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

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Title

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Abstract

Agroforestry systems can be an effective means of stabilizing or even enhancing crop yields under climate change. Although trees compete with crops for soil resources in agroforestry,they can also improve crops' growing conditions, especially ,by providing shade under drought. They can promote higher crop yields and higher harvest quality in the drylands. However, the beneficial effect of tree shade may depend on the seasonal pattern of rainfall, which determines the compensation between yield components. In this study, we evaluated two annual crops (durum wheat and faba bean) in olive agroforestry in northern Morocco. We manipulated water supply in a field experiment to span the high inter-annual rainfall variability at the site and tested whether olive trees reduce or improve crop yields. We assessed the effect of water addition on crop growth, yield components, and final yields and estimated the land equivalent ratio of olive agroforestry. Agroforestry limited crop growth and yield whatever the water regime. The magnitude of grain yield reduction was around 50 % for both crops in 2018, probably due to shade. The number of grains per unit area was the most impacted yield component in both 2018 and 2019. In contrast, water addition only had limited effects on faba bean yield, although it enhanced wheat grain yield by 11% and the number of wheat spikes by 13 %. Agroforestry improved individual grain weight by 39 % for wheat and 17% for faba bean, and enhanced the protein content of wheat grains and straw by 4 % and 9 %. However, improvements in grain weight and in protein content were not sufficient to compensate for yield loss due to shade. Despite lower crop yields, we show that agroforestry systems are still more land productive than sole crops and trees, even under arid conditions. We show how changing water supply may impact the performance of olive agroforestry in a drier future.

Keywords

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

1. Introduction

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

Inspired by agroecological principles, fruit-tree-based agroforestry systems (FT-AFS) can stabilize or enhance food production under climate change in dry areas (Lin, 2007, Krishnamurthy et al., 2019). The most recognized advantage of agroforestry is the increase in the land- and resource-use efficiency, which results from complementary yield sources and positive interactions between trees and crops (Zhang et al., 2007). Specifically, FT-AFS are high-value tree agroforestry systems (den Herder et al., 2017), which deserve greater attention considering their contribution to food production (Wolz et al., 2018; Lauri et al., 2019). A wide range of FT-AFS exists in semiarid regions with different tree species, e.g., apple-, apricot- and jujube agroforestry in China (Qiao et al., 2019), almond agroforestry in Iran (Surki et al., 2020). In most cases, FT-AFS has advantageous land equivalent ratios compared to sole crops and trees (Bai et al., 2016; Zhang et al., 2016; 2018; Panozzo et al., 2019). In Morocco, olive- (*Olea europaea* L.) agroforestry is widespread (Sofo et al., 2007) and belongs to traditional agriculture forms and proved its resilience through millennia. Several species of trees (e.g., fig, carob, quince), cereals (e.g., wheat, barley), grain legumes (e.g., faba bean, chickpea) grow with/under olive trees (Daoui and Fatemi, 2014; Razouk et al., 2016; Lauri et al., 2019). The 'Plan Maroc Vert' aims for the rapid extension of olive groves throughout arable lands (El Mouhtadi et al., 2014), opening novel opportunities for extending olive agroforestry beyond traditional forms. However, FT-AFS are absent from most agricultural policies, and they are disappearing (Nahayo et al., 2017; Ickowitz et al., 2019). Instead, sole cropping systems develop, pushed by input-based intensification and mechanization.

In FT-AFS, trees compete with crops for soil resources, but they can also improve crops' growing conditions under drought, mainly by providing shade. They can promote higher crop yields (Artru et al., 2017; Smethurst et al., 2017) and higher harvest quality (Arenas-Corraliza et al., 2018; Qiao et al., 2019). In natural ecosystems, the 'Stress-Gradient-Hypothesis' (SGH) predicts that negative interactions (competition) between species shift towards positive interactions (facilitation) with increasing abiotic stress (He et al., 2013). The rationale is that tall species like trees can beneficially modify the local environment and play the role of 'nurse' for smaller species like herbaceous crops. Under high-stress conditions, the amelioration of environmental conditions outweighs the direct effects of competition for resources. Although the relevance of the SGH remains unclear in the drylands (Maestre et al., 2005, 2009), meta-analyses suggest that trees have positive effects on biomass productivity when aridity exceeds semiarid conditions (Moustakas et al., 2013; Dohn et al., 2013). For example, acacia trees have negative impacts on crop yields under humid and sub-humid conditions (rainfall > 800 mm year^{-1}) but improve the yields under semiarid conditions (Bayala et al., 2012). Indeed, the shade of trees penalizes crop growth under favorable conditions (Cubbage et al., 2012) due to lower light interception and photosynthesis rates (Zhang et al., 2018; Rivest et al., 2009). However, shade creates a beneficial microclimate for crops (Lott et al., 2009; Mugunga et al., 2017) with buffered temperature (Peng et al., 2015), higher air humidity (Campi et al., 2009), and reduced evapotranspiration (Coussement et al., 2018) under more arid conditions. The validity of the SGH needs to be tested in FT-AFS, but recent examples in semiarid conditions are promising (Gao et al., 2018). The SGH formalizes the way trees can mitigate climate change in Mediterranean FT-AFS, more generally, in the drylands (Luedeling et al., 2016).

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

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

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

2. Material and methods

2.1 Experimental site

We conducted a two-year field experiment (2017-2019) in an olive grove in north-eastern Morocco (Sefrou Province), at the 'La Providence Verte' Louata farm (33°53'48.26"N, 4°40'25.63"O, 615 m). The climate is semiarid with hot and dry summers and cold and wet winters. The average annual temperature and rainfall are 19 °C and 473 mm, respectively (1988-2017). Drought generally occurs between May and October. During the crop cycle (October to July), rainfall was 429 mm in 2017/2018 and 345 mm in 2018/2019, which correspond to 'normal' and 'dry' years, respectively. The soil has a sandy clay loamy texture (28% clay and 54% sand) in the top 0-0.6 m layer. Total N content in this soil layer was 0.09%, Olsen-P 37 mg kg^{-1}, and K_2O 167 mg kg^{-1} (Table A.1, Supplementary Material).

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

2.2 Experimental layout

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

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

2.3 Water regimes

We simulated three different water regimes using drip irrigation. We equipped two-thirds of sub-plots of each type of system ('AFS', 'OR', 'SCS') with ten laterals emerging from the main sub line that carries water coming out from a pump equipped with a sand filter, a water meter, and a pressure regulator. Laterals were spaced 60 cm in 'AFS' and 70 cm in 'SCS', equipped with emitters spaced by 40 cm, and had a flow rate of 2 l.h^{-1}. Additionally, there was a 7 m empty gap between water regimes in 'SCS', which was equivalent to the empty inter-row in 'AFS' to eliminate any possible horizontal water transfer. The remaining sub-plots were not irrigated to have rainfed controls. In each water regime, crops and trees received the same amount of water. For technical reasons, the three water regimes were not randomly distributed but arranged in adjacent areas (Fig. 1).

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

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

2.4 Field measurements and sampling

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

Once they reached maturity, crop plants were entirely harvested at ground level using hand-clippers, taking four randomly selected 0.25 m^{-2} quadrats in 2018 or five adjacent 1 m^{-1} lines in 2019, avoiding borders in each sub-plot. Plants were sorted by organs, oven-dried (70°C, 48h), and weighed to determine the total aboveground biomass and the total grain biomass. Yield components were also assessed (e.g., number of spikes/pods per unit area, number of grains per unit area, and thousand-grain weight). The harvest index was calculated as the ratio between grain biomass and total aboveground biomass.

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

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

2.5 Crop quality

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

2.6 Data analysis

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

Eqn. 1: $\boldsymbol{LER}_{\mathbf{AFS}} = \boldsymbol{LER}_{\mathbf{AFS-Olive}} + \boldsymbol{LER}_{\mathbf{AFS-Crop}}$

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

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

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

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

3. Results

3.1 Dry matter production at flowering

Dry matter production was higher in 2018 than in 2019 for both wheat ($p< 0.001$) and faba bean ($p< 0.001$) and was significantly lower in agroforestry than in sole crops for both wheat ($p < 0.001$, Fig. 3) and faba bean ($p < 0.001$, Fig. 3). The number of tillers or branches per unit area was also significantly lower in agroforestry for both crops ($p<0.001$, Table 1). Water addition had a significant effect on dry matter production for faba bean ($p= 0.002$) but not for wheat ($p= 0.805$). In 2018, the dry matter production of faba bean was highest under the wettest water regime (+ 26 % compared to the other regimes). However, water addition did not impact the number of tillers ($p= 0.993$) nor the number of branches ($p= 0.283$).

3.2 Crop yields and yield components

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

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

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

3.3 Crop quality and protein yield

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

3.4 Olive yield

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

3.5 Land equivalent ratio (LER)

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

4. Discussion

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

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

Contrary to our first hypothesis, the shade of olive trees affected crops always negatively, even under low water availability. In addition, a little variation of shade is expected during the experiment, mainly due to shoot growth inhibition in the high-yield year (Melgar et al., 2008). Differences in biomass production and yield between agroforestry and sole crops were similar for all water regimes during the two years of experiment. In a Mediterranean climate, we expected that tree shade would have strong negative effects under the wettest conditions, where light, more than water, limited crop growth, leading to significant differences between agroforestry and sole crops. In contrast, we expected that the shade would improve crop growth and yield under water-limiting conditions by buffering heat (Peng et al., 2015) and water stresses. Assuming that trees use water from deeper soil layers than crops, the reduced evapotranspiration under tree shade (Coussement et al., 2018) could increase water availability for crops and result in higher water-efficiency. These expectations are supported by the 'Stress-Gradient Hypothesis' (SGH), which was repeatedly tested under dry-to-sub-humid conditions in several savanna-like ecosystems, including agroforestry systems (Dohn et al., 2013). Positive interactions between trees and grasses were attributed to the water economy under dry conditions.

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

Moreover, low nitrogen input (N) and water availability are both the main limitations to crop productivity, especially of cereals, in semiarid Mediterranean environments (Cossani et al., 2010). Theoretically, the maximum crop growth is reached when all resources are equally limiting (Sadras, 2004). In addition, adding water at the appropriate timing increased the growth potential of crops, leading to an increase in their nutrient requirements (e.g., nitrogen). Increasing water availability with irrigation without changing the amount of nutrients accordingly may have created a situation where nutrients became the limiting factor. Our results suggest that the global effect of trees in 'water-limited' agroforestry depends primarily on seasonal precipitation and water demand patterns and on a possible shift in limiting factor between water and nutrient such as nitrogen. We argue that the SGH should carefully account for these interactions between co-limiting factors to provide more relevant predictions in 'water-limited' agroforestry.

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

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

The reduction of final crop grain yields in agroforestry was a direct consequence of reduced grain number per unit area. In cereals, the variations in grain number per unit area determine the final yield more than other yield components (Xie et al., 2016; Kimura et al., 2018; Zhang et al., 2019). The number of grains is also a major yield component for legumes (Lake et al., 2019). Since the number of grains per unit area is closely related to the number of spikes/pods, the way trees affected crops at the tillering/ ramification stage (Sharif et al., 2010), mainly through the shade, was critical for crop yield in agroforestry. The reduced number of tillers (wheat) and branches (faba bean) explained more than 50 % of grain yield reduction under olive trees. However, while the number of tillers directly determined the number of wheat spikes, the number of pods of faba bean was also related to plant growth during pod emergence, which is the most critical stage for faba bean grain yield (Lake et al., 2019). Contrary to cereals, indeterminate legumes can increase the number of pods and thereby yield potential by extending the period between flowering and pod set. However, the shade under olive trees limited this phase compared to sole crops, probably because shade did not represent an advantage regarding the water economy.

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

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

4.3 Olive trees improve grain filling and grain quality

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

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

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

Despite lower crop yields, agroforestry systems generally had higher land productivity than sole crops and trees (LER > 1) during the two years of the experiment. Based on this first empirical evaluation in the South Mediterranean, we confirm that olive agroforestry systems can have high LERs and produce high-quality grains, even under more arid conditions than previous evaluation in Europe (Panozzo et al., 2019). However, a better improvement of land productivity might be achieved through a better vertical root complementarity, which was probably limited due to the previous orchard management as an irrigated orchard leading to a high root density in the topsoil layers down to a 0.6 m depth (Fernández et al., 1991). Contrary to the traditional olive groves, most modern olive orchards with high density (Connor et al., 2014) have uncultivated inter-rows, representing a loss of arable land in a context where food security is a rapidly growing issue. Besides mechanization issues, farmers are concerned about preserving enough resources, mostly water, to support olive production. However, our results reveal that crops did not impact olive yields, although the alternate bearing led to high variability of olive yields. Additionally, the different water regimes did not impact olive yields in the experiment, confirming that olive trees have, in general, high tolerance to water availability fluctuations and water scarcity (Moriana et al., 2003), and also probably to competition for water with intercrops. A step further will be to test different management strategies, especially tree pruning, and adapt the tree density to improve the functioning of the olive agroforestry as a whole. Compared to cereals, legumes are less competitive for soil resources (at least for nitrogen) and reach maturity earlier, leaving more resources available to olive trees, especially at the beginning of summer, when trees start to grow actively, and water availability sinks. Moreover, the indeterminate growth habit of legumes may improve the performance of agroforestry systems by valuing the shade under trees better than cereals (Kato et al., 2019). In the long-term, the capacity of legumes to fix the atmospheric nitrogen can enhance soil nitrogen available (Dwivedi et al., 2015) for the olive trees, improve soil fertility, and hence have positive effects on olive production. Therefore, we highly recommend legumes to enhance and diversify the global productivity of olive groves and invite to consider a greater diversity of legume species. However, further studies on how crops modify water availability would be necessary to confirm the promising potential of olive agroforestry in the drier future of Mediterranean regions.

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

Conclusion

Olive agroforestry is gaining interest in the Mediterranean, but its relevance in a drier future remains uncertain. On the one hand, farmers fear the consequences of more intense negative tree-crop interactions under drought. On the other hand, ecological theory (SGH) predicts an increase in positive tree-crop interactions with increasing environmental stress. We evaluated a case of olive agroforestry along a water availability gradient to move ahead, representative of most rainfed olive groves in the South Mediterranean. We show that olive trees limited crop growth during critical stages before flowering and caused a significant reduction in grain number per unit area and grain yield, whatever the water regime. In contrast, olive trees also improved grain filling and grain protein content, but not sufficient to compensate for the negative effects on crop growth and yield. We concluded that in the case of olive agroforestry, the SGH needs a 'seasonal' reformulation to predict how the net balance in tree-crop interactions will change in a drier future. However, despite lower crop yield than sole crops, LERs > 1 reveal that olive agroforestry is a promising way of improving land and resource productivity, particularly with appropriate farming practices.

Acknowledgment

This research was carried out as part of the SEMIARID Project, ARIMNet 2 call (ERA-NET program), and Grant agreement n°618127. We are thankful for the excellent support provided by managers and staff of 'La Providence Verte' at the Louata farm (Sefrou, Morocco). We are also grateful to Dr. Hatem Belhouchette for his support and contribution to finalize this work. Finally, we warmly acknowledge the Master Students, Ms. Soukaina El Mrini, and Safae Aqil from the Institut Agronomique et Vétérinaire Hassan II, and Mr. Guillaume Weissenberger from AgroParisTech, as well as the technical staff, for their valuable contribution in this work.

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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.

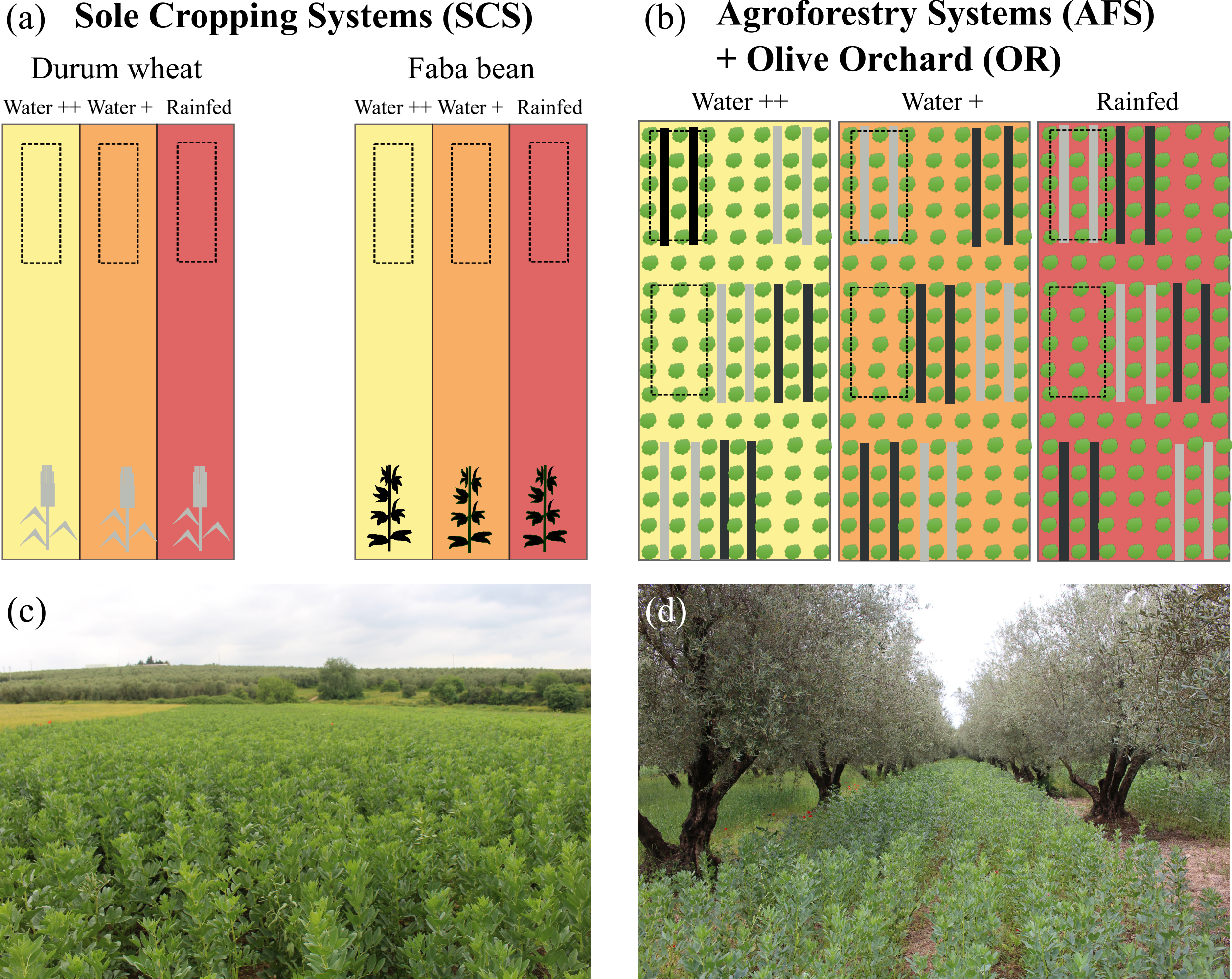
Fig. 3: Dry matter (g m^{-2} ± sd) at flowering in agroforestry (AFS) and sole crops (SCS) for durum wheat (a: 2018; b: 2019) and faba bean (c: 2018; d: 2019). Bar color indicates the water regime: (yellow: Water ++; orange: Water +; red: Rainfed). Significance level (differences between AFS and SCS):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

Fig. 4: Grain yield (g m^{-2} ± 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): * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

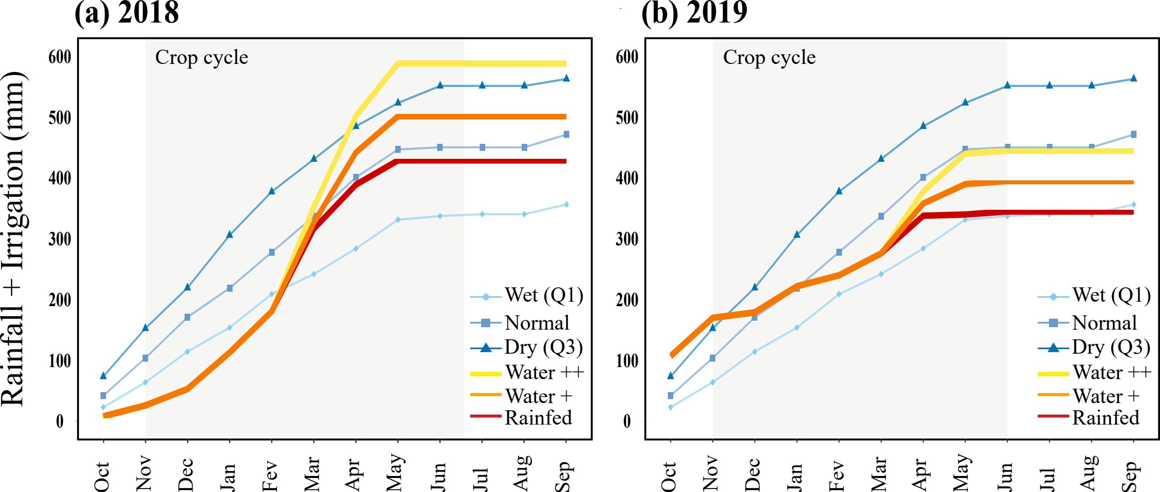
Fig. 5: Straw yield (g m^{-2} ± sd) at harvest in agroforestry (AFS) and sole crops (SCS) for durum wheat (a: 2018; b: 2019) and faba bean (c: 2018; d: 2019). Bar color indicates the water regime (yellow:Water ++; orange: Water +; red: Rainfed). Significance level (differences between AFS and SCS): *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

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).

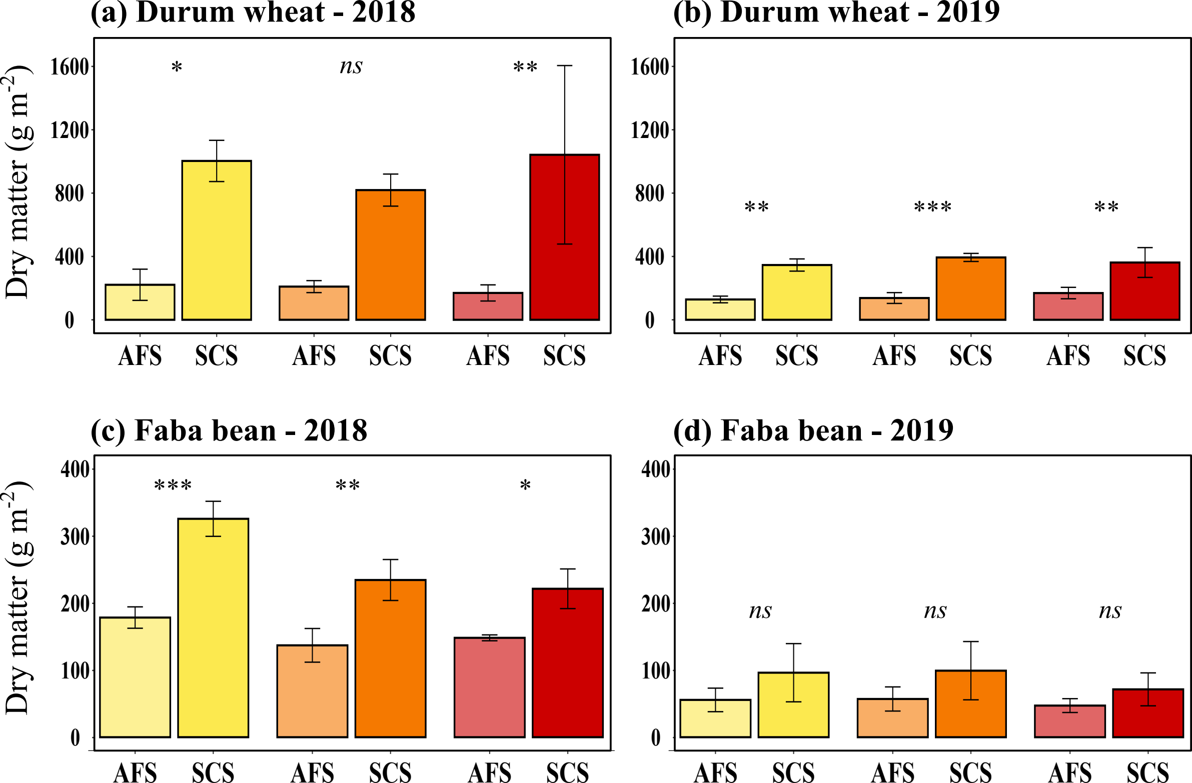
Fig. 7: Olive yield (t ha^{-1}) in agroforestry with durum wheat (AFS_{Dw}), and faba bean (AFS_{Fb}), and in pure olive orchard (OR). Bar color indicates the water regime (yellow: 'Water ++'; orange: 'Water +'; red: 'Rainfed'). Significance level (differences between AFS and SCS): * $p < 0.05$; ** $p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



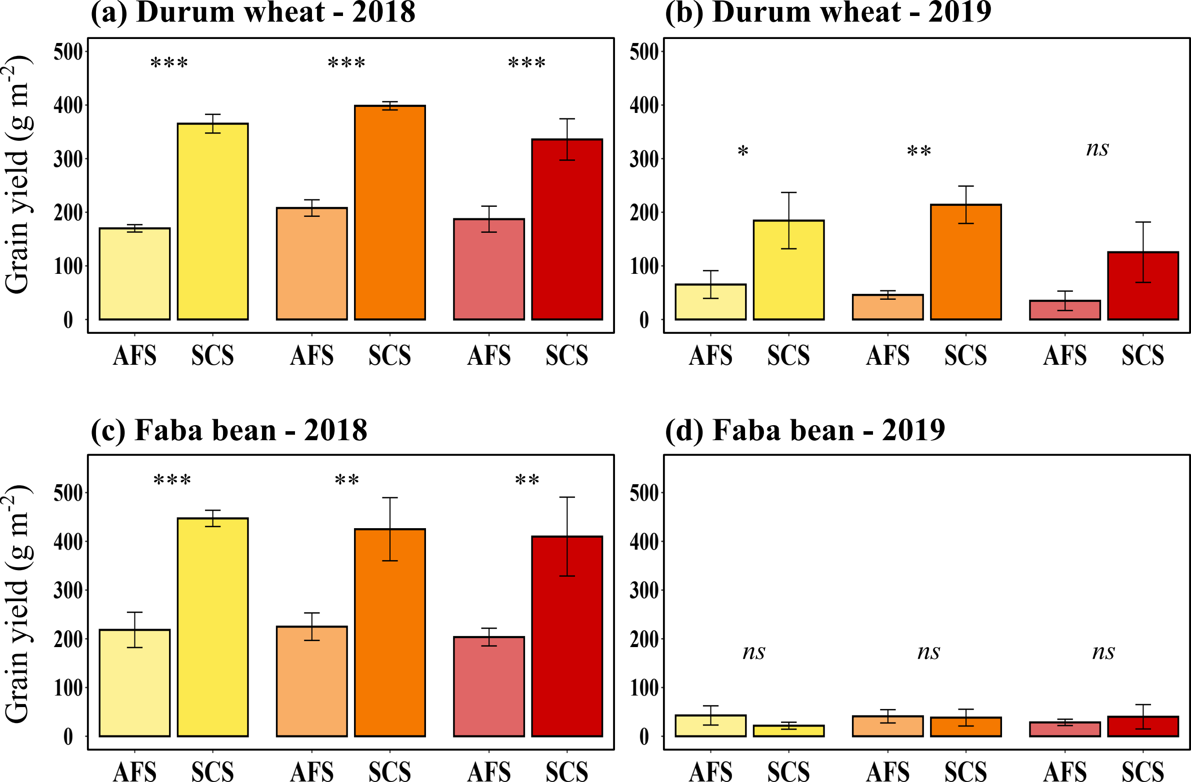
(a) Sole Cropping Systems (SCS)
Durum wheat
Faba bean
Water ++ Water + Rainfed
Water ++ Water + Rainfed
(b) Agroforestry Systems (AFS) + Olive Orchard (OR)
Water ++
Water +
Rainfed
(c)
(d)



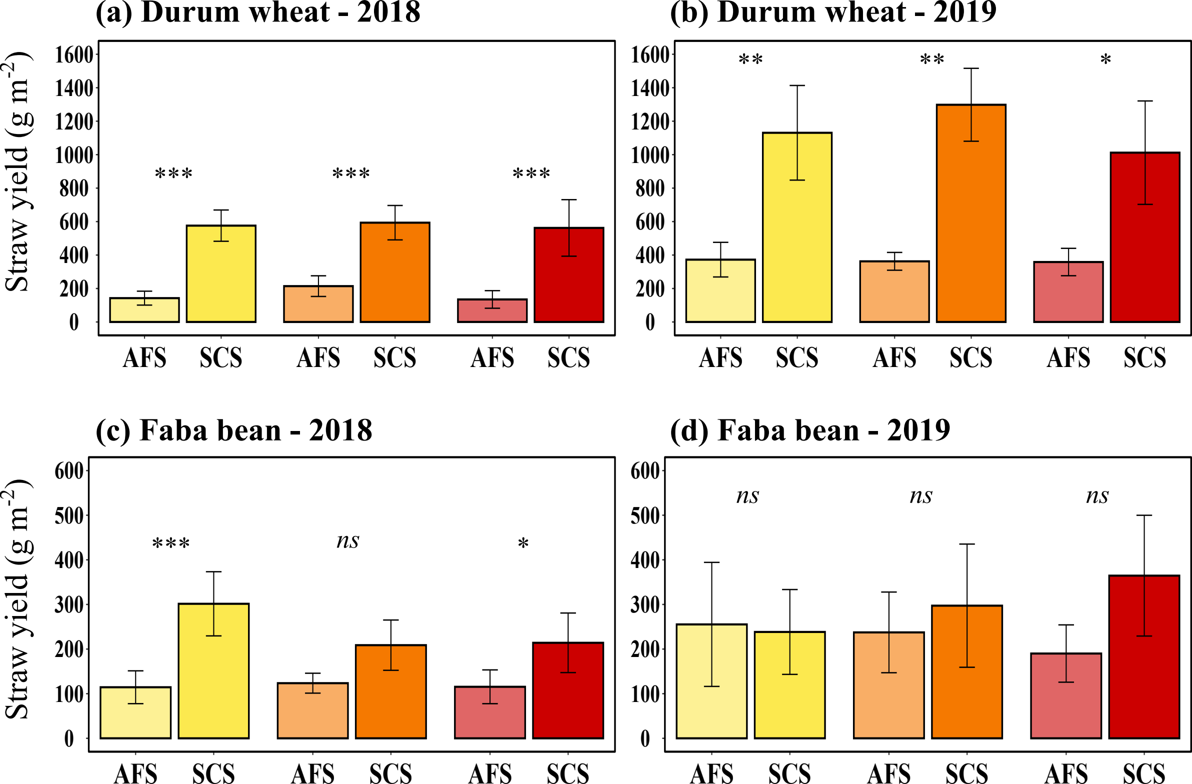
(a) 2018
(b) 2019
Crop cycle
Rainfall + Irrigation (mm)
0
100
200
300
400
500
600
Oct
Nov
Dec
Jan
Fev
Mar
Apr
May
Jun
Jul
Aug
Sep
Wet (Q1)
Normal
Dry (Q3)
Water ++
Water +
Rainfed

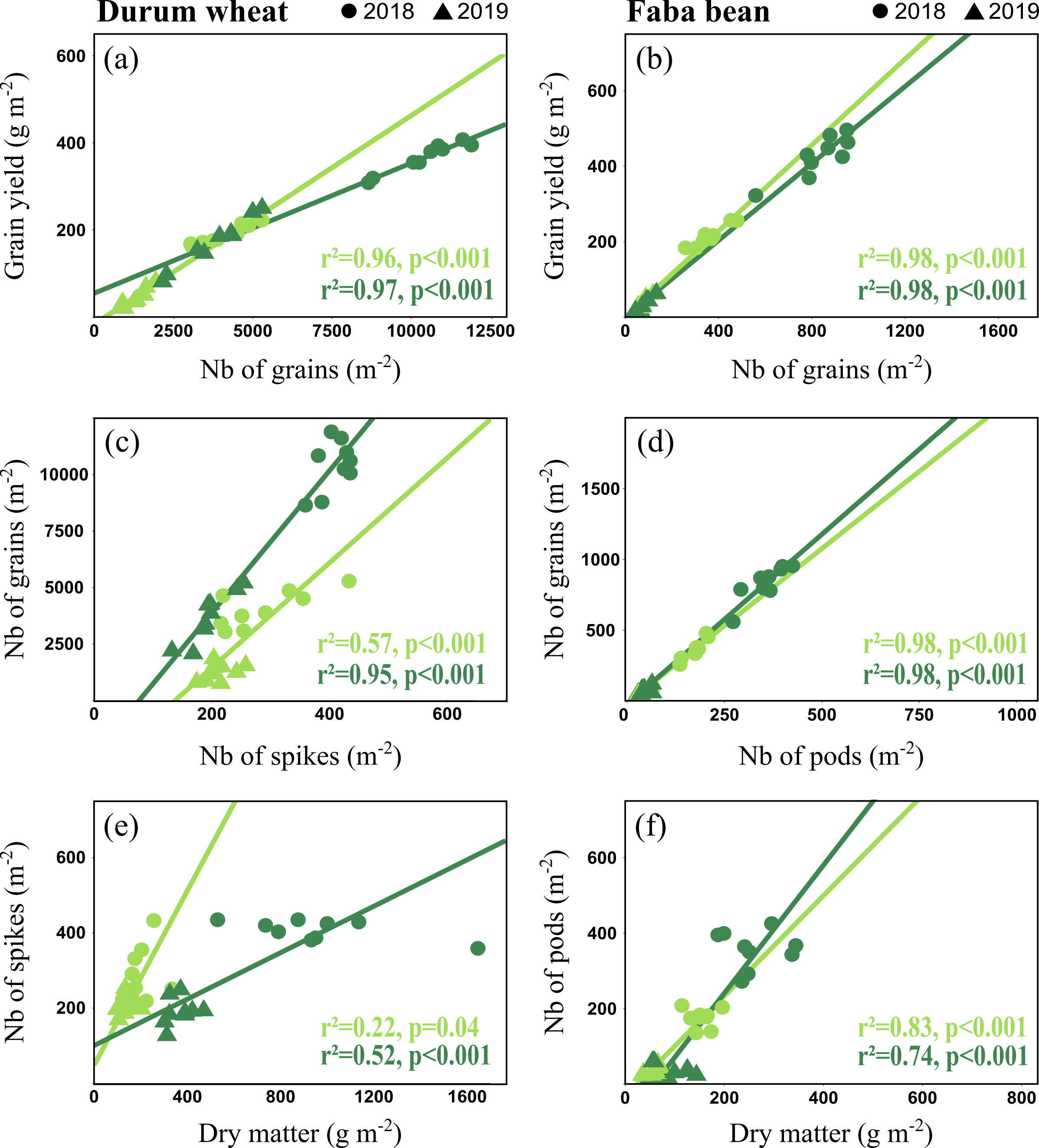


(a) Durum wheat - 2018
(b) Durum wheat - 2019
(c) Faba bean - 2018
(d) Faba bean - 2019
Dry matter (g m-2)
1600
1200
800
400
0
300
200
100
*
ns
**
***
AFS
SCS



(a) Durum wheat - 2018
(b) Durum wheat - 2019
(c) Faba bean - 2018
(d) Faba bean - 2019
Grain yield (g m-2)
0
100
200
300
400
500
AFS
SCS
***
**
*
ns


(a) Durum wheat - 2018
(b) Durum wheat - 2019
(c) Faba bean - 2018
(d) Faba bean - 2019
Straw yield (g m-2)
0
200
400
600
800
1000
1200
1400
1600
100
300
500
***
**
*
ns
AFS
SCS



Durum wheat
● 2018 ▲ 2019
Faba bean
● 2018 ▲ 2019
(a)
Grain yield (g m-2)
600
400
200
0
2500
5000
7500
10000
12500
Nb of grains (m-2)
r²=0.96, p<0.001
r²=0.97, p<0.001
(b)
Grain yield (g m-2)
600
400
200
0
400
800
1200
1600
Nb of grains (m-2)
r²=0.98, p<0.001
r²=0.98, p<0.001
(c)
Nb of grains (m-2)
10000
7500
5000
2500
0
200
400
600
Nb of spikes (m-2)
r²=0.57, p<0.001
r²=0.95, p<0.001
(d)
Nb of grains (m-2)
1500
1000
500
0
250
500
750
1000
Nb of pods (m-2)
r²=0.98, p<0.001
r²=0.98, p<0.001
(e)
Nb of spikes (m-2)
600
400
200
0
400
800
1200
1600
Dry matter (g m-2)
r²=0.22, p=0.04
r²=0.52, p<0.001
(f)
Nb of pods (m-2)
600
400
200
0
200
400
600
800
Dry matter (g m-2)
r²=0.83, p<0.001
r²=0.74, p<0.001

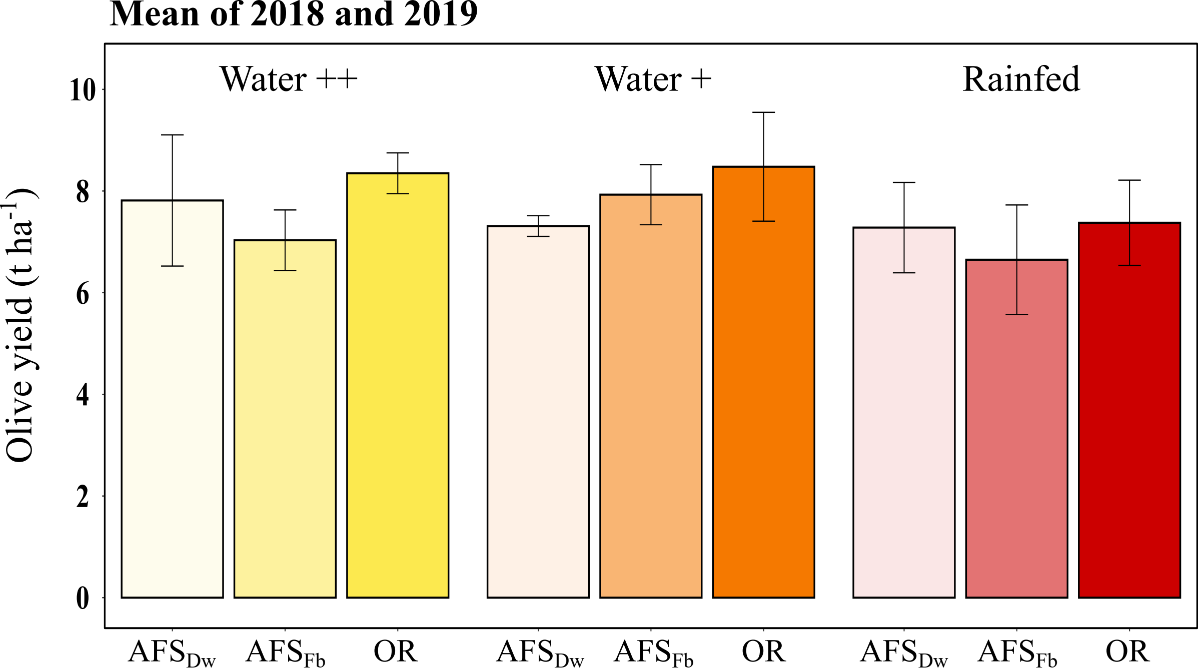

Mean of 2018 and 2019
Water ++
Water +
Rainfed
Olive yield (t ha-1)
0
2
4
6
8
10
AFSDw
AFSFb
OR
AFSDw
AFSFb
OR
AFSDw
AFSFb
OR

Table 1: Number of tillers/ branches (m-2 ± s.d), number of spikes/pods and grains (m-2 ± s.d), weight of 1000 grains TGW (g ± 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 t 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≤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 ± S.E.), grain and straw protein yield (g.m-2 ± 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≤0.05).

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