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Original article

Yield and related traits of three legume crops grown in olive-based agroforestry under an intense drought in the South Mediterranean

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ABSTRACT

Heat and drought stresses have become more frequent and intense in the Mediterranean, strongly influencing arable crop phenology, growth, and grain yield. Agroforestry systems can effectively buffer the adverse climate conditions and stabilize or even increase crop yield under climate change. However, the positive effects of agroforestry remain uncertain due to the possible intense competition between trees and crops, especially for legume crops that have been less studied than cereals in such context. This study aimed to assess the response of the phenology, growth, grain yield, and yield-related traits of chickpea (Cicer arietinum), faba bean (Vicia faba), and lentil (Lens culinaris) to olive-based agroforestry (AFS) as compared to sole crops system (SCS) in the South of the Mediterranean. We conducted a field experiment during two growing seasons marked by an intense drought, either at the beginning (year 1) or at the end (year 2) of the crop cycle. Crop growth and yield were lower in year 1 than in year 2, reflecting the adverse growing conditions caused by the early drought. They were also lower in AFS than in SCS for both years, indicating that trees had competitive effects on crops. In year 1, the yield loss of grains in AFS was 66 % for lentil, 47 % for chickpea, and 43 % for faba bean compared to SCS, confirming the greater shade sensitivity of lentil. In year 2, the reduction was significantly smaller and was about 46 %, 34 %, 38 % for lentil, chickpea and, faba bean, respectively. The number of pods and grains were the most affected yield components by agroforestry and drought timing across the three legumes crops. Similar responses were found when comparing crops at different distances to trees within the AFS field. Crops generally had lower biomass and yield, explained by fewer pods and grains, on the northern side of trees compared to the southern side of trees or the middle of tree inter-rows, causing significant spatial heterogeneity in crops. However, lentil and chickpea had a positive response to shade during the early drought year while a negative response during the late drought year, suggesting that the benefits of the microclimate created by olive trees express depending on drought timing and crop physiology. Our study supports legume integration into AFS, suggesting that chickpea should be considered during high-stress conditions, while faba bean should be preferred during low-stress conditions.

1. Introduction

Current climate change scenarios predict that the decreasing precipitation and increasing temperatures will limit the annual crop production in most Mediterranean countries (IPCC, 2022). Morocco will face the most significant precipitation decrease due to climate change until 2050 (Terink et al., 2013). Climate change scenarios also forecast that the inter-annual variability of droughts will increase, resulting in more frequent winter droughts and more intense summer droughts. Agroforestry is increasingly recognized

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as a promising land management system for climate change adaptation (Li et al., 2021; Tschora and Cherubini, 2020). The most recognized advantage of agroforestry is the increase in the land use efficiency, which results from complementary yield sources and positive interactions between trees and crops (Zhang et al., 2007). Agroforestry offers proven strategies for carbon sequestration, soil enrichment, biodiversity conservation, and air and water quality improvement (Gu et al., 2022; Tschora and Cherubini, 2020). In most cases, agroforestry has advantageous land equivalent ratios compared to sole crops and trees (Temani et al., 2021; Mead, R. and Willey, 1980).

In agroforestry, many studies have been conducted on how trees affect cereal productivity and reveal that the main cause of cereal yield decreases is competition for light (Qiao et al., 2020; Pantera et al., 2018; Artru et al., 2017; Dufour et al., 2013; Rivest et al., 2009; Li et al., 2008). The adverse effects of shade on the growth, flowering, and yield of crops have been repeatedly reported (Du et al., 2020; Xu et al., 2016; Lau et al., 2012). Shade usually limits biomass production and therefore decreases crop yields (L. Li et al., 2010). However, trees can also improve crop growing mainly by providing shade under drought conditions, with buffered temperature (Peng et al., 2015) and reduced evapotranspiration (Coussement et al., 2018) under more arid conditions. In Morocco, legumes are frequently associated with cereals and fruit trees within typical Mediterranean agroforestry systems, which belong to traditional agriculture forms. Such systems proved their resilience to climate fluctuations and perturbations through millennia and therefore represent today a precious source of knowledge for designing climate-resilient agrosystems. To date, most research focused on trees (e.g., olive, fig, carob) and the associated cereals, e.g., wheat and barley (Razouk et al., 2016; Daoui and Fatemi, 2014). However, few studies explicitly focused on legumes and vegetbales in rainfed or irrigated agroforestry (Leauthaud et al., 2022; Amassaghrou et al., 2021; Temani et al., 2021; Ameur et al., 2020; Razouk et al., 2016; Daoui et al., 2012).

Legumes differ in many physiological aspects compared to cereals and potentially have many advantages in agroforestry. Firstly, the critical stage for cereals occurs around flowering. During this period, stress can affect carpel growth by decreasing the size of the ovaries (which form the fruit pericarp), reducing the potential grain weight regardless of conditions during grain filling (Arenas-Corraliza et al., 2018). In contrast, the critical stage occurs at grain filling for legumes which is less sensitive to abiotic stress than flowering (Lake and Sadras, 2014). Secondly, legumes have an undefined growth pattern, allowing crops to increase the number of pods and yield potential as long as the environmental conditions are good enough and possibly better benefit from an advantageous microclimate under trees than cereals. Thirdly, legumes benefit from the symbiotic fixation of nitrogen (Lake et al., 2019; Lake and Sadras, 2014), making them less sensitive to competition for nitrogen with trees in agroforestry. Finally, unlike cereals, legumes did not significantly affect olive yield (Amassaghrou et al., 2021; Chehab et al., 2019). Specifically, Amassaghrou et al.(2021) found that agroforestry associating faba bean and chickpea with olive trees had a land-equivalent ratio (LER) of 1.83 and 1.53, respectively, which was greater than the associations with wheat (LER = 1.23) or barley (LER = 1.29). However, the microclimate induced by trees may induce favorable or unfavorable conditions for legumes, depending on their growth cycle length and their requirements for water, nutrients, and competition for light (Pang et al., 2019; Verghis et al., 1999). Therefore, there is a need to document and compare the physiological and productive responses of different legume crops under trees, to improve the design of agroforestry systems and adapt the management practices.

Chickpea (*Cicer arietinum)*, faba bean (*Vicia faba)*, and lentil (*Lens culinaris)* are the most cultivated species in olive-based agroforestry in Morocco (Amassaghrou et al., 2021; Kmoch et al., 2018). They have different growth needs and responses to shade and water stress, making their relevance for agroforestry dependent on environmental conditions. Chickpea has a non-specific growth nature and is highly sensitive to shade (Verghis et al., 1999). Verghis et al. (1999) reported that chickpea grain yields and dry matter yields were the lowest under the shade because of reduced grain number and increased abortion of reproductive structures. In the rainfed conditions of Morocco, water and heat stresses are also significant constraints to chickpea production (Idrissi et al., 2012; Zhang et al., 2000) and water limitation has been shown to reduce chickpea yield (Soltani et al., 2000). Severe stress during reproductive development, particularly after pod set, can cause significant pod abortion and decreased grain filling (Wang et al., 2006). In comparison, faba bean requires a cooler season, better tolerates early seeding, and is less sensitive to shade than chickpea. Under an artificial shade, Nasrullahzadeh et al. (2007) reported that faba bean physiological maturity, plant height, grain size, and grain yield were significantly higher than in full sunlight. However, faba bean is more sensitive to water stress than chickpea. Water deficit in faba bean causes a significant reduction in leaf area, shoot dry matter, pod number, and grain production (Abid et al., 2017). Finally, lentil is similarly sensitive to shade as chickpea (Darabi et al., 2014). Lentil is a drought tolerance crop, better adapted to low rainfall than faba bean and chickpea, but when water stress occurs during the reproductive phase, it can significantly reduce grain yield, grain weight, harvest index, and dry matter and shorten grain filling by accelerating senescence and maturity (Idrissi et al., 2012).

In this study, we assessed and compared the yield and yield-related traits of three legumes (chickpea, faba bean, and lentil) in olive-based agroforestry during two different climatic years, focusing on the spatial variability of crop growth. Specifically, we asked whether: (1) under exceptionally dry years, the microclimate created by olive trees would reduce crop stress, promote growth and increase yield; (2) the legumes species would have different yield potential under agroforestry regarding their sensitivity to abiotic stress and their physiological requirements; and (3) the heterogeneity and stability of crop production under trees would be related to their location in the field and exposure to sun and shade. Considering the low rainfall during the two years of study, we hypothesized that olive trees would benefit crop growth and yield. However, we expected that the beneficial effect on grain yield would depend on the drought timing. We hypothesized that olive trees would have a stronger positive effect during a late drought, corresponding to pod formation and grain filling, identified as the most critical period for legume yield, than during an early drought corresponding to the vegetative growth phase. Additionally, we hypothesized that shade tolerance would confer a high ability to grow under trees, and therefore we expected that faba bean would be more productive in agroforestry than chickpea and lentil. We also expected that faba bean would better benefit from the microclimate created by trees under intense drought conditions due to its greater sensitivity to water deficit than the other species. Finally, we hypothesized that trees would create a significant spatial heterogeneity in yield and yield-related traits within agroforestry systems, reflecting contrasting levels of tree-crop interactions in the field.

2. Material and methods

2.1. Experimental site

We conducted a field experiment over two successive years in 2015/2016 (year 1) and 2016/2017 (year 2), in a mature rainfed olive grove in the experimental station at the National Institute for Agricultural Research (INRA Morocco) in Douyet, Northern Morocco (34°03′06.6″N, 5°05′15.2″W, 651 m a.s.l). The Douyet region has a Mediterranean climate marked by a dry season between May and October. Over the past 30 years (1987–2017), the mean annual precipitation was 408.4 mm, with significant interannual variations (CV = 38 %) during the growing period of arable crops.

A severe drought occurred during the two years of study, which were drier than 75 % of the years compared to 30 previous years (Fig. 1). In year 1 (2015–2016) and year 2 (2016–2017), global precipitation was estimated at 164.6 mm and 284.2 mm, *i.e.* 61 % and 33 % lower than the historical mean. The cumulative precipitation from the seeding to harvest was 155.6 mm in year 1 and 173 mm in year 2. Although both years had similar precipitation during the growing season (+17.4 mm in year 2), they significantly differed in precipitation distribution, leading to contrasting levels of drought stress (Fig. 1). Year 1 started with a significant drought episode from September to March (- 239 mm compared to the historical mean), whereas year 2 showed a very dry period at the end of the growing season, from March to May (- 72.4 mm). The highest precipitation value was observed in March (58 mm) and December (62 mm) for year 1 and year 2, respectively. In addition, the average temperature assessed monthly was higher than the average recorded in historical temperature.

The experimental station has a clay texture (vertisol), in the top 0–0.5 m layer. Organic Mater in this soil layer was 1.1 %, Olsen-P 20.9 mg kg^{-1}, and K2O 480.5 mg kg^{-1}, soil analysis after harvest in both years are presented in (Table 1).

The olive grove (Olea *europaea. Subsp. Europaea.* Cv.'*Picholine marocaine*') was 50-years old. Olive trees were all of similar size (5 m in height, the average diameter of the circumference was 1.2 m, average canopy diameter was 13.2 m). The density of olive trees was 100 trees. Ha^{-1} with a regular 10 × 10 m plantation design following an East-West orientation. The trees are pruned after the olives have been harvested. In the last five years no fertilizers or fungal or insecticide treatments have been applied to the trees. Olive trees have been managed as a non-irrigated orchard since their plantation.

2.2. Plant material and experimental layout

We compared three widespread Mediterranean food legume crop species, winter chickpea, (Cv. 'Farihane'), faba bean (Cv. 'Aguadulce'), and lentil (Cv.' Bakria'), grown either in sole crop system (SCS) or olive-based agroforestry (AFS) with similar technical management. Plots of SCS and AFS were seeded in two adjacent fields with similar soil properties (Table 1) following a split-plot design with three randomized repetitions (Fig. 2).

Chickpea, faba bean, and lentil were sown on the same date for the two years of the experiment, in December 2015 and December 2016. The sowing rates in SCS and AFS were 100 kg.ha^{-1} for chickpea, 150 kg.ha^{-1} for faba bean and 50 kg.ha^{-1} for lentil. In SCS, each plot covered an area of 85 m^2 (10 m length × 8.5 m width). Crops were seeded in strips of 17 rows equally spaced at a distance of 0.5 m. In AFS, each plot covered an area of 60 m^2 (10 m length × 6 m width). Crops were seeded in strips of 12 rows spaced at a distance of 0.5 m, leaving a 2 m distance between the outer rows of the crop strip and the tree line (Fig. 2). Crop rows were parallel to the olive tree rows with an East-West orientation. According to the local practices, the fertilizer application rate was 48 kg

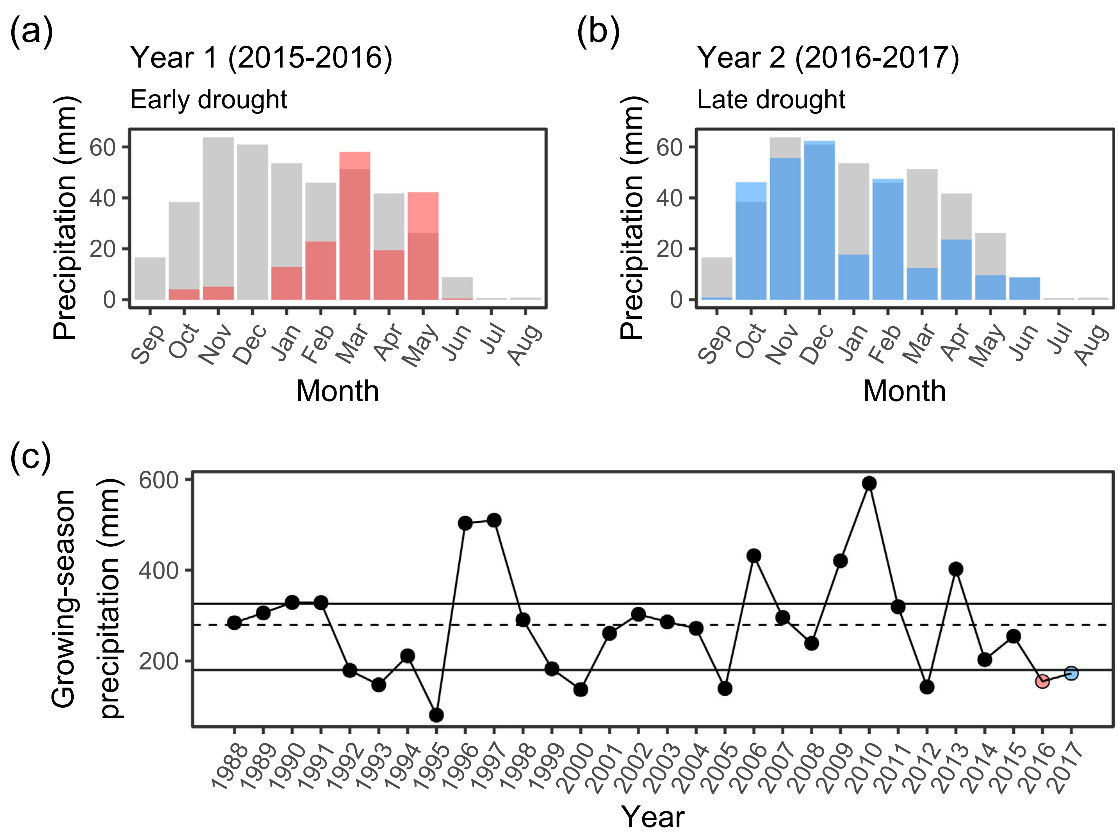

Fig. 1. Distribution of monthly precipitation (mm) for the two years of study (a: 2015–2016 blue bars and b: 2016–2017 red bars), as compared to the mean historical precipitation for the last 30 years (1988–2017) at the study site (gray bars) and (c) the long-term records of growing season precipitation (September-June) over the past 30 years. The dotted line indicates the long-term mean, while the solid lines indicate the 1st (dry years) and the 4rth (mild years) quartiles. (print in color).

Table 1
Soil fertility of sole corp and agroforestry experimental site in Douyet.

	SCS			AFS		
	P_2O_5 (Olsen) (mg/kg soil)	K_2O (mg/kg soil)	MO (%)	P_2O_5 (Olsen) (mg/kg soil)	K_2O (mg/kg soil)	MO (%)
Intial Condition	20.9	480.5	1.1	18.6	470.4	0.7
Year 1	17.6	464.4	0.7	22.7	479.4	1.2
Year 2	38.5	470.6	1.5	38.5	478.4	1.5

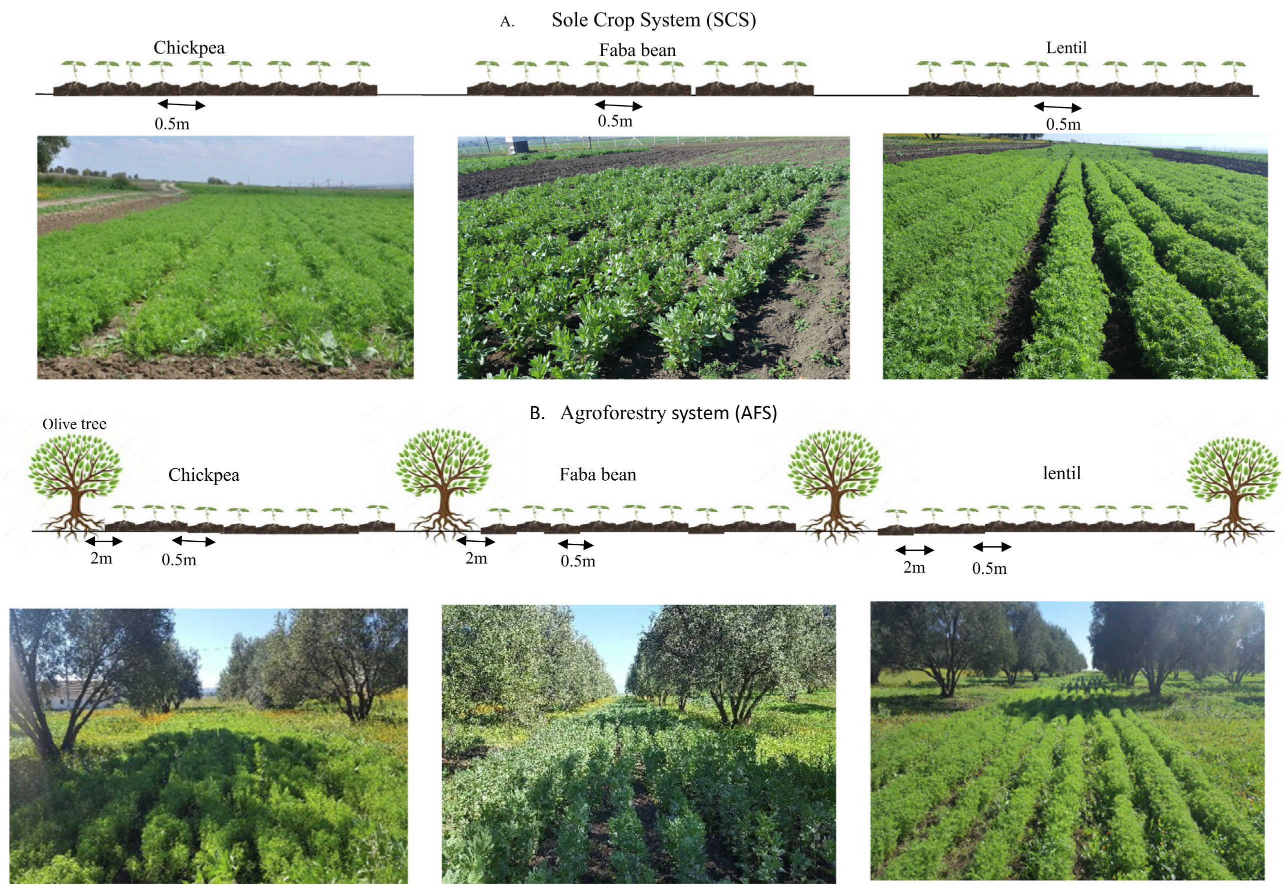

Fig. 2. Experimental layout showing (A) the plot of Sole Crop System (SCS) and (B) the plot of Olive-based Agroforestry system (AFS), chickpea, faba bean, and lentil were sown in an east–west orientation, in SCS, crops were sown in strips spaced by 0.5 m distance. In AFS Crops were sown in strips of 12 rows spaced by 0.5 m distance leaving a 2 m distance between the outer rows of the crop strip and the tree line (print in color).

P_2O_5 ha^{-1} in both SCS and AFS, and P was applied as triple superphosphate at the sowing date. Technical management (weed, disease, and pest control) has been performed to ensure the safe growth of crops.

In 2016, the crops were harvested at maturity on the 20th of May for lentil and the 8th of June for faba bean and chickpea. In 2017, all three crops were harvested on the 25th of May, just after an early heatwave. Olive trees were manually harvested in November 2016 and 2017, and all the fresh olive fruit were weighed to measure the yield. However, the olive yield was very low since olive trees were left untreated for several years (e.g., pruning, fertilization). Therefore, we considered that the effect of introducing legumes on olive tree yield could not be assessed reliably. Hence, we did not estimate the total productivity of the AFS as initially planned. Instead, the work focused on yield and yield components of legumes grown in agroforestry conditions.

2.3. Field measurements and sampling

Crop growth monitoring was performed by three repeated measures at the flowering, pod formation, and maturity stages in 2016 and 2017. At each stage, 45 plants/plot in SCS (all plants inside a 3 m^2 quadrat), and 60 plants/species/plots in AFS (stratified sampling of 5 selected plants/row along 1 m line), were randomly selected to measure plant height and count the number of branches. Once they reached maturity, all plants of the quadrats (SCS) and the selected lines (AFS) were harvested using hand clippers, and their reproductive organs (pods, grains) were sorted out to determine the number of pods per unit area (Nb_pods), the number of grains per unit area (Nb_grains), and thousand kernel weight (TKW). Afterward, samples were weighed to determine the total aboveground biomass and grain yield. The harvest index (HI) was calculated as the ratio between grain biomass and total aboveground biomass. The relative yield index for aboveground biomass ($RY_{Biomass}$) and grain yield (RY_{Yield}) were calculated as the ratio between total biomass and yield in AFS and SCS for each crop species (de Wit and Van den Bergh, 1965):

$$RY = Y_{AFS}/Y_{SCS} \quad (1)$$

where Y_{AFS} and Y_{SCS} are respectively the yields of legumes in AFS and SCS. A ratio higher than 0.5 indicates that crops had higher biomass and/or yield in AFS than in SCS, while a ratio lower than 0.5 indicates that crops were less productive in AFS.

Additionally, crop sampling was distributed over three main zones to represent the spatial heterogeneity caused by trees in the AFS plot. Each sampling zone consisted of 4 adjacent crop lines (over 12) and had contrasting exposure to tree shade and belowground interactions (Fig. 3). In this way, in the middle of the inter-row ('Middle'), the influence of olive trees on crops was expected to be the lowest, with a moderate intensity of shade and weak belowground interactions. On the northern side of the trees ('North'), the shade intensity was low, and the influence of olive trees was mainly belowground. On the southern side of trees ('South'), the influence of trees was the highest, with intense shade and belowground interactions.

2.4. Leaf temperature

Crop leaf temperatures were measured at the three successive stages as previously defined (flowering, pod formation, and maturity) to assess and compare the variation of water stress of crops between SCS and AFS. Leaf temperature was measured by placing a non-contact infrared thermometer on the upper leaf of 15 plants of the 3 m^2 quadrat in SCS and all 60 plants (5 plants/ row) in AFS simultaneously and according to the same measurement model and orientation. After that, leaf temperature depression (ltd) was calculated to account for the actual air temperature (Deva et al., 2020):

$$LTD = Leaf\ temperature - Air\ temperature \quad (2)$$

2.5. Statistical analysis

The statistical analysis were performed in R version 4.0 (RCore-Team. 2020). The differences in crop growth variables, yield components, total biomass, grain yield, and leaf temperature were analyzed with three-way ANOVAs using (1) species (chickpea,faba bean, lentil), (2) type of system (AFS *vs* SCS), and (3) year (2016 *vs* 2017) as fixed factors. A significant analysis (P < 0.05) of the ANOVA allows Tukey multiple comparison tests to compare the differences between two or more groups. In AFS, a refined analysis was performed to test the within-field spatial variations according to the relative position of crops with the trees (North, Middle, South). Differences in crop growth, yield components, ltd and total grain yield between three zones were analyzed with one-way ANOVAs followed by a Tukey *post hoc* test. Finally, the relationships between total grain yields and aboveground biomass, pod number, and TKW were tested with linear regressions.

3. Results

3.1. Grain yield and yield-related traits in AFS and SCS

On average, faba bean and lentil respectivly had the tallest plants (74.3 cm; 41.6 cm), the highest biomass (3230 $kg.ha^{-1}$; 1900 $kg.ha^{-1}$) and grain yield (1723 $kg.ha^{-1}$; 645 $kg.ha^{-1}$) in SCS than in AFS.while the tallest plant was registret in SCS for chickpea (60.3 cm) and the highest grain yield in SCS (783 $kg.ha^{-1}$) whereas the highest biomass was recorded in AFS (3200 $kg.ha^{-1}$). Overall, plant height, aboveground biomass, and grain yield were significantly lower in year 1 than in year 2 (P < 0.001) and were also lower in AFS than in SCS (P < 0.001, Table 2). The difference in grain yield between AFS and SCS was more significant for lentil (e.g., – 56 % yield), than for chickpea (- 41 % yield) and faba bean (- 40 % yield). The difference in yield between years and systems was the most significant for faba bean for which the yield was more than 6 times higher in SCS and AFS in year 2 than year 1 (Table 2). In comparison, lentil yield was 4 times higher in SCS and 7 times higher in AFS in year 2 than year 1, and chickpea yield was 3.7

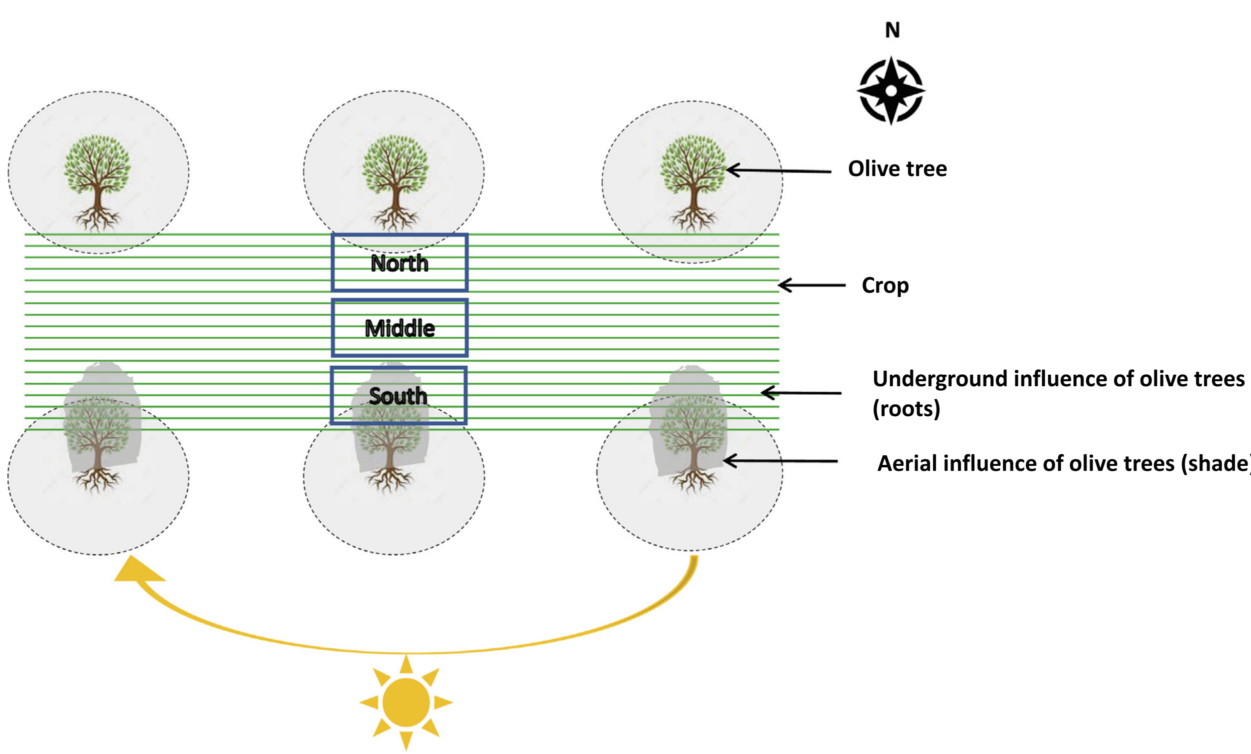

Fig. 3. Sun path in agroforestry and the effect of trees on crops. The strips in blue represent the three different levels of crop exposure to olive tree influence. 'North' represents the lines under strong belowground influence of trees, 'Middle' represents the lines with the lowest influence of trees, 'South' represents the lines under the strongest influence of trees, above- and belowground. (print in color).

Table 2
Plant height (cm), aboveground biomass ($kg.ha^{-1}$), grain yield ($kg.ha^{-1}$) and harvest index (HI) of faba bean, chickpea, and lentil grown either in sole crop system (SCS) or agroforestry system (AFS) in 2015–2016 (year 1) and 2016–2017 (year 2). The highest values in each line are shown in **bold**. Results of ANOVA (F values) are indicated their significance level †, and the letters show the significant differences between systems (SCS *vs* AFS) for each species and year.

Year	Species	Plant height (cm)		Aboveground biomass ($kg.ha^{-1}$)		Grain yield ($kg.ha^{-1}$)		Harvest index	
		SCS	AFS	SCS	AFS	SCS	AFS	SCS	AFS
2016	Chickpea	**60.3 a**	29.6b	**1710 a**	790b	**213 a**	112b	12.4 a	**14.1b**
	Faba bean	**60.3 a**	51.9b	**3220 a**	720b	**243 a**	138b	7.5 a	**19.1b**
	Lentil	**32.0 a**	27.4b	**1380 a**	600b	**118 a**	41b	**8.5 a**	6.8b
2017	Chickpea	**46.3 a**	41.0b	2100 a	**3200b**	**783 a**	516b	**37.2 a**	16.1b
	Faba bean	**74.3 a**	69.7b	**3230 a**	2434b	**1723 a**	1060b	**53.3 a**	43.5b
	Lentil	**41.6 a**	36.1b	**1900 a**	874b	**645 a**	347b	34.0 a	**40.0b**
Statistical significance †	Species*System	64.1***		124.9 ***		629.6 ***		7.05 **	
	Species*Year	102.8 ***		4.5 *		529.9 ***		9.05 **	
	System *Year	91.1 ***		12.9 **		974.1 ***		2.18 ^{ns}	
	Species*Year *System	63.3 ***		9.1**		534.6 ***		10.31***	

†Statistical significance: ^{ns} non-significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

times higher in SCS and 3.6 times higher in AFS in year 2 than year 1. Aboveground biomass and HI also significantly differed between the two years and systems following the same trend for the three species (Table 2).

The number of pods and grains was the most affected yield-related traits across the three legume species. It was in general lower in year 1 than in year 2 and also lower in AFS than in SCS, except for lentil where the number of pods and grains was lower in SCS than AFS in year 2 (Table 3). The difference between AFS and SCS was more significant for chickpea (- 68 % pods), than for lentil (-16 % pods) and faba bean (12 % pods). However, the difference between years was more significant for chickpea (- 71 % in SCS *vs* − 45 % in AFS), than lentil (-13 % in SCS *vs* −55 % in AFS) and for faba bean (-17 % in SCS *vs* – 11 % in AFS). The number of grain, of branches and TKW followed the same trend with less significant differences (Table 3).

$RY_{Biomass}$ ranged from 0.22 to 1.52, and RY_{Yield} ranged from 0.35 to 0.66 across species and years (Table 4). In general, $RY_{Biomass}$ and RY_{Yield} were significantly lower in year 1 than in year 2 ($P < 0.001$). Chickpea had the highest $RY_{Biomass}$ (1.52) and RY_{Yield} (0.66).

3.2. Leaf and air temperatures in AFS and SCS

Leaf temperature depression was lower in AFS than in SCS in year 1, while it was higher in AFS in year 2. and ranged from 0.4 to 5.8 °C for chickpea, 0.9 °C to 4.5 °C for faba bean, and 1.1 °C to 5.5 °C for lentil in AFS at different growth stages (Tbale A.1). In year 2, leaf temperature was higher under AFS conditions for faba bean and lentil during flowering ($P < 0.001$) (Fig. 4). However, leaf temperature was significantly lower than the air temperature in SCS and AFS ($P < 0.001$).

During year 1 in AFS, leaf temperature was higher in the north side and decreased to reach the lower value in the south of the three species (Fig. 5). In year 2 at maturity leaf temperature was higher in the middle for chickpea and lentil and decrease from both sides to reach the minimum in the south. While faba bean leaf temperature was always higher on the north side and low in the south side for both years (Fig. 5).

3.3. Variability of yield and yield-related traits within agroforestry systems

Plant height ($P < 0.001$), pod number ($P < 0.001$), grain number ($P < 0.001$), yield ($P = 2.04$) and HI ($P = 1.54$) varied significantly between the lines and the three exposition zones in AFS in both years (Fig. 6). The lowest plant height, pod number, grain number, yield and HI were recorded in the 'North' crop lines across three species except for chickpea in year 1. However, no significant difference was recorded for aboveground biomass ($P = 1.21$).

For chickpea, yield and yield components and HI were the highest in the 'North' in year 1 and in the 'South' in year 2 (Fig. 6). The coefficient of variation between 'North', 'Middle' and 'South' was 28 % for pod number, 28 % for grain number, 27 % for yield and 34 % for HI. For faba bean, yield components and HI were the highest in the 'South' in year 1 but in the 'Middle' in year 2 ($P < 0.001$). However, the yield was the highest in the 'Middle' for both years ($P = 2.04$). The coefficient of variation between 'North', 'Middle' and 'South' was 27 % for pods number, 13 % for grain number, 22 % for yield and 35 % for HI. For lentil, yield components and

Table 3
Number of branches (m^{-2}), number of pods (m^{-2}), number of grains (m^{-2}), and thousand kernel weight (TKW, g) of chickpea, faba bean, and lentil grown either in sole crop system (SCS) and agroforestry system (AFS) in 2015–2016 (year 1) and 2016–2017 (year 2). The highest values in each line are shown in **bold**. Results of ANOVA (F values) are indicated with their significance level †, and the letters show the significant differences between systems (SCS *vs* AFS) for each species and year.

Year	Species	Branches number (m^{-2})		Pod number (m^{-2})		Grain number (m^{-2})		TKW (g)	
		SCS	AFS	SCS	AFS	SCS	AFS	SCS	AFS
2016	Chickpea	**37 a**	32 a	**128 a**	53b	**68 a**	55b	**264 a**	235b
	Faba bean	**41 a**	35 a	**35 a**	32b	**125 a**	56b	**779 a**	730b
	Lentil	102 a	**122 a**	**54 a**	32b	**58 a**	24b	**39 a**	30b
2017	Chickpea	**35b**	26b	**438 a**	96b	**214 a**	108b	292 a	**351b**
	Faba bean	**51b**	34b	**42 a**	36b	**189 a**	89b	**1208 a**	810b
	Lentil	**174b**	152b	62 a	**72b**	83 a	**88b**	**48 a**	39b
Statistical significance†	Species*System	0.59 ^{ns}		82.87***		26.31***		26.61***	
	Species*Year	16.54***		51.49***		8.31**		36.97***	
	System *Year	4.99*		33.54***		17.25***		21.25***	
	Species*Year *System	1.91 ^{ns}		32.74***		2.98 ^{ns}		18.96***	

†Statistical significance: ^{ns} non-significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Table 4
Relative yield index for biomass ($RY_{Biomass}$) and grain yield (RY_{Yield}) for chickpea, faba bean and lentil grown either in sole crop system (SCS) and agroforestry system (AFS) in 2016 (year 1) and 2017 (year 2). The highest values in each column are shown in **bold** and the lowest values in *italics*. Results of ANOVA (F values) are indicated with their significance level †, and the letters show the significant differences between systems (SCS *vs* AFS) for each species and year.

Year	Species	Branches number (m^{-2})		Pod number (m^{-2})		Grain number (m^{-2})		TKW (g)	
		SCS	AFS	SCS	AFS	SCS	AFS	SCS	AFS
2016	Chickpea	**37 a**	32 a	**128 a**	53 b	**68 a**	55 b	**264 a**	235 b
	Faba bean	**41 a**	35 a	**35 a**	32 b	**125 a**	56 b	**779 a**	730 b
	Lentil	102 a	**122 a**	**54 a**	32 b	**58 a**	24 b	**39 a**	30 b
2017	Chickpea	**35 b**	26 b	**438 a**	96 b	**214 a**	108 b	292 a	**351 b**
	Faba bean	**51 b**	34 b	**42 a**	36 b	**189 a**	89 b	**1208 a**	810 b
	Lentil	**174 b**	152 b	62 a	**72 b**	83 a	**88 b**	**48 a**	39 b
Statistical significance †	Species*System	0.59 ^{ns}		82.87***		26.31***		26.61***	
	Species*Year	16.54***		51.49***		8.31**		36.97***	
	System *Year	4.99*		33.54***		17.25***		21.25***	
	Species*Year *System	1.91 ^{ns}		32.74***		2.98 ^{ns}		18.96***	

†Statistical significance: ^{ns} non-significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

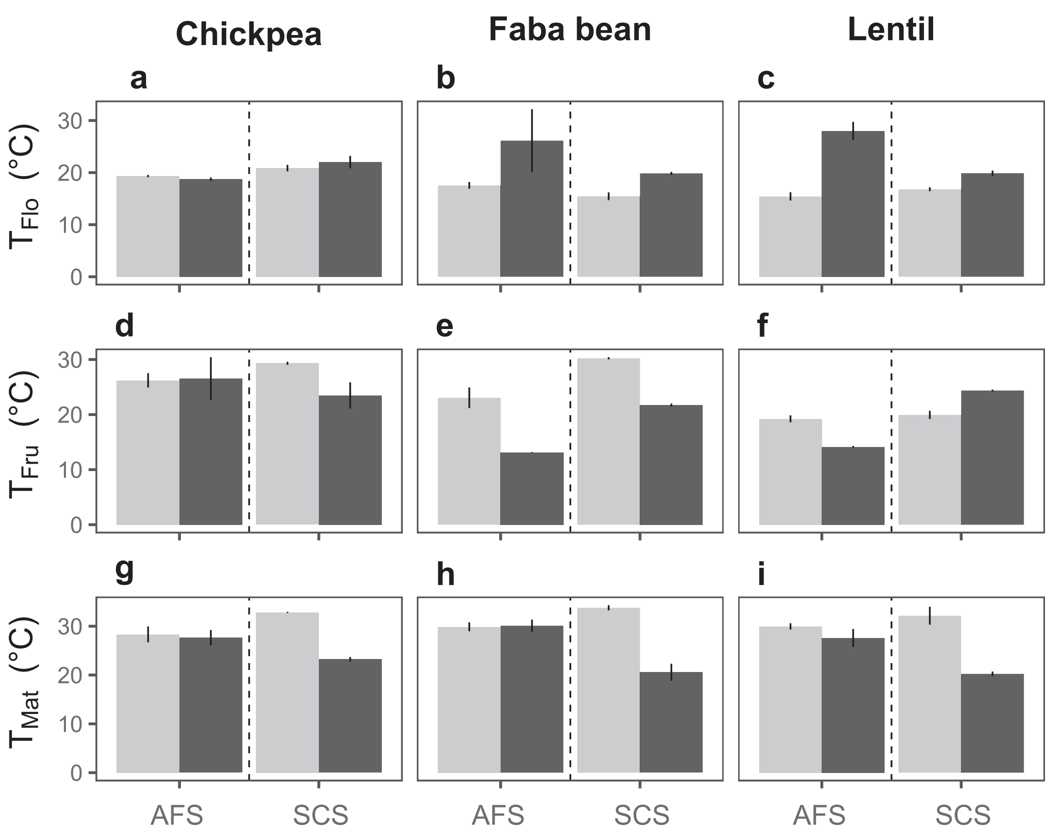

Fig. 4. Leaf temperature comparison of chickpea, faba bean, and lentil grown either in sole crop system (SCS) and agroforestry system (AFS) in 2016 (gray) and 2017 (black) during flowering, pod setting and maturity. Significance level (differences between AFS and SCS) **$P < 0.01$; ***$P < 0.001$; $P = 0.07$.

HI were the highest in the 'South' in both years ($P < 0.001$) and increased consistently from 'North' to 'South' (Fig. 6). The lowest results were recorded in year 1. The coefficient of variation between 'North', 'Middle' and 'South' was 31 % for pods number, 33 % for grain number and 37 % for HI. Meanwhile lentil yield was highest in the 'South' in year 1 and in the 'Middle' in year 2 ($P = 2.04$) with an increased spatial variation of 35 % to 41 %.

3.4. Relationship between yield and yield components

Aboveground biomass, the number of pods, and TKW were significantly correlated with grain yield for chickpea (Fig. 7a,d,g) and faba bean (Fig. 7b,e,h) in almost each of the three exposition zone and not significantly correlated with the number of pods of faba bean in the 'South'. For lentil, aboveground biomass (Fig. 7c) and TKW (Fig. 7i) showed a significant correlation with grain yield, in all zones, except TKW in the 'South'. In contrast, the relationship between yield and the pod number was not significant for lentil (Fig. 7f).

4. Discussion

4.1. The yield of legumes in AFS was only half as much as in SCS

In contrast to our hypothesis, olive trees negatively affected the total biomass and yield of the three legumes, which decreased by 50 % on average in AFS compared to SCS. Amassaghrou et al.

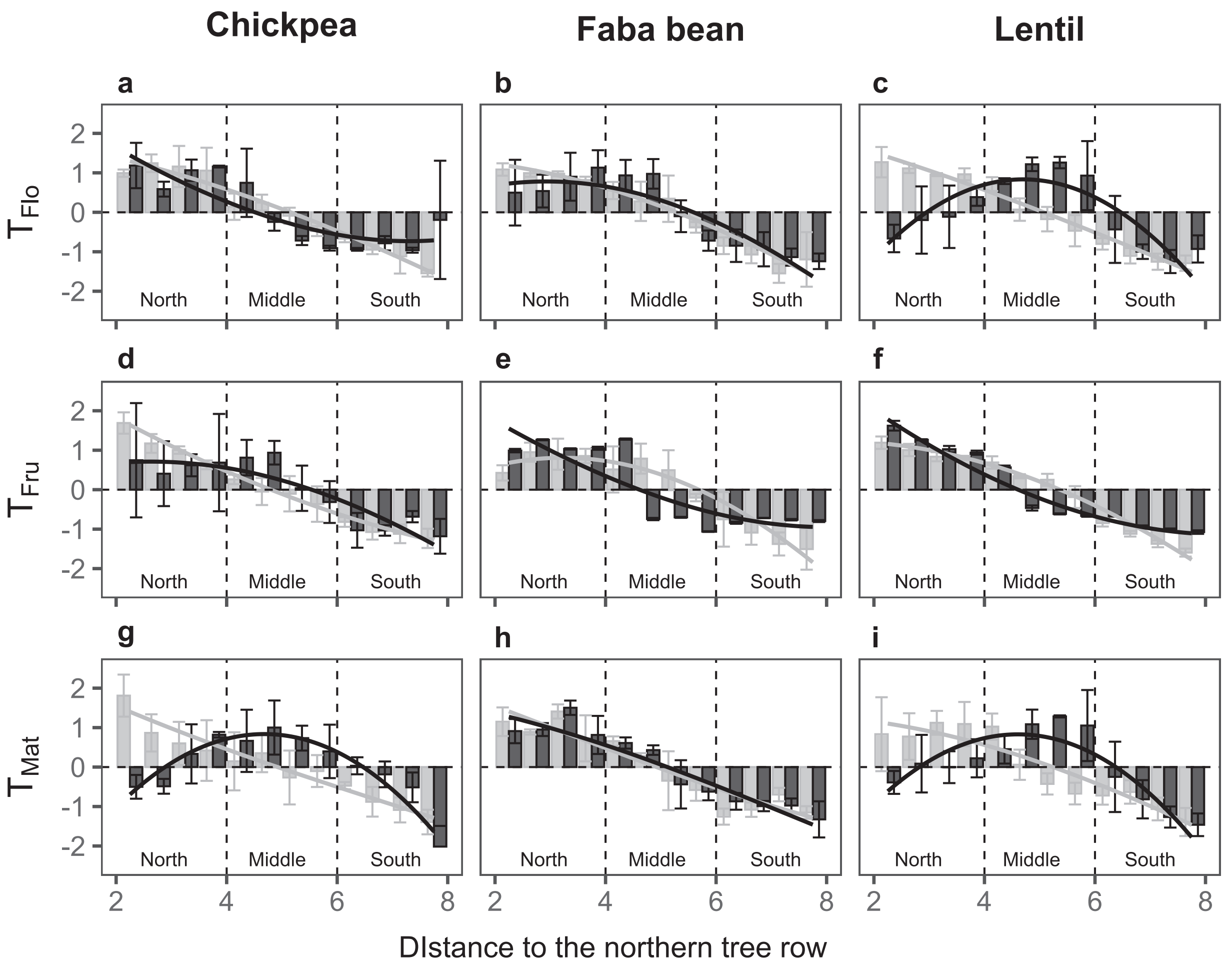

Fig. 5. Deviations of leaf temperature from the mean field values of each sowing row (n = 12 rows) in each of the three sun exposition zones (North, Middle, South) within the agroforestry systems at flowering, fructification and maturity for chickpea, faba bean, and slow in 2016 (gray) and 2017 (black). Spline regression lines show the trends of spatial variability moving from one tree (North) to the other (South).

(2021) found similar results where olive tree reduced grain yields by around 20 % and 56 % for faba bean and chickpea respectively.

Comparable yield reductions have been recorded for wheat, barley under trees, e.g., under paulownia trees (Li et al., 2008), olive trees in rainfed condition (Amassaghrou et al., 2023, 2021; Razouk et al., 2016; Daoui et al., 2014), and under olive tree with irrigation (Temani et al., 2021) wheat yield was reduced by around 50 %, suggesting that permanent shade provided by trees significantly reduce crops yield when compared to unshaded cropping. Compared to cereals, legumes are more productive under olive trees in rainfed or irrigated conditions (Amassaghrou et al., 2021; Temani et al., 2021) and may be more suitable for trees intercropping because they are less competitive for soil resources (at least for nitrogen) and reach maturity earlier, leaving more resources available to olive trees, and finally induce a significant increase in olive and oil yield (Amassaghrou et al., 2023; Chehab et al., 2019). In contrast, cereals usually grow until summer and reduce olive growth (Amassaghrou et al., 2023, 2021; Razouk et al., 2016). Moreover, the capacity of food legumes to fix the atmospheric nitrogen can enhance available soil nitrogen (Duchene et al., 2017; Correia et al., 2015) for olive trees, improve soil fertility, and hence have positive effects on olive production (Amassaghrou et al., 2021).

The relative yield of the three legumes ranged from 0.35 to 0.66 for grain yield and from 0.22 to 1.52 for aboveground biomass. Compared to cereals, which are more frequently associated with olive trees, legumes performed better, opening possibilities for improving the productivity of the actual olive AFS with more legumes. In a similar experiment under Mediterranean conditions, Temani et al. (2021) found that the relative yield was superior for faba bean (0.54) than for wheat (0.19) during a dry year (345 mm) whereas they found a similar relative for both crops (0.28 and 0.32, respectively) during a rainy year (429 mm). These results suggest that faba bean was more productive than wheat in agroforestry under dry conditions. Other studies also confirmed that the relative yield in AFS was higher for legumes than cereals (Amassaghrou et al., 2021; Daoui and Fatemi, 2014; Gea-Izquierdo et al., 2009).

4.2. Olive trees limit crop growth and reduce the number of grains

Agroforestry impacted the vegetative and yield-related traits of all three legumes differently depending on the trait and the species considered. In a previous experiment, agroforestry with olive trees strongly reduced the growth of faba bean (Temani et al., 2021). However, we found the opposite here, especially for faba bean and lentil. In fact, crops grew taller in AFS than in SCS, probably due to stimulated production of gibberellins under shade, triggering an elongation in height (Kurepin et al., 2006).

Olive trees also negatively affected crop ramification, reducing the total number of brunches than pods (Rivest et al., 2009). This reduction is fairly common in agroforestry and mainly because of the shade provided by trees at early crop stages during winter

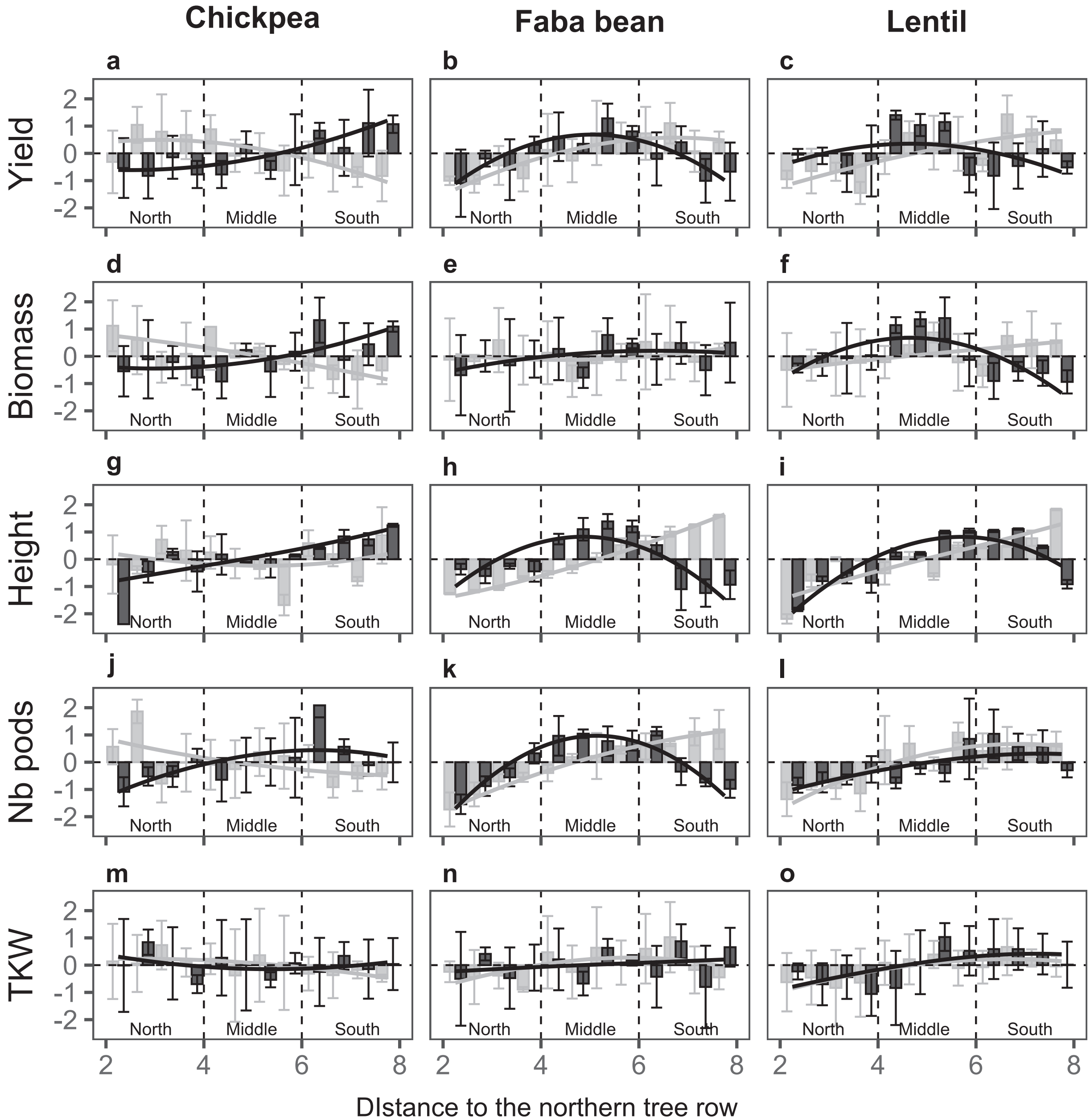

Fig. 6. Deviations of plant height, aboveground biomass, grain yield, harvest index, pod number and grain number, from the mean field values of each sowing row (n = 12 rows) in each of the three sun exposition zones (North, Middle, South) within the agroforestry systems for chickpea (a, d, g, j), faba bean (b, e, h, k), and lentil (c, f, i, l) in 2016 (gray) and 2017 (black). Spline regression lines show the trends of spatial variability moving from one tree (North) to the other (South).

(Inurreta-Aguirre et al., 2018). In legumes the reduction of total grain yields in agroforestry was directly due to the reduced number of grains per unit area. Indeed, the number of grains per plant has been reported to be the component displaying the strongest and most consistent correlation with yield and the most important determinant of yield (Lake et al., 2019; Lake and Sadras, 2014). Since the number of grains per unit area is closely related to the number of pods, the way trees affected crop ramification and pod formation, under shade, was critical for crop yield under trees (Sharif et al., 2010). The highest yield recorded in faba bean compared to other legumes was mainly attributed to the enhancing grain filling period, which led to the production of larger grains. However, the three legume species responded differently to the influence of olive trees. In some cases, trait plasticity (Arenas-Corraliza et al., 2018) enables plants to adapt efficiently to shade and maintain light absorption and biomass productivity at levels similar to monocrops, especially during critical periods. Chickpea and faba bean grown in AFS during the critical period of grain set was probably due to a low tolerance under shade and belowground competition, which directly affected the number of grains produced (Choukri et al., 2020).

4.3. Agroforestry generates a significant spatial variability in yield and yield-related traits of legumes

The environmental heterogeneity created by the aboveground effects of olive trees delayed the dates of flowering and pod formation of intercropping legumes in agroforestry, mainly due to shade

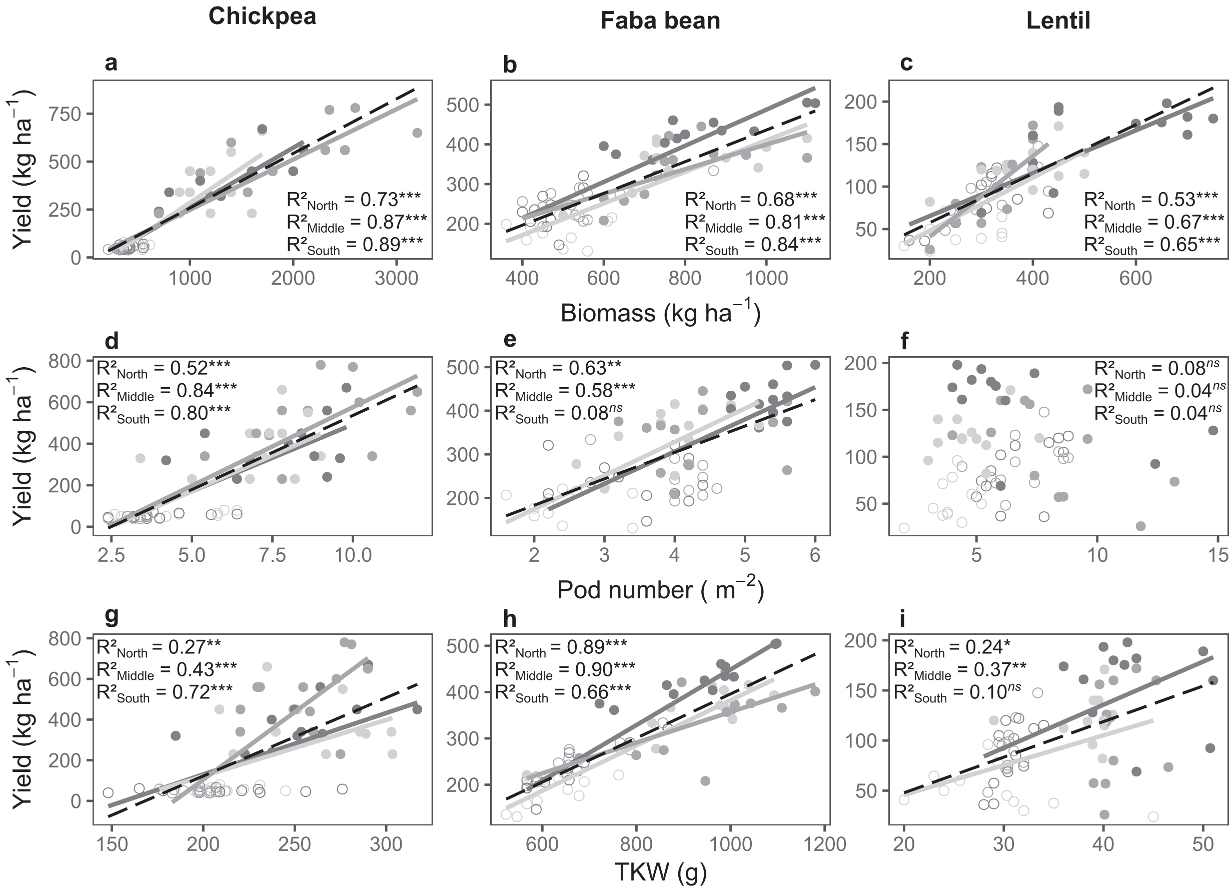

Fig. 7. Relationships between grain yield (kg.ha^{-1}) and (a, b, c) biomass (kg.ha^{-1}) (d, e, f) the number of pods (m^{-2}) and (g, h, i) thousand kernel weight (TKW) for chickpea, faba bean and lentil in the agroforestry system. Data points represent mean values from each sun exposition zones (North: dark gray, Middle: gray, South: light gray) in 2016 (open symbol) and 2017 (filled symbol). The gray solid lines represent the regression lines for each exposition zone over the two years of study, while the black dashed line is the overall regression.

but, the stress occurred in the end of cycle with high temperature didn't affect the date of maturity. Yield-related traits, like the pod number, grain number and final yield responded differently to the environmental heterogeneity in AFS among species and year. For chickpea, the number of pods, the number of grains, and the final yield of chickpea were the highest values in the North of the trees where sun exposure was the highest. Confirming that is, chickpea is less productive under shade, due to reduced numbers of grains per pod and probably an increased abortion of reproductive structures (Verghis et al. 1999). However, this opposite finding was observed during late drought conditions (year 2); chickpea was more productive in the South of trees with intense shade, suggesting that chickpea was more sensitive to water stress and high temperatures during the pod formation phase. Furthermore, tree shade provided a favorable environment for chickpea production during drought (Choukri et al., 2020; Idrissi et al., 2012; Khan et al., 2010; Wang et al., 2006). For faba bean, the maximum yield was obtained in the middle of inter-rows where overall competition for light, water, and nutrients with trees was the lowest. During the two years, the number of lentil pods and grains was higher in AFS than in SCS, and highest in the south under tree shade, suggesting that trees may offer a beneficial climate for lentil, especially at the flowering and grain-filling period (Joshi et al., 2017).

This environment variability created in AFS could be a disadvantage for intervention dates (e.g., control of parasitic weed broomrape, *Orobanche spp.*). However, it is advantageous since it is more resilient to cope with climatic risks (e.g., heat, water stress), and therefore guarantees production in AFS during difficult years.

4.4. Despite similar drought severity, drought timing affected crop growth

Altered drought timing in the two years affected differentially crop growth, despite the similar intensity of water deficit over the entire growing season. In fact, in year 1 (2015–2016), the growing season was marked by an exceptional early drought with no rainfall for 35 days after sowing. Consequently, crop emergence and flowering were delayed by almost 40 days compared to year 2 (2016–2017). Then, at the end of the growing season of year 1 there was more precipitation than usual. In contrast, the growing season of year 2 started with more rainfall than usual but then was marked by an intense terminal drought with infrequent and low precipitation, although more intense than usual, during pod formation and grain filling, which is a 'normal' timing under the Mediterranean climate. Comparing both drought dynamics (early *vs* late) allowed us to understand whether agroforestry could help face increasing aridity and buffer the higher inter-annual rainfall variability. Winter droughts are particularly of concern because they threaten the initial growth potential of crops and usually lead to a strong decrease in the final yield under this conditions farmers fear the consequences of more intense negative tree-crop interactions under drought, but at the same time they look to raise their households' income, increasing or diversifying crops and trees production on their farms (Amassaghrou et al., 2021; Ameur et al., 2020; Kmoch et al., 2018), and agroforestry is an interesting option for small family farms to maintain high productivities(Leauthaud et al., 2022; Panozzo et al., 2020; Bai et al., 2016; Paolotti et al., 2016).

5. Conclusion

Recent years have seen renewed interest in olive-based agroforestry in the South Mediterranean. Increasing aridity and higher rainfall inter-annual variability motivate us to reconsider the benefits of traditional forms of agriculture and the associations of trees and arable crops to mitigate the adverse effects of climate on agricultural yields. Our study compared the yield and yield-related traits of three major legume species between agroforestry and conventional sole-crop systems to understand how legumes respond to interactions with trees during drought. Chickpea, faba bean, and lentil all had about 50 % lower biomass and yield in agroforestry than in sole crop systems. However, there was a significant variability due to drought timing. The negative effects of trees were considerably higher during an early drought (2015–2016) than a late drought (2016–2017) because it strongly affected crop growth and ramification, leading to a lower number of pods and grains, which were key to grain yield for all the species. There was also a significant difference between the species according to their abiotic stress tolerance.

In agroforestry, chickpea and faba bean, had the highest relative yields. Thus, the study suggests that chickpea should be considered during high-stress conditions, while faba bean should be preferred during low-stress conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Appendix A

(See Tables A.1 and A.2)

Table A.1
Air temperature, leaf temperature, and leaf temperature depression of chickpea, faba bean, and lentil in O-AFS and SCS at different stages of crop growth. The highest values of leaf temperature in each line are shown in **bold**. Results of ANOVA (F values) are indicated their significance level †, and the letters show the significant differences between systems (SCS *vs* O-AFS) for each species and year.

year	stage	species	Temperature air T° c	Leaf T° c		ltd	
			Mean	SCS	O-AFS	SCS	O-AFS
2016	Flowering	Chickpea	12.2	**11.8a**	11.2b	−0.4	−1.0
		Faba bean	12.7	**12.2a**	10.1b	−0.5	−2.6
		Lentil	12.2	**11.8a**	10.4b	−0.4	−1.8
	Pod setting	Chickpea	20.7	**20.1a**	18.7b	−0.6	−2.0
		Faba bean	15.2	**15.1a**	14.3b	−0.1	−0.9
		Lentil	17.5	**15.5a**	13.2b	−2.0	−4.3
	maturity	Chickpea	26.3	**25.2a**	22.3b	−1.1	−4.0
		Faba bean	20.0	**18.8a**	16.4b	−0.1	−3.6
		Lentil	26.3	24.9a	20.8b	−1.4	−5.5
2017	Flowering	Chickpea	15.5	**14.6a**	12.9b	−0.9	−2.6
		Faba bean	14.4	11.0a	**12.0b**	−3.6	−2.4
		Lentil	15.2	12.8a	**14.6b**	−2.4	−0.6
	Pod setting	Chickpea	20.4	**16.2a**	14.6b	−4.2	−5.8
		Faba bean	9.6	**9.1a**	8.9b	−0.5	−0.7
		Lentil	9.6	**9.1a**	8.5b	−0.5	−1.1
	maturity	Chickpea	26.3	23.5a	**25.6b**	−2.8	−0.7
		Faba bean	27.9	22.1a	**23.4b**	−5.8	−4.5
		Lentil	20.4	18.3 a	**19.4b**	−2.1	−1.0
Statistical significance †	Flowering	Species*System	10.66***				
		Species*System*Year	6.54**				
	Pod setting	Species*System	21.65***				
		Species*System*Year	20.44***				
	maturity	Species*System	4.9*				
		Species*System*Year	2.92 *ns*				

† Statistical significance: *ns* non-significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$***.

Table A.2
Spatial variability of plant height (cm), the number of pods (m^{-2}), the number of grain (m^{-2}), grain yield ($kg.ha^{-1}$), aboveground biomass ($kg.ha^{-1}$) and the harvest index (%) of chickpea, faba bean, and lentil between the three sun exposition zones (North, Middle, South) within the agroforestry system, in 2016 (year 1) and 2017 (year 2). The highest values for each variable, species and year are shown in **bold** and the lowest values in *italics*. Results of ANOVA (F values) are indicated with their significance level †, and the letters show the significant differences between systems (SCS *vs* O-AFS) for each species and year.

Year	Species	Plant Height			CV	pods			CV	grain			CV	Grain yield			CV	Aboveground biomass			CV	HI			CV
		(cm)			%	number.m-2			%	number.m-2			%	($kg.ha^{-1}$)			%	($kg.ha^{-1}$)			%	%			%
		North	Middle	South		North	Middle	South		North	Middle	South		North	Middle	South		North	Middle	South		North	Middle	South	
2016	Chickpea	25.7a	*24.3b*	**26.6c**	8.9	**58**	52	*44*	28	**65**	*59*	60	28	**126a**	122b	*118c*	27	**1141a**	1117a	*845a*	22	11.0a	*10.9b*	**14.0c**	34
	Faba bean	*8.8a*	52.9b	**60.8c**	3.9	*33*	46	**54**	27	*80*	93	**99**	13	*497a*	**675b**	640c	22	**1540b**	1460b	*1300b*	20	*32.3a*	46.2b	**49.2c**	35
	Lentil	*23.1a*	25.3b	**29.0c**	8.3	*53*	90	**91**	31	*54*	92	**110**	33	*17a*	28b	**34c**	35	*709c*	829c	**855c**	24	*2.4a*	3.4b	**4.0c**	37
2017	Chickpea	*41.5a*	43.2b	**45.0c**	3.5	*94*	104	**120**	24	*114*	137	**167**	28	*298a*	351b	**402c**	28	*3245a*	3622a	**5182a**	41	9.2a	**9.7b**	*7.8c*	46
	Faba bean	62.8a	**71.2b**	*61.0c*	10.5	53	**71**	*38*	19	123	**192**	*95*	15	933a	**1148b**	*912c*	20	**2803b**	2733b	*2050b*	38	*33.3a*	**44.5b**	42.0c	36
	Lentil	*32.8a*	**38.5b**	37.8c	3.5	*64*	90	**91**	44	*88*	130	**143**	36	*34a*	56b	**59c**	41	1029c	**1449c**	*880c*	33	*3.3a*	4.1b	**6.4c**	58
† Statistical significance	Species*zone	5.22***				2.76***				2.45***				2.04**				1.21 ^{ns}				1.54*			

† Statistical significance: ^{ns} non-significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

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