. They can promote higher crop yields and higher harvest quality in the
22 drylands. However, the beneficial effect of tree shade may depend on the seasonal pattern of
23 rainfall, which determines the compensation between yield components. In this study, we
24 evaluated two annual crops (durum wheat and faba bean) in olive agroforestry in northern
25 Morocco. We manipulated water supply in a field experiment to span the high inter-annual
26 rainfall variability at the site and tested whether olive trees reduce or improve crop yields. We
27 assessed the effect of water addition on crop growth, yield components, and final yields and
28 estimated the land equivalent ratio of olive agroforestry. Agroforestry limited crop growth and
29 yield whatever the water regime. The magnitude of grain yield reduction was around 50 % for
30 both crops in 2018, probably due to shade. The number of grains per unit area was the most
31 impacted yield component in both 2018 and 2019. In contrast, water addition only had limited
32 effects on faba bean yield, although it enhanced wheat grain yield by 11% and the number of

33 wheat spikes by 13 %. Agroforestry improved individual grain weight by 39 % for wheat and
34 17% for faba bean, and enhanced the protein content of wheat grains and straw by 4 % and 9
35 %. However, improvements in grain weight and in protein content were not sufficient to
36 compensate for yield loss due to shade. Despite lower crop yields, we show that agroforestry
37 systems are still more land productive than sole crops and trees, even under arid conditions.
38 We show how changing water supply may impact the performance of olive agroforestry in a
39 drier future.

40 **Keywords**

41 faba bean, Morocco, land equivalent ratio, stress-gradient hypothesis, tree-crop interactions,
42 wheat, yield components

43 **1. Introduction**

44 In the Mediterranean, the rapid population growth increases food demand (Bodirsky et al.,
45 2015), making global food security a major concern (Smith et Glauber, 2019). Despite the
46 increasing use of irrigation, fertilizers, and pesticides (Iglesias et al., 2018), overall food
47 production is insufficient and causes severe environmental degradation. Climate change is
48 likely to induce more frequent extreme drought in the future (Ahmed et al., 2013), adding
49 uncertainty to the already food insecure situation (Sieber et al., 2015). In the South
50 Mediterranean, increasing aridity and drought threaten food production (Iglesias et al., 2011).
51 The yield of rainfed crops entirely depends on rainfall, which is already highly variable from
52 year to year (Latiri et al., 2010; Tafoughalti et al., 2018). Water scarcity also affects the
53 quality of crop production, which dampens the economic and nutritive values of harvests.
54 Today, farmers from these regions need to adopt new sustainable cropping strategies to
55 reconcile crop productivity with conserving water resources.

56 Inspired by agroecological principles, fruit-tree-based agroforestry systems (FT-AFS) can
57 stabilize or enhance food production under climate change in dry areas (Lin, 2007,
58 Krishnamurthy et al., 2019). The most recognized advantage of agroforestry is the increase in
59 the land- and resource-use efficiency, which results from complementary yield sources and
60 positive interactions between trees and crops (Zhang et al., 2007). Specifically, FT-AFS are
61 high-value tree agroforestry systems (den Herder et al., 2017), which deserve greater attention
62 considering their contribution to food production (Wolz et al., 2018; Lauri et al., 2019). A
63 wide range of FT-AFS exists in semiarid regions with different tree species, e.g., apple-,

64 apricot- and jujube agroforestry in China (Qiao et al., 2019), almond agroforestry in Iran
65 (Surki et al., 2020). In most cases, FT-AFS has advantageous land equivalent ratios compared
66 to sole crops and trees (Bai et al., 2016; Zhang et al., 2016; 2018; Panozzo et al., 2019). In
67 Morocco, olive- (*Olea europaea* L.) agroforestry is widespread (Sofa et al., 2007) and
68 belongs to traditional agriculture forms and proved its resilience through millennia. Several
69 species of trees (e.g., fig, carob, quince), cereals (e.g., wheat, barley), grain legumes (e.g.,
70 faba bean, chickpea) grow with/under olive trees (Daoui and Fatemi, 2014; Razouk et al.,
71 2016; Lauri et al., 2019). The 'Plan Maroc Vert' aims for the rapid extension of olive groves
72 throughout arable lands (El Mouhtadi et al., 2014), opening novel opportunities for extending
73 olive agroforestry beyond traditional forms. However, FT-AFS are absent from most
74 agricultural policies, and they are disappearing (Nahayo et al., 2017; Ickowitz et al., 2019).
75 Instead, sole cropping systems develop, pushed by input-based intensification and
76 mechanization.

77 In FT-AFS, trees compete with crops for soil resources, but they can also improve crops'
78 growing conditions under drought, mainly by providing shade. They can promote higher crop
79 yields (Artru et al., 2017; Smethurst et al., 2017) and higher harvest quality (Arenas-Corraliza
80 et al., 2018; Qiao et al., 2019). In natural ecosystems, the 'Stress-Gradient-Hypothesis' (SGH)
81 predicts that negative interactions (competition) between species shift towards positive
82 interactions (facilitation) with increasing abiotic stress (He et al., 2013). The rationale is that
83 tall species like trees can beneficially modify the local environment and play the role of
84 'nurse' for smaller species like herbaceous crops. Under high-stress conditions, the
85 amelioration of environmental conditions outweighs the direct effects of competition for
86 resources. Although the relevance of the SGH remains unclear in the drylands (Maestre et al.,
87 2005, 2009), meta-analyses suggest that trees have positive effects on biomass productivity
88 when aridity exceeds semiarid conditions (Moustakas et al., 2013; Dohn et al., 2013). For
89 example, acacia trees have negative impacts on crop yields under humid and sub-humid
90 conditions (rainfall > 800 mm year⁻¹) but improve the yields under semiarid conditions
91 (Bayala et al., 2012). Indeed, the shade of trees penalizes crop growth under favorable
92 conditions (Cubbage et al., 2012) due to lower light interception and photosynthesis rates
93 (Zhang et al., 2018; Rivest et al., 2009). However, shade creates a beneficial microclimate for
94 crops (Lott et al., 2009; Mugunga et al., 2017) with buffered temperature (Peng et al., 2015),
95 higher air humidity (Campi et al., 2009), and reduced evapotranspiration (Coussement et al.,
96 2018) under more arid conditions. The validity of the SGH needs to be tested in FT-AFS, but

97 recent examples in semiarid conditions are promising (Gao et al., 2018). The SGH formalizes
98 the way trees can mitigate climate change in Mediterranean FT-AFS, more generally, in the
99 drylands (Luedeling et al., 2016).

100 However, the shift from negative to positive effects of trees predicted by the SGH
101 may strongly depend on the seasonal pattern of rainfall. In Mediterranean areas, autumn and
102 winter are usually cold and rainy seasons with low evapotranspiration rates (Milner et al.,
103 2012). In contrast, spring and summer are hot and very dry seasons with high
104 evapotranspiration rates (Cramer and Hoffman, 2015). Water availability is usually high
105 enough to sustain crop growth for most winter crops during their vegetative stage (Arenas-
106 Corraliza et al., 2018). However, water deficit affects crops during their reproductive stage.
107 Consequently, we expect that tree shade would negatively affect crop growth before
108 flowering, especially in evergreen species such as olive trees, which provide a permanent
109 shade. By reducing crop growth, tree shade may also reduce the number of tillers (Inurreta-
110 Aguirre et al., 2018) and spikes for cereals (Sharif et al., 2010), and the number of
111 ramifications and pods for legumes (Lake et al., 2019), and finally, may reduce the number of
112 grains per unit area which is a major yield component for crops (Xie et al., 2016; Zhang et al.,
113 2019). In contrast, we can expect that tree shade would buffer drought stress during grain
114 filling after flowering and improve grain sizes and quality (Campanha et al., 2004; Arenas-
115 Corraliza et al., 2018; Qiao et al. 2019). The microclimate under trees helps to preserve soil
116 water availability, extends the grain filling period (Wang et al., 2015), and improves the
117 biomass remobilization towards grains (Li et al., 2010).

118 By buffering terminal drought, the loss of yield caused by reduced growth can be
119 compensated by larger grain size and quality. Depending on the seasonal balance between
120 negative and positive effects of tree shade, the compensation between yield components can
121 lead to lower or higher crop yield in agroforestry than in sole crops. In the Mediterranean,
122 summer drought will extend and intensify under climate change. Therefore, the positive
123 effects of tree shade during filling will gain in significance in the future, leading potentially to
124 higher yields in agroforestry. Yield compensation processes might be even more significant in
125 crops with indeterminate growth, such as faba bean, due to their ability to pursue growth after
126 flowering under favorable conditions. Kato et al. (2019) showed that indeterminate soybean
127 varieties have a higher number of pods, grains, and yields than determinate varieties because
128 of prolonged growth. Therefore, as long as trees maintain a microclimate favorable to growth

129 in FT-AFS, the introduction of indeterminate growth crops such as faba bean should promote
130 an increase in yield and system productivity.

131 Despite their relevance in a drier future, research on FT-AFS in the South Mediterranean
132 has been minimal. In this study, we provide a quantitative evaluation of cereal (e.g., wheat)
133 and legume (e.g., faba bean) crop productivity in olive agroforestry under contrasting water
134 regimes in Northern Morocco. We manipulated water supply during two successive years to
135 span the entire interannual rainfall variability at the site and tested the following hypotheses
136 derived from the SGH: (i) olive trees reduce crop yields under the wettest water regimes but
137 improve yields under the driest water regimes; (ii) olive trees negatively affect crop growth
138 before flowering but improve grain filling after flowering; and (iii) overall, olive agroforestry
139 systems are more land-productive than soles crops and trees, especially under the driest water
140 regimes. We assessed the effect of water addition on crop growth, yield components, and final
141 yields of both crops (durum wheat and faba bean) and compared the land equivalent ratios of
142 olive agroforestry systems under the different water regimes.

143 **2. Material and methods**

144

145 **2.1 Experimental site**

146 We conducted a two-year field experiment (2017-2019) in an olive grove in north-
147 eastern Morocco (Sefrou Province), at the 'La Providence Verte' Louata farm (33°53'48.26"N,
148 4°40'25.63"O, 615 m). The climate is semiarid with hot and dry summers and cold and wet
149 winters. The average annual temperature and rainfall are 19 °C and 473 mm, respectively
150 (1988-2017). Drought generally occurs between May and October. During the crop cycle
151 (October to July), rainfall was 429 mm in 2017/2018 and 345 mm in 2018/2019, which
152 correspond to 'normal' and 'dry' years, respectively. The soil has a sandy clay loamy texture
153 (28% clay and 54% sand) in the top 0-0.6 m layer. Total N content in this soil layer was
154 0.09%, Olsen-P 37 mg kg⁻¹, and K₂O 167 mg kg⁻¹ (Table A.1, Supplementary Material).

155 The olive grove (*Olea europea*, subsp. *europaea*, cv. 'Picholine marocaine') produces
156 olive oil since its plantation in 1954 (65-years old trees in 2019). The density of olive trees
157 was 200 trees.ha⁻¹ with a regular 7×7 m plantation design. Olive trees were all of similar size
158 (5 m height) and were managed in the same way since the plantation as an irrigated grove.
159 Before the experiment, inter-rows were left uncultivated and regularly weeded mainly with
160 herbicides.

161 **2.2 Experimental layout**

162 We evaluated two different olive agroforestry systems ('AFS'), one with intercropped
163 durum wheat (*Triticum durum*, cv. 'Karim') and the other with intercropped faba bean (*Vicia*
164 *faba*, cv. 'Alfia 17'). We compared agroforestry systems to corresponding sole crops ('SCS')
165 and pure olive orchard ('OR') used as controls. Agroforestry systems and the orchard control
166 were located in the same olive grove (Fig. 1). Sole crops were sown in an adjacent open field
167 plot (100 m apart) with similar soil properties (Table A.1, Supplementary Material). In the
168 olive grove, 27 sub-plots of 490 m² (35 m × 14 m) were assigned to either agroforestry
169 systems (18 plots) or pure olive orchards (9 plots). Similarly, 18 sub-plots of 245 m² (35 m ×
170 7 m) were assigned to sole crops in the open field. The experiment covered an area of 1.47 ha
171 in the olive grove and 0.88 ha for sole crops. The spatial distribution of sub-plots was
172 designed to apply three water regimes in adjacent areas, separated by an empty (uncultivated
173 and non-irrigated) inter-row (see below), with three replicates of each type of system (Fig. 1).

174 The annual crops were sown in 4 m-wide strips using a mechanical seeder on November
175 29th in 2017 and December 22th in 2018. A rotation between wheat and faba bean was applied
176 between the two years. The sowing rates were 150 kg.ha⁻¹ (0.15 m between lines) for durum
177 wheat and 120 kg.ha⁻¹ (0.50 m between lines) for faba bean (Fig. 1). In agroforestry systems,
178 crop strips started 1.5 m far from olive tree rows. The fertilizer application rate was different
179 for wheat (63 kg ha⁻¹ N, 34 kg ha⁻¹ P in 2018; 30 kg ha⁻¹ N, 34 kg ha⁻¹ P in 2019) and faba
180 bean (9 kg ha⁻¹ N, 23 kg ha⁻¹ P in both 2018 and 2019). In 2018, crops were harvested at
181 different dates for sole crops (June 13th) and agroforestry (July 17th) due to significant
182 maturity delay, but not in 2019 (June 11th). Olive trees were harvested in December
183 (December 11th in 2018 and December 13th in 2019).

184 **2.3 Water regimes**

185 We simulated three different water regimes using drip irrigation. We equipped two-
186 thirds of sub-plots of each type of system ('AFS', 'OR', 'SCS') with ten laterals emerging from
187 the main sub line that carries water coming out from a pump equipped with a sand filter, a
188 water meter, and a pressure regulator. Laterals were spaced 60 cm in 'AFS' and 70 cm in
189 'SCS', equipped with emitters spaced by 40 cm, and had a flow rate of 2 l.h⁻¹. Additionally,
190 there was a 7 m empty gap between water regimes in 'SCS', which was equivalent to the
191 empty inter-row in 'AFS' to eliminate any possible horizontal water transfer. The remaining
192 sub-plots were not irrigated to have rainfed controls. In each water regime, crops and trees

193 received the same amount of water. For technical reasons, the three water regimes were not
194 randomly distributed but arranged in adjacent areas (Fig. 1).

195 To represent the entire interannual rainfall variability, we did a frequential analysis of
196 rainfall of the past 29 years (Fig. 2). On this basis, we aimed to determine the amount of water
197 addition needed for a typical 'wet' (563 mm), 'normal' (471 mm), and 'dry' (356 mm) years
198 (Fig. 2). Accordingly, we defined three levels of water supply: high water supply ('Water ++'),
199 a medium water supply ('Water +'), and no water supply ('Rainfed') to reach the amounts
200 needed. However, the challenge in such water manipulation was to re-adjust the amount of
201 water addition dynamically with rainfall each month. In 2018, rainfall was already sufficient
202 to consider the year as a 'normal' year (429 mm). Therefore, we added water to simulate a
203 very 'wet' year (+ 159.3 mm) and a moderately wet year (+ 72.7 mm). In 2019, rainfall was
204 more typical of a 'dry' year (345 mm). We took the advantage to simulate a 'moderately dry'
205 year (+ 50 mm), and a 'normal' year (+ 100 mm) with lower water addition than in 2018. In
206 doing so, our experience spanned a large water gradient.

207 We distributed irrigation water on a month-basis to fit with natural rainfall distribution.
208 For instance, we did not add water during dry months (e.g., June, July) because no rainfall
209 occurs during these months, even in 'wet' years. However, we added water in spring (e.g.,
210 March, April) because differences in spring explained the most interannual rainfall variability.
211 Irrigation events were carried out from March to May in 2018. For the high water supply
212 (Water ++), irrigation was applied during 24, 51, and 31 hours over the first, second and the
213 third irrigations in 2018. However, water addition for the medium water supply (Water +) was
214 carried out during 6, 28 and 13 hours over the three irrigation periods in 2018. In 2019,
215 irrigation was applied from April to May during 27 and 40 hours for the high water supply
216 (Water ++) and during 13 and 20 hours for the medium water supply at each of the two
217 irrigations. In both years, the maximum daily irrigation duration was eight hours.

218 ***2.4 Field measurements and sampling***

219 Crop growth was assessed for 10 randomly selected plants avoiding borders in each
220 sub-plot at the flowering stage in 2018 and 2019. Plant ramification was determined by
221 counting the number of viable, non-senescent tillers (for wheat) or branches (for faba bean).
222 Plant biomass was estimated destructively by sampling the entire plants. Plant samples were
223 then oven-dried to a constant weight at 70°C (during 48h) and weighed.

224 Once they reached maturity, crop plants were entirely harvested at ground level using
225 hand-clippers, taking four randomly selected 0.25 m² quadrats in 2018 or five adjacent 1 m⁻¹
226 lines in 2019, avoiding borders in each sub-plot. Plants were sorted by organs, oven-dried
227 (70°C, 48h), and weighed to determine the total aboveground biomass and the total grain
228 biomass. Yield components were also assessed (e.g., number of spikes/pods per unit area,
229 number of grains per unit area, and thousand-grain weight). The harvest index was calculated
230 as the ratio between grain biomass and total aboveground biomass.

231 The olive yield per tree was estimated at harvest in each sub-plot based on a total of 9
232 olive trees in each water treatment. Trees were selected in the middle of each sub-plot to
233 avoid border effects. Olives were harvested by hand, and all fresh fruits were weighed before
234 transportation to the olive oil mill. Due to olive alternate bearing, statistical evaluation of the
235 LERs between years was not possible since the second year (2019) yields were too low or
236 even null. We therefore estimated olive yields over the two years of the experiment (see
237 below).

238 A preliminary assessment of the spatial distribution of radiation was carried out to
239 estimate the shade created by olive trees using a 14 × 14 m grid with a mesh size of 1 × 1 m.
240 The measurements were made using a LightScout silicon pyranometer (LightScout,
241 Spectrum Technologies, Inc. USA). The photosynthetically active radiation (PAR) was
242 measured at 10 am, 12 pm, and 14 pm on a sunny day, repeated once during the two years of
243 the experiment. Due to the limited number of replications of these measurements, the results
244 were include in the appendix (Fig. A.1, Supplementary Material).

245 ***2.5 Crop quality***

246 We determined both grain and straw protein content as indicators of crop quality. Non-
247 destructive near-infrared spectroscopy (NIRS) analyses were performed for each plant sample
248 after fine grinding. We used a scanning spectral range of (400–2.498 nm), which covers the
249 widest wavelength range and the visible spectrum to collect the spectral data of whole grains
250 and straw biomass. The protein level was assessed using an in-house calibration system (PLS
251 Model) developed at the ICARDA quality laboratory (Rabat, Morocco) for both grain and
252 straw. To validate the results obtained by the NIRS method, a subsample of wheat and faba
253 bean was analyzed after harvest using the standard destructive Kjeldahl digestion method for
254 protein content determination. For technical reasons, the analysis was only carried out in
255 2018.

256 **2.6 Data analysis**

257 We calculated the land equivalent ratio (LER), defined as the relative land area
258 required for sole crops and trees to achieve the same total yield as agroforestry (Mead and
259 Willey, 1980). We used crop grain yields and the average of olive yields over two years for
260 each agroforestry system. The partial land equivalent (pLER) ratio for olive was calculated by
261 averaging olive yields over the two years of the experiment (2018 and 2019) to account for
262 the effect of alternate bearing. The pLER of annual crops was calculated accounting for
263 acropped area reduction of - 43%, which resulted from the uncultivated strips left on both
264 sides below trees (= 3 m width) in the inter-row (= 7 m width).

265 Eqn. 1: $LER_{AFS} = LER_{AFS-Olive} + LER_{AFS-Crop}$

266 Eqn. 2: $LER_{AFS-Olive} = \left(\frac{\text{Average of olive yields}_{AFS}}{\text{Average of olive yields}_{OR}} \right)$

267 Eqn. 3: $LER_{AFS-Crop} = \left(\frac{\text{Crop yield}_{AFS}}{\text{Crop yield}_{SCS}} \right)$

268 The LER indicates a higher (or lower) productivity of agroforestry ('AFS') than the
269 corresponding orchard ('OR') and sole crops ('SCS') when the value is above (or below) 1.
270 The value is equal to 1 when agroforestry does not impact land productivity. Thus, if olive
271 yields do not differ significantly between cropping systems ('OR' and 'AFS'), the olive pLER
272 is equal to 1.

273 We tested the differences in crop growth, yield components, final grain yield, and grain
274 protein content using ANOVAs with three factors: (1) the type of system ('AFS', 'OR', 'SCS'),
275 (2) the amount of water addition ('Water ++', 'Water +', Rainfed) and (3) the year (2018,
276 2019). Each crop species (durum wheat and faba bean) was tested separately. After significant
277 ANOVA ($p < 0.05$), the means were compared with Tukey multiple comparison test. The
278 relationships between final grain yields, total aboveground biomass at the flowering stage,
279 and yield components were tested with linear regressions. All statistical analyses were
280 performed using R (R Development Core Team 2009-2018, version 3.6.0).

281 **3. Results**

282

283 **3.1 Dry matter production at flowering**

284 Dry matter production was higher in 2018 than in 2019 for both wheat ($p < 0.001$) and
285 faba bean ($p < 0.001$) and was significantly lower in agroforestry than in sole crops for both

286 wheat ($p < 0.001$, Fig. 3) and faba bean ($p < 0.001$, Fig. 3). The number of tillers or branches
287 per unit area was also significantly lower in agroforestry for both crops ($p < 0.001$, Table 1).
288 Water addition had a significant effect on dry matter production for faba bean ($p = 0.002$) but
289 not for wheat ($p = 0.805$). In 2018, the dry matter production of faba bean was highest under
290 the wettest water regime (+ 26 % compared to the other regimes). However, water addition
291 did not impact the number of tillers ($p = 0.993$) nor the number of branches ($p = 0.283$).

292 ***3.2 Crop yields and yield components***

293 Similarly to dry matter production, grain yield was higher in 2018 than in 2019 for
294 both wheat (277 g.m⁻² vs. 111.2 g.m⁻², $p < 0.001$) and faba bean (321 g.m⁻² vs. 35.28 g.m⁻², $p <$
295 0.001). In contrast, straw yields were lower in 2018 than in 2019 for both wheat (755 g.m⁻² vs.
296 370 g.m⁻², $p < 0.001$) and faba bean (263 g.m⁻² vs. 179 g.m⁻², $p = 0.007$). Consequently, the
297 harvest index was significantly higher in 2018 than in 2019 for both wheat ($p < 0.001$, Table
298 1) and faba bean ($p < 0.001$, Table 1). In 2018, the grain yield was significantly lower in
299 agroforestry than in sole crops ($p < 0.001$, Fig. 4) for both wheat (- 50 %) and faba bean (- 48
300 %). The straw yield was also lower in agroforestry than in sole crops ($p < 0.001$, Fig. 5),
301 although wheat (- 71 %) was more impacted than faba bean (- 51 %). In 2019, only the grain
302 and straw yields of wheat were affected ($p < 0.001$). Water addition improved grain yield only
303 of wheat ($p = 0.004$) but not of faba bean ($p = 0.641$). It did not impact straw yields (wheat: $p =$
304 0.250; faba bean: $p = 0.954$) nor the harvest index (wheat: $p = 0.089$; faba bean: $p = 0.215$).

305 The number of wheat spikes ($p < 0.001$), faba bean pods ($p < 0.001$) and the number of
306 grains per unit area of wheat ($p < 0.001$) and faba bean ($p < 0.001$) were all significantly lower
307 in agroforestry than in sole crops, especially in 2018 (Table 1). The thousand-grain weight
308 (TGW) was always higher in agroforestry for faba bean (+ 17 %, $p < 0.001$) but only in 2018
309 for wheat (Table 1). Water addition positively impacted the number of spikes ($p = 0.002$;
310 Table 1), the grain number ($p < 0.001$) and the thousand-grain weight of wheat ($p = 0.006$) but
311 did not impact the number of pods ($p = 0.847$; Table 1), the grain number ($p = 0.488$) nor
312 thousand-grain weight of faba bean ($p = 0.286$). For wheat, the highest number of spikes and
313 grains per unit area was observed for the medium water supply in 2018, which corresponds to
314 intermediately wet years, while the highest thousand-grain weight was observed under the
315 highest water supply in 2018 (Table 1). Additionally, the interaction between water addition
316 and cropping system was significant for the number of spikes ($p = 0.018$) and the thousand-
317 grain weight of wheat ($p = 0.017$).

318 The number of grains per unit area was a significant determinant of grain yield for
319 wheat in agroforestry ($r^2 = 0.96$, $p < 0.001$, Fig. 6a) and in sole crops ($r^2 = 0.97$, $p < 0.001$), and
320 for faba bean in agroforestry ($r^2 = 0.98$, $p < 0.001$, Fig. 6b) and in sole crops ($r^2 = 0.98$, $p <$
321 0.001). The number of grains varied positively with the number of spikes per unit area in both
322 agroforestry ($r^2 = 0.57$, $p < 0.001$, Fig. 6c) and sole crops ($r^2 = 0.95$, $p < 0.001$, Fig. 6c) for
323 wheat, and with the number of pods per unit area in both agroforestry ($r^2 = 0.98$, $p < 0.001$,
324 Fig. 6d) and sole crops ($r^2 = 0.98$, $p < 0.001$, Fig. 6d) for faba bean. Despite significant
325 variations in the number of tillers, dry matter production of wheat only partially explained the
326 variations in the number of spikes of wheat either in agroforestry ($r^2 = 0.22$, $p = 0.046$, Fig. 6e)
327 or in sole crops ($r^2 = 0.52$, $p < 0.001$, Fig. 6e). In contrast, dry matter production strongly
328 determined the number of pods per unit area of faba bean in agroforestry ($r^2 = 0.83$, $p < 0.001$,
329 Fig. 6f) and in sole crops ($r^2 = 0.74$, $p < 0.001$, Fig. 6f).

330 ***3.3 Crop quality and protein yield***

331 The protein content was higher in agroforestry for both wheat grains (+ 4 %, $p = 0.003$)
332 and straw (+ 9 %, $p = 0.001$) compared to sole crops (Table 2). However, the protein content
333 of faba bean did not vary significantly for grains ($p = 0.990$) and was even lower in
334 agroforestry for straw (- 5 %, $p = 0.017$). Although the protein content of wheat grains ($p =$
335 0.555 , Table 2) did not vary between water regimes, the addition of water reduced the protein
336 content of grains of faba bean by 3 % between rainfed and high water supply ($p = 0.017$). In
337 contrast, water addition positively impacted both the straw protein content of wheat ($p <$
338 0.001) and faba bean ($p = 0.027$). For instance, water addition enhanced the protein content of
339 wheat straw by 8 % between medium water supply and rainfed regime ($p = 0.014$) while the
340 straw protein content of faba bean increased by 7 % between high water supply and medium
341 water regime ($p = 0.026$). Despite the positive impacts on protein content, the protein yield
342 was lower in agroforestry for both wheat ($p < 0.001$) and faba bean ($p < 0.001$). Water addition
343 improved the protein straw yield of both wheat ($p = 0.011$) and faba bean ($p = 0.026$), but the
344 grain protein yield only of wheat with medium water supply ($p = 0.032$).

345 ***3.4 Olive yield***

346 The olive yield was by far higher in 2018 (7.41 ± 1.19 tons.ha⁻¹) than in 2019 (0.16 ± 0.43
347 tons.ha⁻¹). The strong inter-annual variation (- 97 %) probably reflected the alternate bearing
348 of olive trees. The olive yields average did not vary between agroforestry and pure orchard
349 ($p = 0.110$, Fig. 7). Water addition did not impact olive yield ($p = 0.131$).

350 **3.5 Land equivalent ratio (LER)**

351 In 2018, the land equivalent ratio (LER) was always > 1 and ranged from 1.12 to 1.32
352 without a clear distinction between wheat and faba bean (Table 3). In 2019, the magnitude of
353 variation was higher, and the LER ranged from 1.12 to 2.35, with a significant difference
354 between wheat and faba bean ($p= 0.011$). In 2018, the partial land equivalent ratio (pLER) of
355 wheat was higher ($p= 0.004$, Table 3), while it was higher in 2019 for faba bean ($p= 0.031$,
356 Table 3). Water addition did not impact LER ($p= 0.117$) in 2018, nor pLER either for wheat
357 ($p= 0.550$) or faba bean ($p= 0.353$) in both 2018 and 2019.

358 **4. Discussion**

359

360 **4.1 The shade of olive trees reduces crop yields whatever the water regime**

361 Agroforestry reduced yields and the biomass production of both wheat and faba bean.
362 Although wheat was slightly more affected than faba bean, the magnitude of yield reduction
363 was around 50 % on average for both crops, more than other examples from temperate and
364 Mediterranean areas. The usual magnitude of reduction ranges from -10 to -30 % (e.g., -20 %
365 for wheat under walnut trees in Southern France (Dufour et al., 2013). However, comparable
366 yield reductions have been recorded for wheat under a dense shade, e.g., under paulownia
367 trees (Li et al., 2008) or artificial shelters (Artru et al., 2017), suggesting that the shade
368 provided by mature unpruned olive trees was significant for crops. Contrary to deciduous tree
369 species (e.g., walnut), olive trees provide a permanent shade that impacts the entire crop
370 cycle. Furthermore, the density of olive trees in our experiment was higher than recommended
371 in agroforestry, which is usually below 200 trees.ha⁻¹ (Singh et al., 2007).

372 Contrary to our first hypothesis, the shade of olive trees affected crops always
373 negatively, even under low water availability. In addition, a little variation of shade is
374 expected during the experiment, mainly due to shoot growth inhibition in the high-yield year
375 (Melgar et al., 2008). Differences in biomass production and yield between agroforestry and
376 sole crops were similar for all water regimes during the two years of experiment. In a
377 Mediterranean climate, we expected that tree shade would have strong negative effects under
378 the wettest conditions, where light, more than water, limited crop growth, leading to
379 significant differences between agroforestry and sole crops. In contrast, we expected that the
380 shade would improve crop growth and yield under water-limiting conditions by buffering heat
381 (Peng et al., 2015) and water stresses. Assuming that trees use water from deeper soil layers

382 than crops, the reduced evapotranspiration under tree shade (Coussement et al., 2018) could
383 increase water availability for crops and result in higher water-efficiency. These expectations
384 are supported by the 'Stress-Gradient Hypothesis' (SGH), which was repeatedly tested under
385 dry-to-sub-humid conditions in several savanna-like ecosystems, including agroforestry
386 systems (Dohn et al., 2013). Positive interactions between trees and grasses were attributed to
387 the water economy under dry conditions.

388 However, water was probably not the limiting factor of crop growth and yield in our
389 experiment, explaining why differences between water regimes were not significant. Despite
390 low annual precipitations, Mediterranean climates usually have rainy winters with relatively
391 low evapotranspiration rates (Arenas-Corraliza et al., 2018), allowing them to fulfill crop
392 demands at the beginning of the growing cycle. Water availability was possibly high enough
393 to support crop growth even under our driest (rainfed) water regime, explaining why adding
394 or saving extra water did not benefit crops at early stages. Instead, wheat production peaked
395 with medium water additions, suggesting that adding too much water probably caused
396 hypoxia in the rooting zone (Malik et al., 2001), especially in the most clayey soil horizons. In
397 addition, the timing of water supply is of prime importance when considering the impact of
398 water supply. The precipitation events were well-synchronized with the critical crop phases in
399 the first year, making consequences of low water availability probably less significant and
400 explaining the good dry matter production recorded at flowering. In contrast, the lower dry
401 matter production in 2019 might be explained by a delayed sowing and earlier water stress
402 due to lower precipitations (- 30 % compared to 2018) coupled with later irrigation. However,
403 the high straw biomass recorded at harvest in 2019 suggests a compensatory vegetative crop
404 growth after re-irrigation (Han et al., 2015), although it didn't compensate for grain
405 production. The lower grain yields might have resulted from the early water stress in 2019
406 during tillering, reducing the floral meristem differentiation (Ji et al., 2010), and consequently
407 spikes number. Therefore, a seasonal reformulation of the SGH should therefore refine the
408 predictions of how trees impact underlying crops under Mediterranean climates.

409 Moreover, low nitrogen input (N) and water availability are both the main limitations
410 to crop productivity, especially of cereals, in semiarid Mediterranean environments (Cossani
411 et al., 2010). Theoretically, the maximum crop growth is reached when all resources are
412 equally limiting (Sadras, 2004). In addition, adding water at the appropriate timing increased
413 the growth potential of crops, leading to an increase in their nutrient requirements (e.g.,
414 nitrogen). Increasing water availability with irrigation without changing the amount of

415 nutrients accordingly may have created a situation where nutrients became the limiting factor.
416 Our results suggest that the global effect of trees in 'water-limited' agroforestry depends
417 primarily on seasonal precipitation and water demand patterns and on a possible shift in
418 limiting factor between water and nutrient such as nitrogen. We argue that the SGH should
419 carefully account for these interactions between co-limiting factors to provide more relevant
420 predictions in 'water-limited' agroforestry.

421 **4.2 Olive trees limit crop growth and reduce the number of grains per unit area**

422 In agroforestry, olive trees negatively affected crop growth during the pre-flowering
423 phase, resulting in a lower biomass production than sole crops. They also negatively affected
424 crop tillering/ramification, reducing the total number of spikes (wheat) and pods (faba bean)
425 per unit area (Rivest et al., 2009 ; Liu et al., 2015). Reduced crop growth and tillering is quite
426 common in agroforestry (Gill et al., 2009; Kaur et al., 2010; Inurreta-Aguirre et al., 2018)
427 mainly because of the shade provided by evergreen trees such as olive tree at early crop stages
428 during winter. In legumes, nitrogen fixation is related to the provision of photosynthetic
429 assimilates and dry matter production (e.g., soybean, Trang et Giddens, 1980; Mahieu et al.,
430 2016). In turn, reduced growth meant lower canopy expansion, light capture capacity, and
431 lower photosynthetic rates (King et al., 2014), especially during critical stages, which limited
432 grain yield potential (Fan et al., 2018).

433 The reduction of final crop grain yields in agroforestry was a direct consequence of
434 reduced grain number per unit area. In cereals, the variations in grain number per unit area
435 determine the final yield more than other yield components (Xie et al., 2016; Kimura et al.,
436 2018; Zhang et al., 2019). The number of grains is also a major yield component for legumes
437 (Lake et al., 2019). Since the number of grains per unit area is closely related to the number of
438 spikes/pods, the way trees affected crops at the tillering/ ramification stage (Sharif et al.,
439 2010), mainly through the shade, was critical for crop yield in agroforestry. The reduced
440 number of tillers (wheat) and branches (faba bean) explained more than 50 % of grain yield
441 reduction under olive trees. However, while the number of tillers directly determined the
442 number of wheat spikes, the number of pods of faba bean was also related to plant growth
443 during pod emergence, which is the most critical stage for faba bean grain yield (Lake et al.,
444 2019). Contrary to cereals, indeterminate legumes can increase the number of pods and
445 thereby yield potential by extending the period between flowering and pod set. However, the

446 shade under olive trees limited this phase compared to sole crops, probably because shade did
447 not represent an advantage regarding the water economy.

448 The lower biomass of spikes and pods was another critical determinant of the lower
449 grain number per unit area under olive trees. Indeed, smaller spikes/pods contain fewer grains
450 (Zhang et al., 2019). The reduction of global crop biomass production led to a lower amount
451 of biomass available to allocate to spikes/pods (Schittenhelm et al., 2004), resulting in smaller
452 spikes/pods with lower grain number potential. Shade may also affect the fertility of spikes in
453 cereals (Sharif et al., 2010; Qiao et al., 2019), generally associated with spike biomass in
454 cereals (Zhang et al. 2019), and reduce the floral initiation and retention in legumes (Rivest et
455 al., 2009; Patrick et Stoddard, 2010). With lower fertility, the fruiting efficiency, *i.e.*, the
456 number of grain per unit of spike/pod biomass, was certainly lower in agroforestry, which
457 added another possible negative effect of olive trees on the grain number per unit area.

458 In some cases, crops can efficiently acclimate to shade thanks to trait plasticity
459 (Arenas-Corraliza et al., 2018) and maintain light capture and biomass productivity to similar
460 levels than in sole crops, especially during the critical phases. However, even if we noticed
461 significant morphological changes on crops (e.g., stem elongation, increase in leaf area), they
462 were not sufficient to fully compensate for the reduction of light under olive trees. Indeed, it
463 is highly probable that the commercial varieties we used for wheat and faba bean in the
464 experiment were selected to tolerate the high irradiation in sole cropping systems rather than
465 the shade in agroforestry. Looking for crop varieties with adequate physiological and
466 morphological responses to shade will be promising to buffer the effects of trees on crop
467 growth in Mediterranean agroforestry (Arenas-Corraliza et al., 2018).

468 **4.3 Olive trees improve grain filling and grain quality**

469 In agroforestry, olive trees improved grain filling and led to higher grain weight and
470 quality at harvest than in sole crops. The thousand-grain weight and the grain protein content
471 were higher for both wheat and faba bean. However, the total gain was insufficient to
472 compensate for yield reductions due to the strongly reduced number of grains per unit area.
473 The apparent positive effects of olive trees resulted from the combination of two different
474 effects. The first was a reduced 'dilution' effect (Artru et al., 2017): crops concentrated more
475 nitrogen into fewer grains (Li et al., 2010), which increased the protein content of the grains
476 (Arenas-Corraliza et al. 2018; Qiao et al. 2019). However, it is rare that resource

477 concentration in a smaller number of grains permits full compensation of yield potential loss
478 due to a low numbers of grains.

479 A real facilitative effect of olive trees also occurred through beneficial microclimate
480 modifications by reducing solar radiation and creating a more moderate temperature regime
481 (Peng et al., 2015). Cooler temperatures under trees also delayed the physiological maturity
482 by one month (in 2018) and, therefore, extended the duration of grain filling (Inurreta-Aguirre
483 et al., 2018), allowing a better remobilization of more dry matter in fewer grains. For crops
484 with indeterminate growth, like faba bean, the positive effects might be even higher due to a
485 more extended grain filling period (Wang et al., 2015) related to a higher number of
486 reproductive nodes (Kato et al., 2019). Combined with the lower numbers of grains, the better
487 remobilization of nitrogen of crops towards grains can explain why protein content was higher
488 under trees (Artru et al., 2017; Dufour et al., 2013). However, despite heavier grains, with
489 higher protein content, the reduction in the number of grains per unit area had a more
490 significant impact on grain yield and protein yield in agroforestry.

491 **4.4 Overall, olive agroforestry is more productive than sole crops and trees**

492 Despite lower crop yields, agroforestry systems generally had higher land productivity
493 than sole crops and trees ($LER > 1$) during the two years of the experiment. Based on this first
494 empirical evaluation in the South Mediterranean, we confirm that olive agroforestry systems
495 can have high LERs and produce high-quality grains, even under more arid conditions than
496 previous evaluation in Europe (Panozzo et al., 2019). However, a better improvement of land
497 productivity might be achieved through a better vertical root complementarity, which was
498 probably limited due to the previous orchard management as an irrigated orchard leading to a
499 high root density in the topsoil layers down to a 0.6 m depth (Fernández et al., 1991).
500 Contrary to the traditional olive groves, most modern olive orchards with high density
501 (Connor et al., 2014) have uncultivated inter-rows, representing a loss of arable land in a
502 context where food security is a rapidly growing issue. Besides mechanization issues, farmers
503 are concerned about preserving enough resources, mostly water, to support olive production.
504 However, our results reveal that crops did not impact olive yields, although the alternate
505 bearing led to high variability of olive yields. Additionally, the different water regimes did not
506 impact olive yields in the experiment, confirming that olive trees have, in general, high
507 tolerance to water availability fluctuations and water scarcity (Moriana et al., 2003), and also
508 probably to competition for water with intercrops. A step further will be to test different

509 management strategies, especially tree pruning, and adapt the tree density to improve the
510 functioning of the olive agroforestry as a whole. Compared to cereals, legumes are less
511 competitive for soil resources (at least for nitrogen) and reach maturity earlier, leaving more
512 resources available to olive trees, especially at the beginning of summer, when trees start to
513 grow actively, and water availability sinks. Moreover, the indeterminate growth habit of
514 legumes may improve the performance of agroforestry systems by valuing the shade under
515 trees better than cereals (Kato et al., 2019). In the long-term, the capacity of legumes to fix the
516 atmospheric nitrogen can enhance soil nitrogen available (Dwivedi et al., 2015) for the olive
517 trees, improve soil fertility, and hence have positive effects on olive production. Therefore,
518 we highly recommend legumes to enhance and diversify the global productivity of olive
519 groves and invite to consider a greater diversity of legume species. However, further studies
520 on how crops modify water availability would be necessary to confirm the promising potential
521 of olive agroforestry in the drier future of Mediterranean regions.

522 Our work finally reveals methodological difficulties to precisely determine LERs of fruit-
523 based agroforestry, especially for alternate fruit species such as olive. Results of LER were
524 highly variable from one year to another. However, we did not observe a clear trend with the
525 water regime tested which might be due to water supply delay. Multiple factors can cause
526 alternate yields, including climate variability, water stress (Haouari, 2013), and orchard
527 management (Kour et al., 2018), making a definite diagnosis complicated. Consequently, we
528 argue that the alternate bearing of olive trees probably hindered our LER assessment in case
529 of very low olive yields or very low crop yields as for faba bean in the second year of the
530 experiment. Therefore, we suggest a careful interpretation of the extremely low or high LERs.
531 Altogether, we stress the need to have more extended time series and/or spatial repetitions of
532 yield data for consolidated conclusions about olive agroforestry systems. Implementing long-
533 term experiments, capitalizing on experimental networks around the Mediterranean, and using
534 modeling tools more extensively should together build promising approaches.

535

536 **Conclusion**

537 Olive agroforestry is gaining interest in the Mediterranean, but its relevance in a drier
538 future remains uncertain. On the one hand, farmers fear the consequences of more intense
539 negative tree-crop interactions under drought. On the other hand, ecological theory (SGH)
540 predicts an increase in positive tree-crop interactions with increasing environmental stress.
541 We evaluated a case of olive agroforestry along a water availability gradient to move ahead,

542 representative of most rainfed olive groves in the South Mediterranean. We show that olive
543 trees limited crop growth during critical stages before flowering and caused a significant
544 reduction in grain number per unit area and grain yield, whatever the water regime. In
545 contrast, olive trees also improved grain filling and grain protein content, but not sufficient to
546 compensate for the negative effects on crop growth and yield. We concluded that in the case
547 of olive agroforestry, the SGH needs a 'seasonal' reformulation to predict how the net balance
548 in tree-crop interactions will change in a drier future. However, despite lower crop yield than
549 sole crops, LERs > 1 reveal that olive agroforestry is a promising way of improving land and
550 resource productivity, particularly with appropriate farming practices.

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Figure caption

Fig. 1: Experimental layout showing (a) the plot of sole crops ('SCS'), (b) the plot of agroforestry ('AFS') and olive orchard ('OR'), (c) sole faba bean and (d) agroforestry (olive+faba bean) in spring 2018. The three water regimes were applied in adjacent areas equipped with drip irrigation and are indicated as follows: 'Water ++' for high water supply (yellow), 'Water +' for medium water supply (orange) and 'Rainfed' for the control treatment without any water addition (red). In agroforestry, grey and black stripes correspond to the randomly distributed durum wheat faba bean plots respectively. Black dotted rectangles are the sampling sub-plots in agroforestry and in sole crops shown here as example. Sampling sub-plots were repeated three times in each water treatments for each type of system (SCS, AFS, OR).

Fig. 2: Rainfall frequency analysis over the past 29 years showing the total cumulated water supply (rainfall + irrigation) in (a) 2018, and (b) 2019, in relation to long-term quantiles ('dry' years, Q1; 'normal' years, Q2; 'wet' years, Q3). The three water regimes are indicated as follows: 'Water ++' for high water supply (yellow), 'Water +' for medium water supply (orange), and 'Rainfed' for the control treatment without any water addition (red). The clear grey rectangle represents the duration of the crop growth cycle.

Fig. 3: Dry matter ($\text{g m}^{-2} \pm \text{sd}$) at flowering in agroforestry (AFS) and sole crops (SCS) for durum wheat (a: 2018; b: 2019) and faba bean (c: 2018; d: 2019). Bar color indicates the water regime: (yellow: Water ++; orange: Water +; red: Rainfed). Significance level (differences between AFS and SCS): * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Fig. 4: Grain yield ($\text{g m}^{-2} \pm \text{sd}$) at harvest in agroforestry (AFS) and sole crops (SCS) for durum wheat (a: 2018; b: 2019) and faba bean (c: 2018; d: 2019). Bar color indicates the water regime (yellow: Water ++; orange: Water +; red: Rainfed). Significance level (differences between AFS and SCS): * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Fig. 5: Straw yield ($\text{g m}^{-2} \pm \text{sd}$) at harvest in agroforestry (AFS) and sole crops (SCS) for durum wheat (a: 2018; b: 2019) and faba bean (c: 2018; d: 2019). Bar color indicates the water regime (yellow: Water ++; orange: Water +; red: Rainfed). Significance level (differences between AFS and SCS): * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

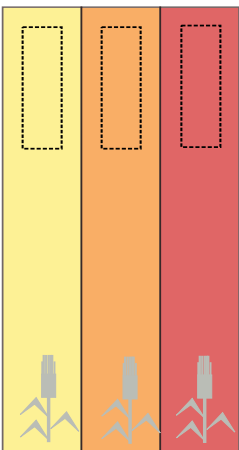
Fig. 6: Cascading relationships between grain yield (g m^{-2}) and the number of grains (m^{-2}) for either (a) wheat and (b) faba bean; between the number of grains (m^{-2}) and (c) the number of spikes (m^{-2}) for wheat or (d) the number of pods (m^{-2}) for faba bean; between (e) the number of spikes (m^{-2}) for wheat, or (f) the number of pods (m^{-2}) for faba bean and dry matter (g m^{-2}) at flowering. Linear regressions were performed separately for agroforestry (light green lines) and sole crops (dark green lines), in both 2018 (circle shape) and 2019 (triangle shape).

Fig. 7: Olive yield (t ha^{-1}) in agroforestry with durum wheat (AFS_{Dw}), and faba bean (AFS_{Fb}), and in pure olive orchard (OR). Bar color indicates the water regime (yellow: 'Water ++'; orange: 'Water +'; red: 'Rainfed'). Significance level (differences between AFS and SCS): * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

(a) Sole Cropping Systems (SCS)

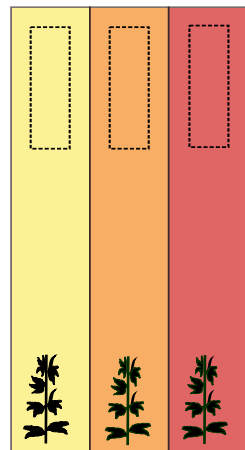
Durum wheat

Water ++ Water + Rainfed



Faba bean

Water ++ Water + Rainfed

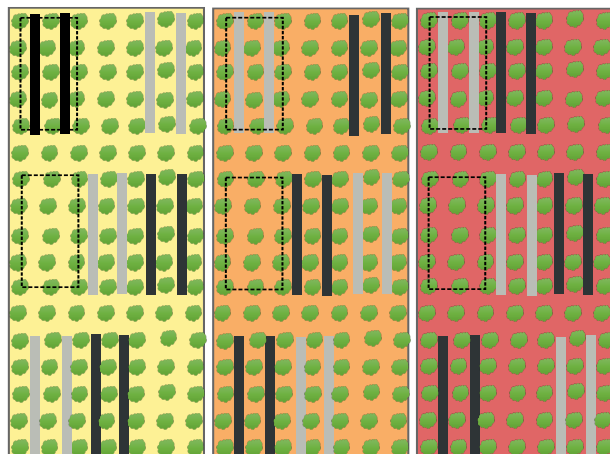


(b) Agroforestry Systems (AFS) + Olive Orchard (OR)

Water ++

Water +

Rainfed



(c)

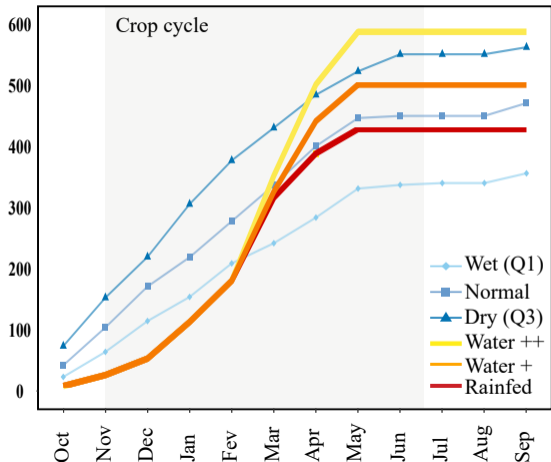
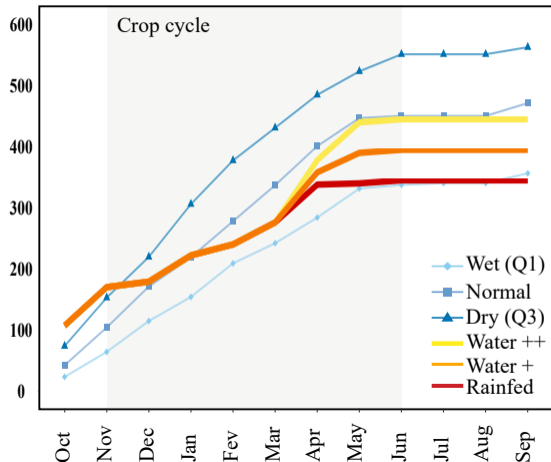


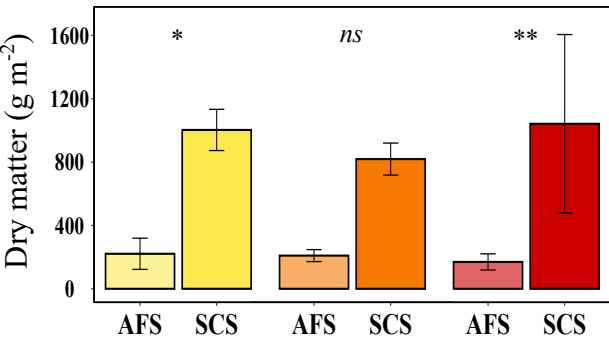
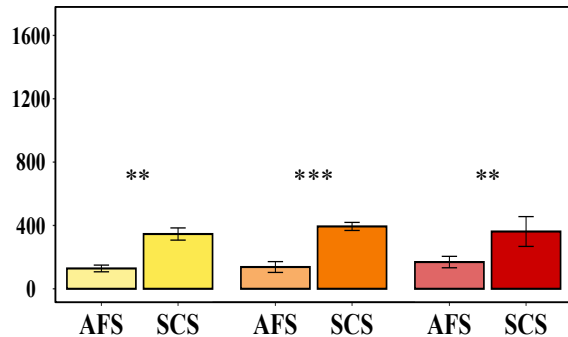
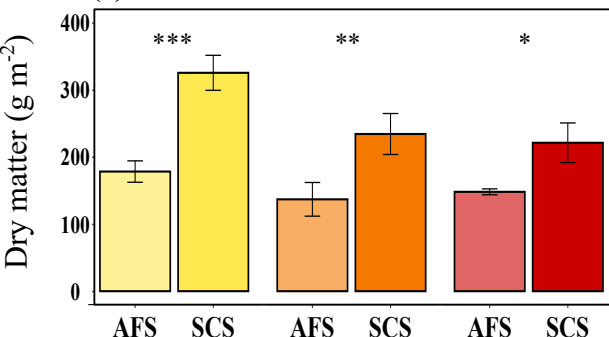
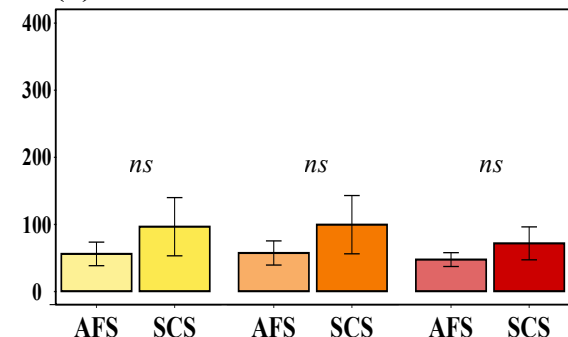
(d)

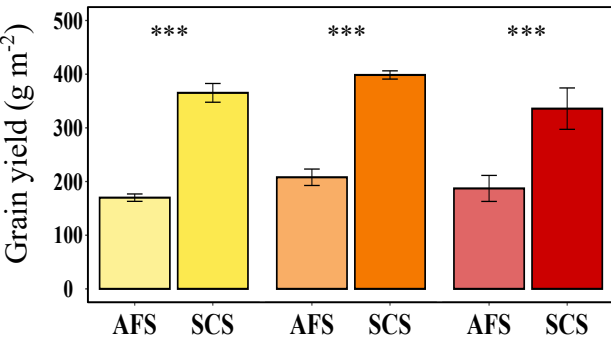
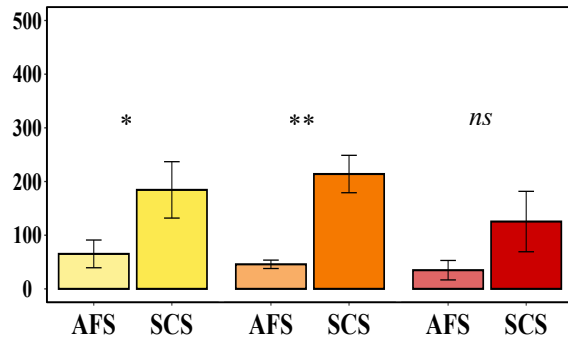
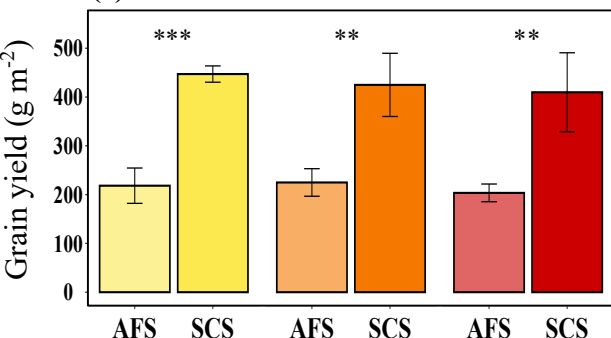
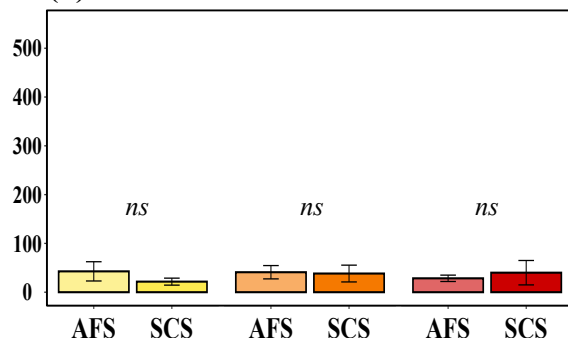


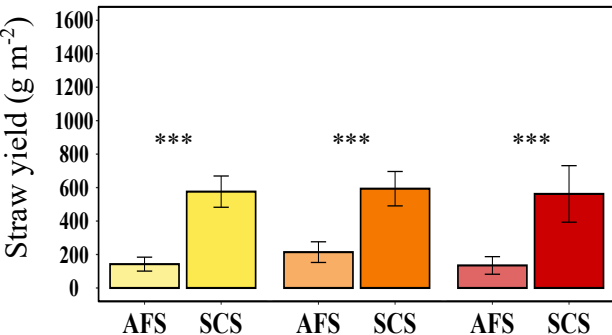
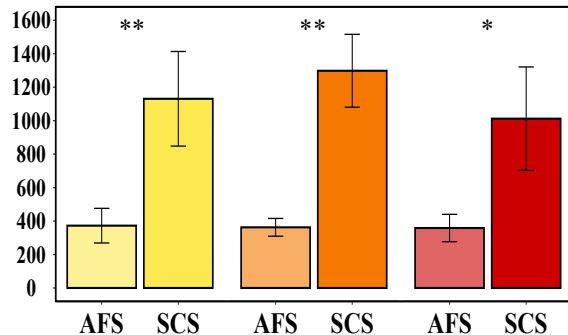
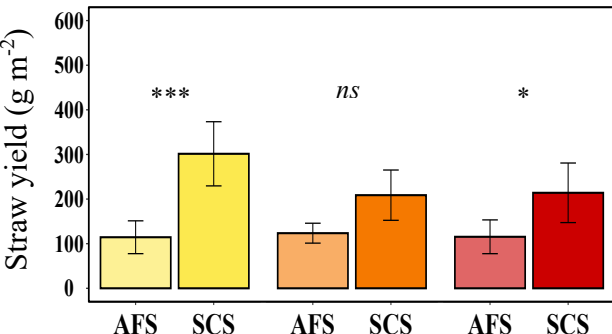
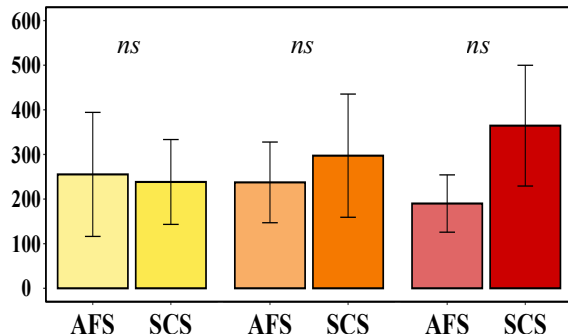
(a) 2018

Rainfall + Irrigation (mm)

**(b) 2019**

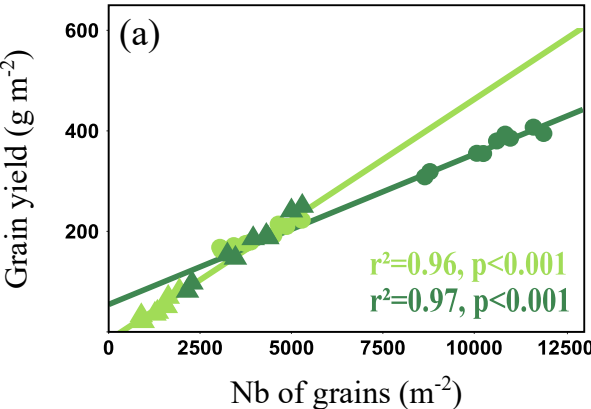
(a) Durum wheat - 2018**(b) Durum wheat - 2019****(c) Faba bean - 2018****(d) Faba bean - 2019**

(a) Durum wheat - 2018**(b) Durum wheat - 2019****(c) Faba bean - 2018****(d) Faba bean - 2019**

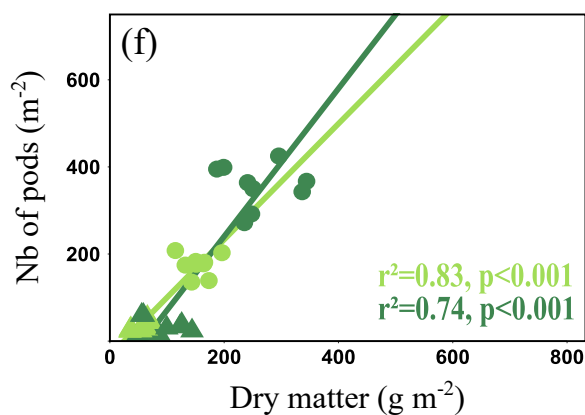
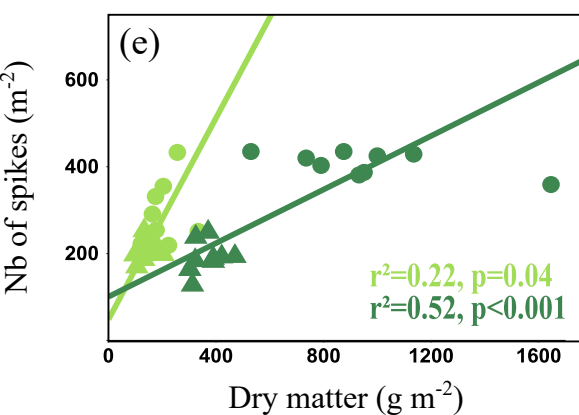
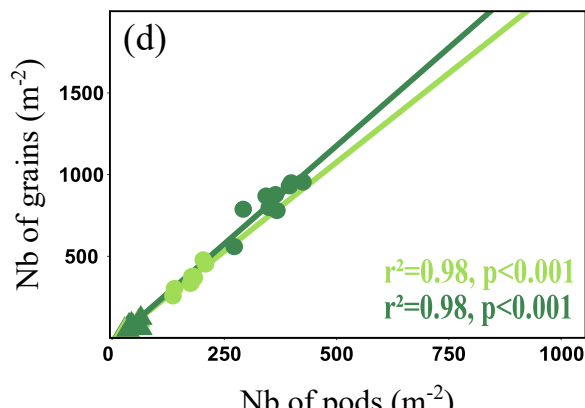
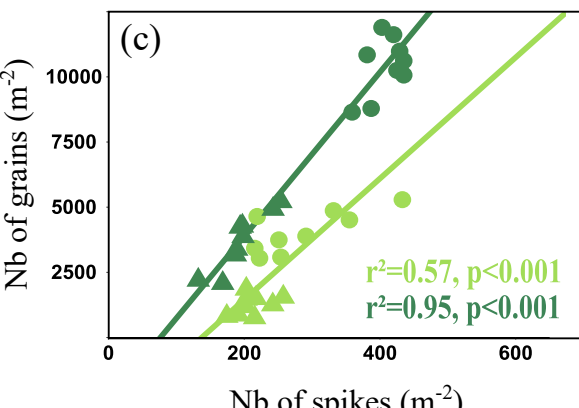
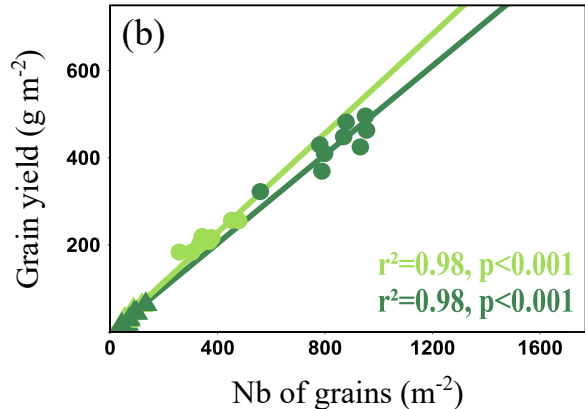
(a) Durum wheat - 2018**(b) Durum wheat - 2019****(c) Faba bean - 2018****(d) Faba bean - 2019**

Durum wheat

● 2018 ▲ 2019

**Faba bean**

● 2018 ▲ 2019



Mean of 2018 and 2019

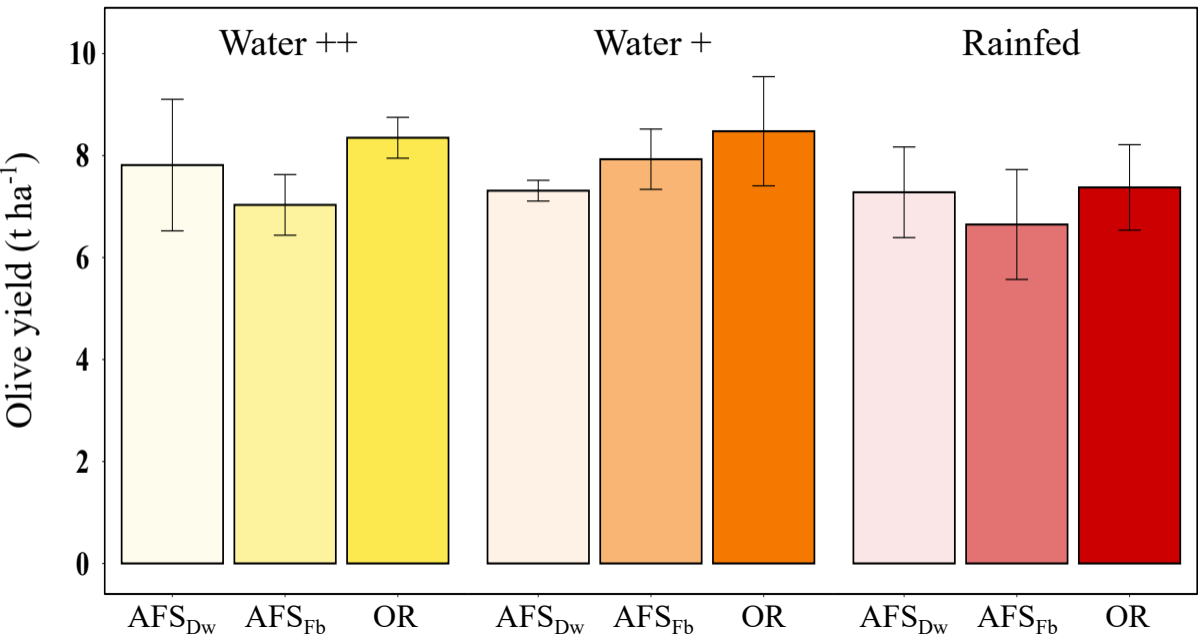


Table 1: Number of tillers/ branches ($m^{-2} \pm s.d$), number of spikes/pods and grains ($m^{-2} \pm s.d$), weight of 1000 grains TGW ($g \pm s.d$) and the harvest index (HI) of durum wheat and faba bean in 2018 and 2019 in agroforestry (AF) and sole crops (SC), according to the three water regimes (High water supply (Water ++), Medium water supply (Water +), and Rainfed). Lowercase letters indicate significant differences between cropping system among water regimes (HSD Tukey test, $P \leq 0.05$).

Species	Year	Water supply	Number of tillers/ branches (m^{-2})		Number of spikes/ pods (m^{-2})		Number of grains (m^{-2})		TGW (g)		HI	
			AF	SC	AF	SC	AF	SC	AF	SC	AF	SC
Durum wheat	2018	Water ++	312±16b	587±31a	240±21b	429±5a	3417±331b	10434±485a	52.1±3.2a	35.1±0.6b	0.54±0.03a	0.38±0.02a
		Water +	354±104b	656±35a	373±53a	401±19a	4889±388b	11453±545a	43.4±0.2a	35.0±1.4a	0.49±0.02a	0.40±0.00a
		Rainfed	280±60b	744±47a	244±40b	393±38a	3858±800b	9350±109a	53.0±8.4a	36.4±0.8b	0.58±0.02a	0.37±0.00a
	2019	Water ++	241±21b	395±27a	211±42a	206±31a	1485±535b	3904±954a	43.4±2.3a	46.9±3.0a	0.14±0.02a	0.14±0.02a
		Water +	231±15a	300±30a	220±20a	215±33a	1391±162b	4654±555a	32.9±1.8b	45.8±2.0a	0.11±0.01a	0.14±0.02a
		Rainfed	224±20a	295±54a	203±12a	166±33a	1111±384a	2796±1003a	30.5±5.0b	44.0±4.2a	0.08±0.02a	0.10±0.01a
Faba bean	2018	Water ++	28.3±0.7b	39.6±0.9a	174±32b	378±42a	386±87b	867±87a	583±39a	520±34a	0.65±0.01a	0.59±0.04a
		Water +	31.2±3.7a	38.2±5.1a	186±18b	347±53a	387±60b	845±90a	589±24a	505±24a	0.64±0.01a	0.67±0.01a
		Rainfed	31.2±2.5a	36.8±1.9a	165±25b	343±63a	322±58b	789±201a	657±83a	534±69a	0.63±0.03a	0.65±0.02a
	2019	Water ++	20.1±2.7a	36.5±7.5a	42.0±15.3a	25.9±4.0a	76.6±36.2a	50.6±14.0a	551±31a	429±103a	0.14±0.01a	0.08±0.01a
		Water +	17.2±0.4b	42.5±16.5a	37.7±8.5a	33.8±11.8a	73.0±12.9a	74.6±34.5a	548±86a	515±22a	0.15±0.02a	0.11±0.00a
		Rainfed	17.2±0.4a	28.0±7.6a	28.2±0.7a	54.4±16.8a	51.6±7.1a	80.3±48.6a	546±55a	498±32a	0.13±0.01a	0.10±0.07a

Table 2: Grain and straw protein content (% of dry matter basis \pm S.E.), grain and straw protein yield ($\text{g}\cdot\text{m}^{-2} \pm \text{s.d}$) at harvest in agroforestry (AF) and sole crops (SC) of durum wheat and faba bean in 2018, according to three water regimes (High water supply (Water ++), Medium water supply (Water +), and Rainfed). Lowercase letters indicate significant differences between cropping system per water regimes (HSD Tukey test, $P \leq 0.05$).

Species	Year	Water supply	Grain protein content		Straw protein content		Grain protein yield		Straw protein yield	
			(% Dry matter basis)		(% Dry matter basis)		$(\text{g}\cdot\text{m}^{-2})$		$(\text{g}\cdot\text{m}^{-2})$	
			AF	SC	AF	SC	AF	SC	AF	SC
Durum wheat	2018	Water ++	11.7 \pm 0.1a	11.4 \pm 0.3a	5.82 \pm 0.27a	5.49 \pm 0.29a	20.0 \pm 0.8b	41.7 \pm 2.1a	8.26 \pm 1.06b	31.6 \pm 4.1a
		Water +	11.7 \pm 0.4a	11.1 \pm 0.0a	6.12 \pm 0.24a	5.54 \pm 0.28a	24.5 \pm 2.4b	44.3 \pm 1.1a	13.17 \pm 2.88b	32.9 \pm 2.4a
		Rainfed	11.6 \pm 0.1a	11.1 \pm 0.3a	5.67 \pm 0.25a	4.98 \pm 0.22a	21.8 \pm 2.7b	37.6 \pm 5.1a	7.64 \pm 1.13b	27.9 \pm 2.0a
Faba bean	2018	Water ++	19.4 \pm 0.1a	19.2 \pm 0.4a	5.35 \pm 0.08a	5.55 \pm 0.15a	42.3 \pm 6.7b	86.1 \pm 5.0a	6.13 \pm 1.26b	16.7 \pm 2.5a
		Water +	19.5 \pm 0.1a	19.6 \pm 0.1a	4.87 \pm 0.24a	5.25 \pm 0.24a	43.9 \pm 5.2b	83.5 \pm 12.9a	6.02 \pm 0.54b	10.9 \pm 1.1a
		Rainfed	19.9 \pm 0.1a	19.9 \pm 0.4a	5.21 \pm 0.10a	5.49 \pm 0.35a	40.5 \pm 3.6b	81.6 \pm 14.5a	6.01 \pm 1.12b	11.6 \pm 2.7a

Table 3: Land equivalent ratios of olive-durum wheat and olive-faba bean agroforestry systems in 2018 and 2019, according to three water regimes (High water supply (Water ++), Medium water supply (Water +), and Rainfed). Partial LERs (pLERs) are indicated in brackets for crops and olive, respectively.

Year	Water supply	LER	
		Durum wheat + Olive	Faba bean + Olive
2018	Water ++	1.26 (0.26 + 1.00)	1.27(0.27 + 1.00)
	Water +	1.29 (0.29 + 1.00)	1.30 (0.30 + 1.00)
	Rainfed	1.32 (0.32 + 1.00)	1.28 (0.28 + 1.00)
2019	Water ++	1.20 (0.20 + 1.00)	2.35 (1.35 + 1.00)
	Water +	1.12 (0.12 + 1.00)	1.66 (0.66 + 1.00)
	Rainfed	1.19 (0.19 + 1.00)	1.54 (0.54 + 1.00)