

Article

Impact of Olive Trees on the Microclimatic and Edaphic Environment of the Understorey Durum Wheat in an Alley Orchard of the Mediterranean Area

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Abstract: In the current context of climate change, the impact of trees in agroforestry systems is expected to mitigate water and heat stresses, particularly in semi-arid environments. Within this framework, in a two-year trial conducted at INRAE in Southern France, the dynamics of microclimatic parameters and the edaphic environment of durum wheat were investigated under a yearly-pruned (AF) and a never-pruned (AF+) 6-m apart alley olive orchard, in comparison with controls under full sun. Here it was recorded a reduction of photosynthetic active radiation (PAR) by 30% and 51% in AF and AF+, respectively, during the wheat cycle, together with a marked reduction of wind speed compared to controls (−85% in AF and −99% in AF+). A significant buffer effect was also highlighted for air temperature, averagely +1.7 °C during the night and −3.2 °C during the daytime under the moderate shading of AF. The positive effect of trees on soil water conservation increased with the intensity of shading, particularly during the critical wheat stage of grain filling, with benefits on wheat root mycorrhization, and NH₄⁺ and NO₃[−] abundance in the arable layer. Despite some of the environmental modifications being favorable for the understorey wheat, these were not translated into yield improvements, suggesting that the severe shading associated with the small inter-row and evergreen trees has a prevailing effect, that requires to be managed through appropriate tree pruning.

Keywords: intercropping; agroforestry; PAR; air temperature; water conservation; arbuscular mycorrhizal fungi

1. Introduction

Olive trees, grown in rows or as scattered trees, have been intercropped with cereals such as wheat for centuries in the Mediterranean area [1]. As a consequence of agricultural intensification, these traditional agroforestry systems have no longer been implemented in the last decades in a large part of this area. However, a renewed interest in olive alley-cropping is currently emerging with the aim to improve the sustainability of both olive orchards and wheat cultivation. Indeed, among 9.5 million hectares of olive groves distributed across the Mediterranean area, a large part concerns ancient orchards with low productivity and a high risk of abandonment [2]. Besides, there is an increasing need to improve the resilience of wheat to climate change, while providing ecosystem services in agreement with the requirements of the European Agricultural Policy. This is particularly relevant in the Mediterranean area, which has been identified as one of the most prominent

“Hot-Spots” in future climate change projections [3,4], consisting of a marked decrease in precipitations, particularly during summer [5,6], associated with greater occurrence of spring/summer heat and drought stresses. The inter-annual weather variability is also expected to increase [7–9], while warming will enhance evapotranspiration and the potential incidence and severity of drought [10]. The negative impact of climate change on crop production has already been documented [11–13]. The increase of evapotranspiration and crop water requirements modify plant phenology [14,15], resulting in reduced yield and quality. Indeed, under heat/drought stress the growing cycle of wheat is shortened, and the onset of the senescence process is anticipated, in this way compromising the grain filling process and yield [16–18].

Agroforestry systems have a high potential to provide ecosystem services related to microclimate buffering by reducing water evapotranspiration and preserving soil moisture through shading, windbreak, controlling soil erosion, and increasing soil fertility [19–23]. Up to date, the multiple ecosystem services provided by agroforestry have been associated with improvements in crop growth and yield mainly in tropical and subtropical regions [20,24–27]. Agroforestry farming is reported as an opportunity, notably in South America [28–30] and Africa [31–34], for its high potential to address various on-farm adaptation needs [35–37]. Alley-cropping systems involving legume trees in the tropics are reported to enhance crop resilience to climate change [32,36,38]. For instance, the widespread systems including white leadtree (*Leucaena leucocephala* (Lam.) de Wit) and apple-ring acacia (*Faidherbia albida* (Delile) A. Chev.) trees intercropped with sorghum, cowpea or coffee, demonstrated to enhance soil carbon sequestration and crop productivity, thanks to the increase of soil mineral nutrients and the buffer effect on temperature [32,39–42]. A large number of experimental studies also documented the positive effects of shading by trees on cocoa cultivation, through the enhancement of soil fertility and water conservation [37,43–46].

In temperate regions, despite some experimental evidence summarized by Fagerholm et al. [47] and Torralba et al. [19], there is a need to better quantify the role of agroforestry practices in ecosystem services delivery. This is particularly relevant in the Mediterranean area, where the risk of yield losses associated with climate issues is increasing and therefore the impact of trees on the microclimatic and edaphic environment might be beneficial for understorey crops.

In this study, durum wheat was intercropped for two years in the alleys of an olive orchard subjected to different levels of pruning in southern France, in a site where the productivity of this olive orchard and the yield and quality of wheat have already been investigated [48,49].

In this paper, the microclimatic parameters and the edaphic environment available for durum wheat were compared among three experimental conditions (treatments): (i) in wheat monoculture without trees; (ii) in alley-cropping with olive trees under severe shading within a never-pruned olive orchard, mimicking abandoned orchards; (iii) and in alley-cropping within a yearly pruned olive orchard. The purpose was to evaluate the potential role of olive trees to provide environmental ecosystem services and ensure higher resilience to climate change compared to wheat monoculture, by assessing (i) the impact of trees on microclimatic parameters and edaphic environment and (ii) the effect of the different experimental conditions on durum wheat growth and yield.

2. Materials and Methods

2.1. Study Site

The experiments were carried out at the French National Research Institute for Agriculture, Food and the Environment (INRAE) experimental DiaScope unit at Mauguio–Montpellier in the south of France (43°35′ N, 3°45′ E; 12 m a.s.l.; flatland) for two years from 2015 to 2017. Based on historical data (30 years), the site has a sub-humid Mediterranean climate, with a yearly average temperature of ~15 °C, and a maximum daily temperature that increased from 34 °C at the end of the last century up to 38 °C in 2017. The sunshine

duration at the site is one of the highest in France, i.e., 7 h 22 min per day as annual average vs. the French average of 4 h 46 min. The historical average annual precipitation is about 750 mm with high heterogeneity in the rainfall pattern across years. The number of rainy days is relatively low, i.e., <60 per year (Table S1).

2.2. Experimental Design

Durum wheat (*Triticum durum* Desf.) was sown in mid-November of each year in three experimental conditions (treatments; Figure S1): two olive orchards, one never pruned (named “AF+”) and one yearly pruned (named “AF”), in comparison with open-field controls (without trees, named “C”) under organic management. Twenty-five durum wheat genotypes were cultivated in the olive alleys, following local sowing and harvest recommended dates (Table S1). The trial was arranged as a randomized block design with three replicates per treatment by cultivating wheat in annual rotation with legume crops, i.e., chickpea and fababean according to the year. Here only the data concerning the plots of one wheat genotype, hosting the sensors and tools for measuring microclimatic and edaphic parameters, are presented.

In the AF treatment (Figure S1d), the olive trees were yearly pruned from 2012. The orchard was planted in 2002 and consisted of 8 rows (6 × 6 m apart) in a 0.5-ha area, with two plots lines of wheat hosted in the inter-row (Figure S1d). Olive trees belong to the *Picholine* clone, with tree rows oriented along the main axis NW-SE.

The AF+ treatment was implemented in an olive grove that was planted in 2002 as well, with the same planting design and row orientation as in AF, located close to AF treatment (20 m to the west; Figure S1c). In this orchard, the olive trees were clones of the *Arbequine* × *Oliviere* crossing and had never been pruned. As a consequence, the canopy size was larger than in AF, and only one plots line was sown in each olive inter-row.

In each year, the control treatment without trees was set up close to AF and AF+ under full sun conditions.

2.3. Microclimate Parameters

A Météo-France weather station located at the INRAE station, 100 m from the experimental fields, provided daily air temperature, air humidity, rainfall, global radiation and PAR (photosynthetic active radiation) and wind speed, from the beginning of the trial (2015). Additional sensors (Table S2) were placed in the experimental area (in the center of the alley) hosting the three treatments (control, AF, and AF+). To avoid any possible interaction of wheat genotype, all the sensors were placed in the plots of the same genotype (i.e., cv 1). Except for wind speed, air temperature and relative humidity, which were recorded in 2016–17 only, all the other microclimate parameters were recorded both in 2015–16 and 2016–17 growing seasons. During April 2017 (2nd year), PAR availability in AF treatment was also measured at different distances from the tree line, i.e., at +1 m and +3 m (center of the alley).

2.4. Edaphic Parameters

Sensors for measuring soil moisture were placed in the plots of cv 1, close to the sensors for microclimate parameters, at four different depths, i.e., 30, 60, 90, 110 cm, as described in Table S2.

A number of 13 geo-referenced soil samples were also collected in the three treatments in February 2016 and 2017, at 0–30, 30–60 and 60–90 cm depth. The total amount of nitrogen (N), nitrate (NO₃[−]) and ammonium (NH₄⁺) were determined following the Dumas dry-combustion method.

The mycorrhizal analysis was carried out in 2016–17 on the roots of 6 durum wheat varieties, 3 modern and 3 old varieties, chosen to represent the genetic diversity of the 25 investigated wheat genotypes. At BBCH 50 (heading stage), in each treatment (C, AF and AF+) and for the 6 varieties, all the plants over a rectangular sampling area at the center of the plot (2 wheat rows × 40 cm of length) were collected. All the plants on the sampling

area and the soil attached to roots (until 30 cm of depth) were collected in plastic bags and stored at -4°C . Mycorrhizal analyses were carried out at the *Tropical and Mediterranean Symbioses Laboratory* (LSTM- CIRAD Baillarguet, France). Plant roots of each sample were cleaned from soil particles, and 3 replicates of 90 root fragments (1-cm long), collected from the central part of the root length, were analyzed in each variety and treatment. Root fragments were stained, observed under a microscope (Provis, Olympus), and rated according to a range of classes as described by the MO-M-C-04 protocol, according to Delteil et al. [50]. Data were processed through MycoCalc software [51], which provided the following parameters: (i) rate of root length with internal mycorrhizal structures (vesicles or hyphae) (ii) intensity of mycorrhizal colonization in root fragments, and (iii) abundance of arbuscules in the mycorrhizal parts of root fragments.

2.5. Yield Components

Three days before harvest, plants of a sampling area (two wheat rows $\times$ 40 cm of length) were sampled in each plot for counting the number of plants, and tillers and spikes per plant, and that of grains per spike. After oven-drying (80°C for 48 h), the shoot biomass (dry weight) was also determined. Harvest took place from 30 June to 6 July according to the considered year (Table S1), using a mini-combine harvester. The grains of each plot were weighed and subjected to humidity determination. For each replicate/treatment, 3 samples were used for calculating the thousand-grain weight (TGW). Here the data of cv 1 only are presented, where all the sensors were placed.

2.6. Statistical Analysis

Data on microclimatic and edaphic parameters, wheat yield and mycorrhizal colonization, measured in C, AF and AF+ treatments, were subjected to ANOVA using R studio software ver. 2.7 [RStudio Public Benefit Corporation (PBC), Boston, MA, USA]. Separation of means was set at $p \leq 0.05$ with the Tukey's HSD test. Hourly data of air temperature and relative humidity from wheat sowing to harvest, in C and AF treatments, were classified as "day" or "night", according to the sunset and sunrise times of each day, thanks to the R package "RAtmosphere".

3. Results

3.1. Solar Radiation

The photosynthetic active radiation (PAR) reaching the wheat canopy under full sun conditions (control treatment) was $380 \mu\text{mol s}^{-1} \text{m}^{-2}$ as the average of the whole growing cycle. As compared to this value, PAR was reduced by 30% in AF and by 51% in AF+ (two-year average).

Within the moderate shade treatment (AF), the difference in PAR availability vs. the control treatment decreased during the wheat cycle, i.e., from -39% during stem elongation to -23% during grain filling (maturity), as two-year average. At the same time, the reduction of PAR in the severe shading treatment (AF+) in comparison with the open field showed small variations across the wheat cycle, ranging from -47% during heading and anthesis to -55% at maturity in 2017 (Figure 1).

As regards the distance from the tree line, significant differences were observed in PAR levels at the center of the alley (+3 m from olives trunk) and at the wheat plot boundaries (1 m from the tree line) in AF treatment. During heading and anthesis in 2017, PAR was averagely reduced by 33% in the middle of the alley and by 78% at +1 m from the tree line, as compared to full sun conditions.

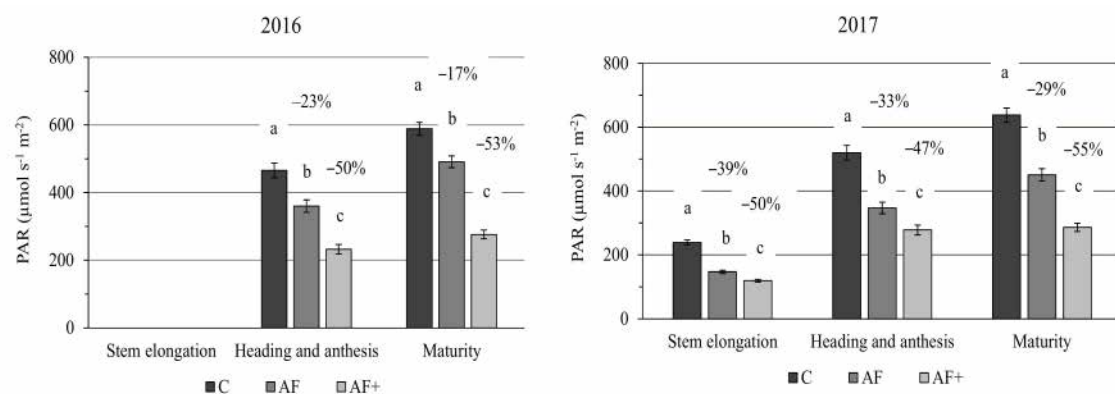


Figure 1. Photosynthetic active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$; mean $\pm$ S.E.) recorded in three treatments (C = Control, AF = yearly pruned olive grove, AF+ = never pruned olive grove) during 2015–16 (left) and 2016–17 (right) wheat-growing seasons at stem elongation (from sowing to 7 April), heading and anthesis (from 8 April to 10 May), and maturity (from 11 May to harvesting). Numbers above histograms indicate the percentage variation as compared to controls within each wheat cycle period. Within the same period and year, different letters indicate significant differences according to the Tukey's HSD test ($p \leq 0.05$).

3.2. Air Temperature and Relative Humidity

No significant differences were observed between the agroforestry treatments (AF and AF+) and controls (C) for maximum and minimum daily air temperature and relative humidity. However, a buffer effect was clearly noticed in the moderate shade treatment (AF) as highlighted by the dynamics of daily temperature and relative humidity in the olive alleys in comparison with the open field (Figure 2). From 6 a.m. to midday (i.e., Time2) (Figure 2-left, Table S3), the air temperature was significantly lower in AF as compared to C, with a mean difference of -1.8°C (maximum of -3.2°C at 9 a.m.). Additionally, the average difference between air temperature in AF vs. C within Time2 increased from the early stages of the wheat cycle to later stages (i.e., -1.8°C , -2.4°C and -2.6°C during stem elongation, heading and anthesis, and maturity, respectively). On the contrary, from 1 p.m. to midnight (Time3), the air temperature was higher in AF as compared to C ($+1.2^\circ\text{C}$ on average, $+1.7^\circ\text{C}$ as maximum at 7 p.m.), with a lower variation between the two treatments as compared to Time2, but significant between 5 p.m. to 7 p.m. As regards the growth periods, within Time3 the difference of air temperature between AF and C was low but significant during stem elongation ($+0.6^\circ\text{C}$ in AF vs. C), while it was considerably higher during heading and anthesis, and maturity ($+1.6^\circ\text{C}$ and $+1.5^\circ\text{C}$, respectively) ($p \leq 0.05$).

The air relative humidity (RH) showed an opposite daily dynamic than the air temperature. From 6 a.m. to midday (Time2, Figure 2-right), RH was higher in AF than C (significantly from 7 a.m. to 10 a.m.), on average by $+3.4\%$, with a maximum variation at 9 a.m. ($+7.7\%$). Similarly to air temperature, the difference in RH between treatments within Time2 increased over time: it was minimum during stem elongation ($+2.4\%$ in AF vs. C) and maximum during wheat grain maturity ($+6.1\%$ in AF vs. C). From 1 p.m. to midnight (Time3), on the contrary, average RH was lower in AF than under full sun (significantly from 4 p.m. to 9 p.m.), on average by -6.1% , with a maximum variation at 7 p.m. (-9%). Within Time3, when comparing RH during the different growth periods, the difference between treatments was minimum during heading and anthesis (-5.0% in AF vs. C) and maximum during maturity stage (-7.9% in AF vs. C) (Table S3).

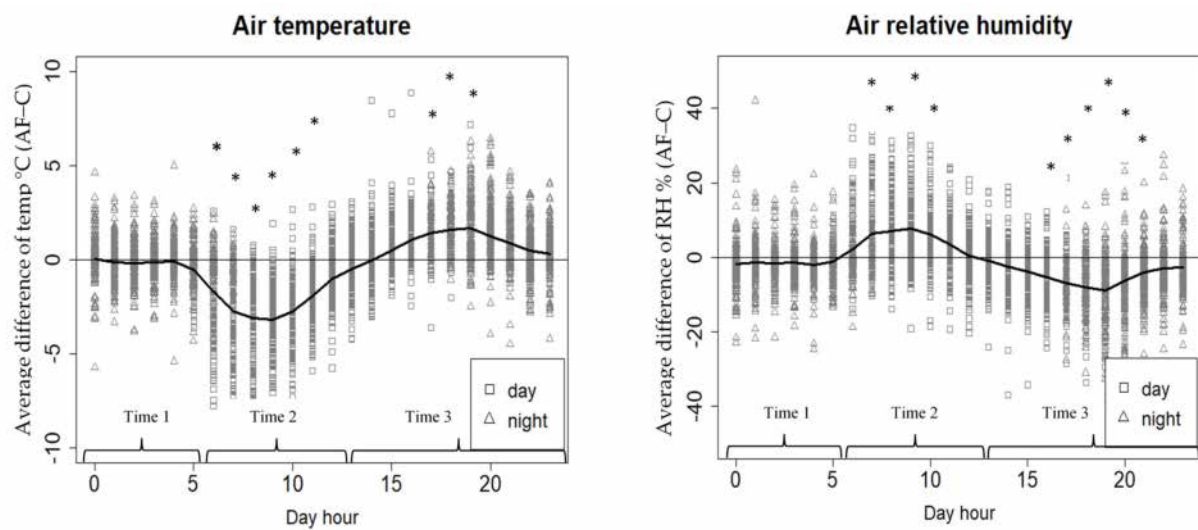


Figure 2. Hourly dynamics of air temperature (temp; **left**) and relative humidity (RH; **right**) recorded in C and AF treatments expressed as AF and C difference: temp.AF-temp.C (°C) and RH.AF-RH.C (%) for each hour of the day during the 2016–17 wheat growing season, from sowing to harvesting. Above the x axis, day length is divided into 3 intervals: Time1 = 12 pm–5 am, Time2 = 6 am–12 am, Time3 = 1 pm–11 pm. For each hour of the day, asterisks indicate a significant difference between values recorded in C and AF treatments ($p \leq 0.05$).

3.3. Wind Speed

Wind speed was significantly reduced in both agroforestry treatments, i.e., by 85.5% and 99.6% in AF and AF+, respectively, compared to open field (2.0 m s^{-1}), as the average between sowing to harvesting in 2017 (Table 1). The greatest difference between AF and C treatments was measured during the latest period of wheat “maturity” (-93% vs. C). In AF+ treatment, wind speed was markedly reduced during all growth stages (average of 0.01 m s^{-1}). Considering the whole wheat cycle, the maximum wind speed values recorded in C, AF and AF+ treatments were 24 m s^{-1} , 9.8 m s^{-1} and 4.5 m s^{-1} , respectively.

Table 1. Average wind speed and number of hours with means and maximum wind speed $> 4.7 \text{ m s}^{-1}$ (17 Km h^{-1}) recorded in C, AF and AF+ treatments within 2016–17 growing season at stem elongation (from sowing to 7 April), heading and anthesis (from 8 April to 10 May) and maturity (from 11 May to harvesting). Within the same cycle period, means with different letters are significantly different according to the Tukey’s HSD test ($p \leq 0.05$).

Cycle Period	Means			Wind Speed			Hourly Max		
	C	AF	AF+	C	AF	AF+	C	AF	AF+
Stem elongation	2.17 ^a	0.37 ^b	0.01 ^c	277 ^a	11 ^b	0 ^c	1083 ^a	142 ^b	0 ^c
Heading and anthesis	2.03 ^a	0.25 ^b	0.01 ^c	37 ^a	0 ^b	0 ^b	327 ^a	13 ^b	0 ^b
Maturity	1.60 ^a	0.12 ^b	0.01 ^c	9 ^a	0 ^b	0 ^b	347 ^a	6 ^b	0 ^c
Average	2.02 ^a	0.29 ^b	0.01 ^c	323 ^a	11 ^b	0 ^c	1757 ^a	161 ^b	0 ^c

When wind speed is above 17 Km h^{-1} (i.e., 4.7 m s^{-1} ; Beaufort Scale Level 3 [52]), the application of chemical treatments is not recommended. Throughout the measurement period (210 days), the number of hours with a maximum wind speed $> 4.7 \text{ m s}^{-1}$ in the Control treatment was 1757 h, (equal to 73 days), the majority of which during stem elongation (1083 h), and a shorter period during heading and anthesis (327 h) and maturity (347). In AF treatment, the number of hours with a maximum wind speed $> 4.7 \text{ m s}^{-1}$ was

161, (equal to 7 days), of which 142 were recorded during stem elongation, while in AF+ treatment this threshold wind speed was never exceeded.

3.4. Edaphic Environment

3.4.1. Soil Moisture Content

Significant differences among treatments were observed on soil water content, which varied depending on the wheat growth stage and soil depth (i.e., 30, 60, 90, and 110 cm). During stem elongation, the mean water pressure potential was below 60 KPa in all the treatments at any depth (Figure 3). Within this period, the water potential decreased significantly from 50 KPa to 10 KPa in all the treatments and at any depth, as a consequence of precipitation and water percolation after any abundant event.

Significant differences among treatments were revealed from the first week of April onwards in both years. During the heading and anthesis time, at 30 cm depth, a significant increase of water potential from 50 KPa at the beginning of April up to 180 KPa on the second week of May was observed in both C and AF treatments, while in AF+ treatment the water pressure potential remained low, just over 40 KPa (as average) in both years. At 60 cm of depth, a different pattern was observed in the two years during heading and anthesis: in 2016, water pressure potential was on average 40 KPa in controls, 55 KPa in AF (+48% vs. C, $p \leq 0.05$) and 22 KPa in AF+ (−41% vs. C, $p \leq 0.05$) (Figure 4); on the contrary, in 2017 a significant increase of water stress was observed under full sun conditions from the first week of April onward, as the water potential of C increased from an average of 50 KPa at the beginning of April up to 300 KPa in the second week of May (Figure 3). During this period, both agroforestry treatments maintained a significantly higher soil water content (+71% in AF and +82% in AF+) as compared to controls. At 90 and 110 cm of soil depth, the water pressure potential of the control treatment during heading and anthesis increased more importantly in 2017 than in 2016; nevertheless, both agroforestry treatments showed a significantly higher soil water content as compared to full sun conditions, with the most shaded treatment (AF+) displaying the greatest effect (on average −35% and −75% of water pressure potential in AF and AF+, respectively).

The greatest differences among treatments were observed during the last period of the wheat cycle, from 11 May to harvesting (end of June), during the grain filling period (Figures 3 and 4). At this time, both C and AF treatments showed a significant increase of water stress in topsoil (30 cm depth), water pressure potential ranging from 180 KPa in the second week of May to >400 KPa at the end of June. Considering that 300 KPa is the reliability limit of the values recorded by the Watermark probes, at 30 cm depth of both C and AF treatments the water pressure potential exceeds this threshold in both years from the last week of May onward, with higher water stress in 2017. The AF+ treatment, instead, showed a significantly higher water content in the topsoil (30 cm) as compared to both C and AF at this time: on average +73% in 2016 and +5% in 2017. From 60 cm to 110 cm of soil depth, the hierarchy in soil water content clearly was AF+ > AF > C from mid-May until harvesting in both years. Regardless of soil depth and year, the most shaded treatment (AF+) showed the lowest water pressure potential.

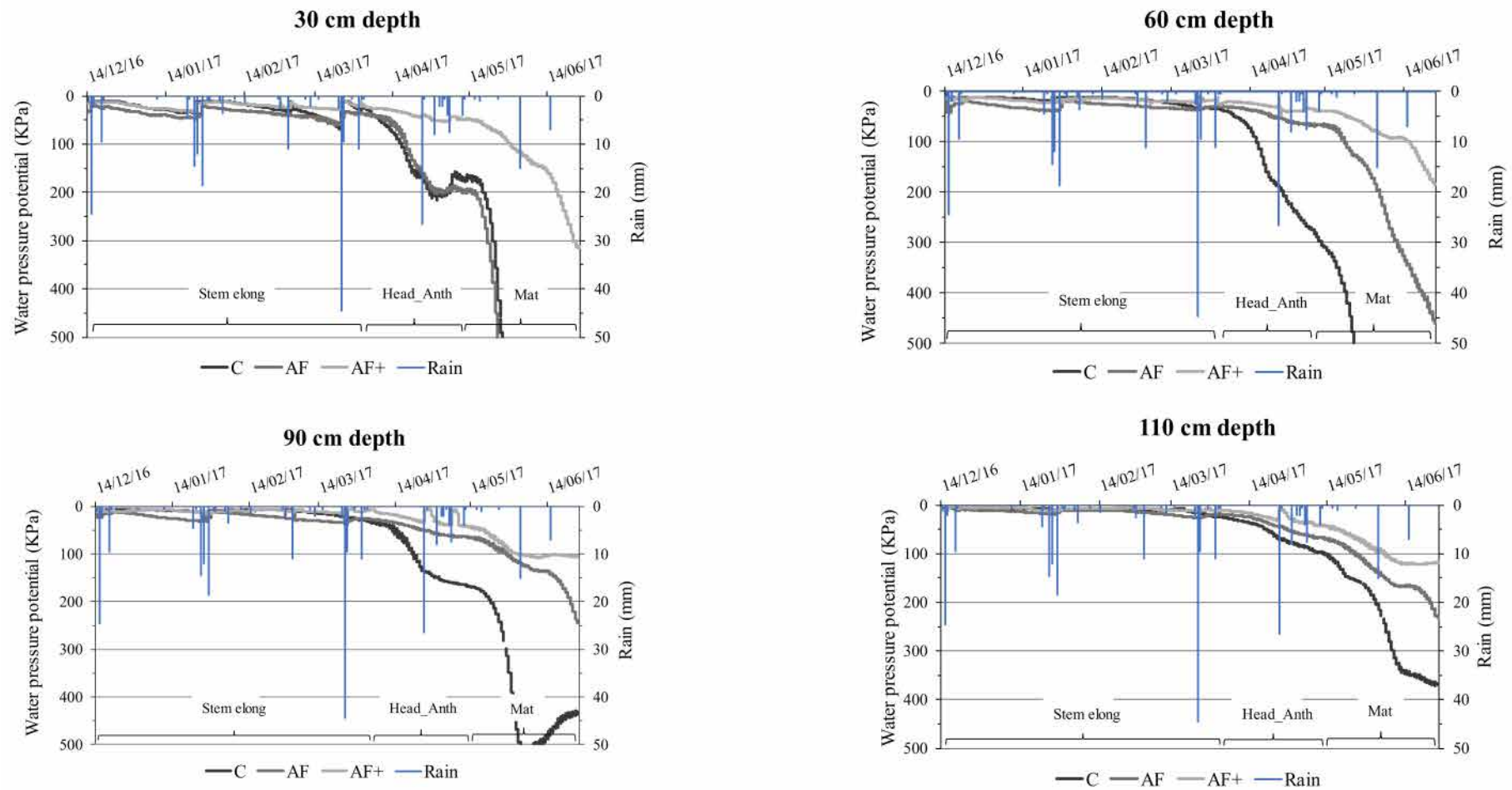


Figure 3. Soil water potential as hourly average pressure potential (KPa) recorded by tensiometers placed in the three treatments (C, AF and AF+) at four soil depths, i.e., 30 (top-left), 60 (top-right), 90 (bottom-left) and 110 (bottom-right) cm, during the 2nd year (2016–17) wheat growing season. Timeline in the x axis is divided into three wheat cycle periods: stem elongation (Stem elong) (from sowing to 7 April), heading and anthesis (Head_Anth) (from 8 April to 10 May) and maturity (Mat) (from 11 May to harvesting). The secondary vertical axis indicates daily rainfall (mm) within the same period.

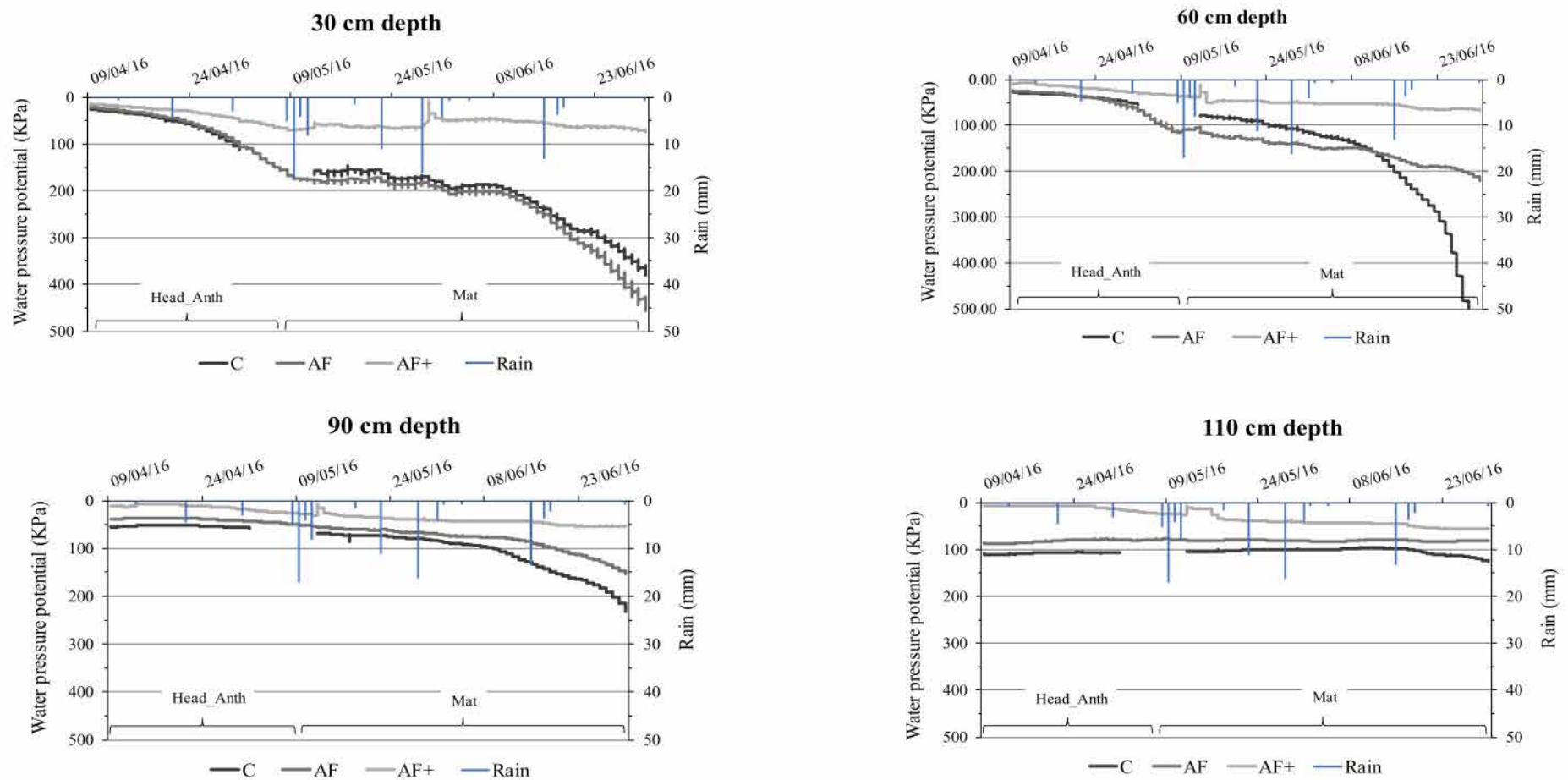


Figure 4. Soil water potential as hourly average pressure potential (KPa) recorded by tensiometers placed in the three treatments (C, AF and AF+) at four soil depths, i.e., 30 (top-left), 60 (top-right), 90 (bottom-left) and 110 (bottom-right) cm, during the 1st year (2015–16) wheat growing season. Timeline in the x axis is divided into three periods: stem elongation (Stem elong) (from sowing to 7 April; data not available in 2015–16), heading and anthesis (Head_Anth) (from 8 April to 10 May) and maturity (Mat) (from 11 May to harvesting). The secondary vertical axis indicates daily rainfall (mm) within the same period.

3.4.2. Soil Fertility

In the first year trial (2015–16), the average soil ammonium (NH_4^+) concentration in the 0–90 cm depth interval was not statistically different among the three treatments, it being 1.8, 1.9 and 2.0 ppm (mg kg^{-1}) in C, AF and AF+ respectively. However, considering the different soil layers, the two agroforestry treatments showed a higher ammonium concentration at 0–30 cm depth (+30% in AF and +23% in AF+) and a lower one at 30–60 cm depth (−21% in AF and −20% in AF+) compared to controls, although it was not significant (Figure 5). A significant increase of $[\text{NH}_4^+]$ was observed in the second year in all the treatments, particularly in the two agroforestry treatments. Indeed, in 2016–17, AF and AF+ had significantly higher soil ammonium concentrations than C in 0–90 cm soil layer. The greatest difference was observed in topsoil (0–30 cm), AF and AF+ having +63% and +75% of $[\text{NH}_4^+]$ vs. C.

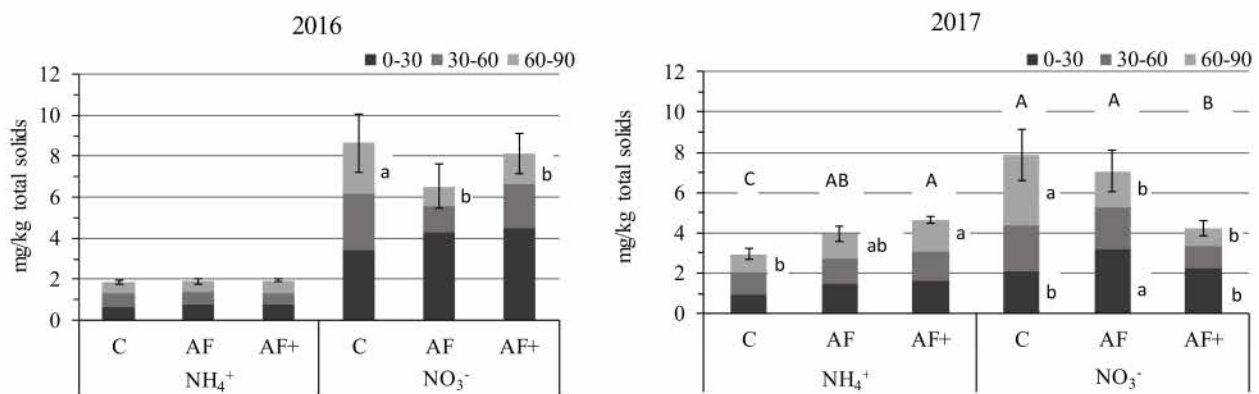


Figure 5. NH_4^+ and NO_3^- concentration (mg Kg^{-1} TS, TS = total solids; mean $\pm$ S.E., $n = 13$) of the soil samples collected in the three treatments (C, AF and AF+) during February both in 2016 (left) and 2017 (right). Each soil sample was divided into three subsamples according to the depth: 0–30, 30–60 and 60–90 cm. Standard error bars refer to the average NH_4^+ and NO_3^- concentration of the entire samples (0–90 cm depth). For each year and each ion, different capital letters indicate significant difference between treatments considering the 0–90 cm soil profile; small letters indicate significant difference between treatments within each of the three-soil subsample (0–30, 30–60 and 60–90 cm), according to Tukey’s HSD test ($p \leq 0.05$).

Unlike $[\text{NH}_4^+]$ dynamics, a general decrease of $[\text{NO}_3^-]$ (−24% on average; 0–90 cm) was observed from the first to the second year. In 2015–16, the nitrate concentration was not significantly different among the three treatments with regard to the 0–90 cm soil profile. However, higher $[\text{NO}_3^-]$ was measured in the topsoil layer (0–30 cm) of AF (+25%) and AF+ (+30%) ($p > 0.05$). Beneath 30 cm of depth, instead, $[\text{NO}_3^-]$ was lower in AF and AF+ than in C, significantly for the deepest soil layer (60–90 cm) (Figure 5). In 2016–17, the average nitrate concentration was similar in C and AF treatments, but significantly lower in AF+ (−47% vs. C) (0–90 cm). When comparing different soil depth intervals, in AF significantly higher $[\text{NO}_3^-]$ values were observed in the 0–30 cm layer (+53% vs. C), whereas lower values at greater depth and significantly for the 60–90 cm interval (−49% and −76% in AF and AF+, respectively, vs. C).

3.5. Mycorrhizal Colonization

All the wheat root fragments (100% of frequency) grown in the two agroforestry treatments were colonized by arbuscular mycorrhizal fungi (AMF), vs. 96% of controls ($p \leq 0.05$; Table 2). The intensity of mycorrhizal colonization, expressed as a percentage of the length of the colonized root fragment, was significantly higher in agroforestry treatments (+51% and +41% in AF and AF+ respectively), as well as the abundance of AMF arbuscules (+74% in AF and +66% in AF+).

Table 2. Mycorrhizal colonization of roots (0–30 cm of depth) of durum wheat growing in the three treatments (C, AF and AF+) collected at heading stage in 2017, expressed as: frequency of mycorrhiza in the root system (% of colonized fragments), intensity of mycorrhizal colonization (% of fragment length colonized) and arbuscular abundance (% of fragment length with arbuscular presence) (n = 18). Average results in AF and AF+ treatments are expressed also in percentage variation as compared to the C treatment. Within a column, means with different letters are significantly different according to Tukey's HSD test ($p \leq 0.05$).

Treatment	Frequency		Intensity		Arbuscular Abundance	
	Mean (%)	%var./C	Mean (%)	%var./C	Mean (%)	%var./C
C	96.4 ^b		43.8 ^b		17.2 ^b	
AF	100.0 ^a	+4%	66.0 ^a	+51%	30.0 ^a	+74%
AF+	99.8 ^a	+4%	61.7 ^a	+41%	28.6 ^a	+66%

Wheat plants in AF showed higher values than AF+, with regard to the three parameters used to describe mycorrhizal colonization, however, it was not statistically significant.

3.6. Durum Wheat Yield and Yield Components

The average yield of the wheat cultivar 1 was reduced by 50% in AF and 76% in AF+ compared to controls C (1.6 t ha^{-1}), as two-year average (Table 3). Concerning the yield components, the number of tillers and spikes per plant and the shoot dry weight were markedly reduced under both the shading treatments, significantly for plant biomass. The most affected yield component was the number of grains per spike: -83% in both agroforestry treatments vs. C. On the contrary, the thousand-grain weight (TGW) was higher in AF ($+12\%$) than in C, although not significantly, while AF+ negatively affected TGW (-30%).

Table 3. Yield and yield components of the durum wheat cultivar 1 in three treatments (C, AF and AF+), as the average of 2015–16 and 2016–17 wheat growing seasons (n = 4). TGW: thousand-grain weight. Yield and yield components in AF and AF+ treatments are also expressed as percentage variation vs. controls. Means with different letters are significantly different according to the Tukey’s HSD test ($p \leq 0.05$).

Treatment	Yield		Tillers/Plant		Spikes/Plant		Grains/Spike		TGW		One Plant Biomass	
	t ha ^{−1}	% var./C	n.	% var./C	n.	% var./C	n.	% var./C	g	% var./C	g DM	% var./C
C	1.6 ^a		2.4 ^a		2.1 ^a		27.2 ^a		52.0 ^{ab}		119.9 ^a	
AF	0.8 ^{ab}	−50%	1.8 ^{ab}	−26%	1.5 ^a	−27%	4.3 ^b	−84%	58.1 ^a	+12%	31.1 ^b	−74%
AF+	0.4 ^b	−76%	1.4 ^b	−39%	1.1 ^a	−49%	4.6 ^b	−83%	36.6 ^b	−30%	23.6 ^b	−80%

4. Discussion

This trial provided useful results on the potential of olive alley systems to provide adequate microclimatic and edaphic conditions for an understorey winter durum wheat, in the context of climate change.

4.1. Air Temperature and Relative Humidity

Air temperature buffering is an important environmental benefit linked to agroforestry practices, with particularly favorable effects in heat-sensitive crops in tropical regions [35,37]. Within tropical agroforestry systems including coffee and *Faidherbia albida* trees, the mitigation of extreme temperatures is considered as a key strategy to designing more resilient and climate-smart farming systems [32,37,53]. However, mitigation and/or adaptation to heat stress is becoming increasingly relevant worldwide, including the Mediterranean area. Here we observed a significant buffer effect between day and night temperatures in the moderate shading agroforestry treatment (AF), as durum wheat cultivated in the olive alleys experienced a lower temperature during the daytime (maximum reduction of 3.2 °C) and higher during the night (maximum +1.7 °C), compared to full sun open field conditions. Recently, the same variation patterns in day and night temperatures were observed in a durum wheat-walnut agroforestry system in the south of France (−1.2 °C and +1.17 °C, respectively, with clear days) [14,54] and in a wheat-poplar AF system in Germany (−3.4 °C during the daytime and +1.6 °C at night) [55]. In our study, the most interesting result was related to the greatest buffering effect observed later in the season, during the grain filling period of wheat, which is the most sensitive to high temperatures and drought, and decisive for productivity and quality.

The effect of olive trees on air temperature showed a high potential towards the improvement of crop resilience to climate changes. However, while reducing daytime temperatures can have beneficial effects on crop growth [32,35], warmer nights may impair wheat growth and yield. García et al. [56] observed a yield reduction of 7% for each °C increase during the nighttime in durum wheat and barley compared to ambient temperatures in growth chambers. In these conditions accelerated development rate and lower carbon assimilation rate, due to higher dark respiration, were suggested by Grant et al. [57]. Durum wheat needs cold temperatures during winter to ensure an optimal tillering [58,59], while warming temperatures during this period are usually translated into a lower number of tillers per plant, as we observed in our study, i.e., −26% and −27% in AF and AF+, respectively.

The relative humidity of air in the alleys showed a day–night pattern similar to that observed for air temperature. Although a higher air relative humidity (RH) is reported among the environmental benefits of agroforestry, this was noticed only during some hours of the day, i.e., from 5 a.m. to midday (maximum +9%). Lin [53] obtained similar results for a longer period of the day, i.e., from 8 a.m. to 16 p.m., in an agroforestry system with coffee trees. According to this author, lower humidity during night hours may have not affected the plants negatively, as daytime measurements are more important in determining water use in plants.

4.2. Wind Speed

The presence of a high population of olive trees had a significant windbreak effect, as wind speed was decreased from −85.5% of yearly pruned trees (AF) to −99.6% with unpruned trees (AF+). Wind speed is of high importance in regulating evapotranspiration, but also to correctly managing chemical and fertilizer applications by foliar spraying. It was not the case in our organic cropping system, but it is well known that the efficiency of spraying depends on the crop stage and the accuracy of irroration. In France, phytosanitary applications are forbidden when wind speed is $\geq 19 \text{ km h}^{-1}$ (level 3–4 in the Beaufort scale), but not recommended even $>17 \text{ km h}^{-1}$. The latter is often exceeded in open fields of the Mediterranean area. In this study, wind speed exceeded this threshold for $>300 \text{ h}$ during the growing season of wheat. The presence of trees drastically reduces wind speed, giving

the chance to choose the most appropriate timing for chemical treatments, and also to reduce drift risks. The greatest windbreak effect was observed during wheat anthesis and grain filling, an interesting result as protection against pathogens is strategic at this time.

4.3. Soil Moisture

Water conservation is considered the most relevant ecosystem service that agroforestry systems can provide [20,47], and it becomes particularly useful in arid and semiarid regions, as in the Mediterranean area. In our study, as expected, soil water availability raised as the shade level increased, despite the tree-crop competition. The severe shading treatment (AF+) had a significantly higher soil moisture level as compared to the other two treatments, regardless of the soil layer considered (within the 0–110 cm profile) and wheat stage. The moderate shading treatment (AF) showed soil moisture contents similar to controls in the arable layer (0–30 cm), but significantly higher in deeper layers. Water conservation in our olive orchard was particularly evident from wheat heading to harvesting when drought events are increasingly frequent in the Mediterranean area and detrimental to crop yield. The beneficial effect of trees on soil moisture conservation is widely documented in tropical and subtropical regions, supporting the negative correlation between shade level and evapotranspiration [60]. A key question in tree-crop interactions is whether trees could uptake water from deeper soil horizons to reduce competition with annual crops in topsoil [32]. In this regard, some authors are also considering the process of hydraulic lift as a possible way for increasing soil moisture in shallow soil layers [60–64]. Although the hydraulic lift has been reported in species such as *Quercus*, *Pinus* and jujube tree with a high contribution in agroforestry farming systems [65–67], scientific evidence is not yet available in temperate climates with olive trees.

Therefore, the preservation of soil moisture recorded in the two agroforestry systems seems to be related to the effects of microclimate buffering exerted by the olive trees during the whole crop cycle, i.e., shading, reduced air temperature for some day hours and wind-break effect. A reduction of soil evaporation and crop transpiration were reported by other authors to explain higher soil moisture [55,61,62]. However, soil moisture conservation is debated in recent literature, as some authors consider water as the main limiting factor in intercropping between woody plants and crops. Gillespie et al. [68], while intercropping maize with oak trees, did not observe yield reductions when belowground competitions for water and nutrients were limited by polyethylene barriers. Wanvestraut et al. [69] confirmed this result and reported a 26% yield reduction in cotton without underground barriers. Although it is difficult to separate the effect of belowground competition for water and nutrients, some authors report that crop productivity in agroforestry systems of semiarid regions is mainly limited by water competition [60,61,68,70]. In this view, our results showing improved soil moisture content are very interesting for increasing crop resilience to climate change. Although root biomass of wheat is mainly confined in the arable layer, the maximum rooting of wheat is 100–120 cm, depending on soil depth and fertility [71]. It is therefore expected that wheat can exploit the greater water availability even in AF, beneath 60 cm of depth.

4.4. Soil Fertility

There is much evidence of the positive role of agroforestry farming in maintaining or improving soil fertility in tropical environments [28,72], while investigations are still lacking in temperate climates [19]. In our study, only soil nitrogen content was considered, as ammonium (NH_4^+) and nitrate (NO_3^-) concentrations across the soil profile. Here we remind that there was not any fertilizer application since the orchard plantation, and therefore nitrogen was mainly delivered by legumes in rotation with durum wheat.

In aerated soils, nitrate is the major nitrogen form [73], and we confirm it was three to four times more abundant than ammonium in this study. $[\text{NH}_4^+]$ and $[\text{NO}_3^-]$ were found higher in agroforestry treatments than in the open field in the arable layer (0–30 cm), thus benefiting wheat. This is probably due to higher soil organic matter as a result of the

additional turnover of olive leaves, fine roots and plant residues in the orchard alleys, as observed by other authors [21,74,75]. However, further studies are required to clarify these processes in our alley-cropping system.

The lower soil nitrate concentration measured within agroforestry treatments when considering the deeper soil profile (60 and 90 cm depth), might be due to mineralization slowdown [76] or to significant competition for this nutrient between wheat and olive trees. Although difficult, further investigations on vertical and horizontal (from the trunk till the center of the alley, where soil samples were taken) root distribution of olive trees, will be useful to better understand if competition for nitrogen is the main belowground limiting factor. Actually, the period of our study was probably short to establish a long-term evolution in soil characteristics with or without wheat intercropping; therefore, it will be useful to continue monitoring nitrogen concentration in the following years to better assess the potential of this agroforestry model in soil fertility in the Mediterranean area [19,77].

4.5. Arbuscular Mycorrhizal Fungi (AMF)

Thanks to the symbiotic association with plant roots, AMF can facilitate the mobilization and acquisition of nutrients, especially the low mobile phosphorus (P), protect plants from pathogens and improve water relations [78–80]. As consequence, investigating the potential contribution of AMF in mediating tree-crop interactions is relevant, especially in low external input systems, like in organic farming. In our study, the roots of wheat intercropped with both the yearly pruned and the never pruned olive trees showed a significantly higher intensity of colonization and arbuscular abundance, as compared to wheat grown in monoculture, an effect possibly related to greater soil moisture. These data corroborate previous results, demonstrating that agroforestry promotes beneficial biological interactions between useful microorganisms and plant species [81–85]. Tree-based intercropping, indeed, is known to act as a reservoir for an abundant mycelial network for crops [86], and also to enhance the richness of AM fungal communities compared to monoculture [87]. AMF are known to improve active nutrient acquisition, including N, as well as other processes, such as enlarging soil volumes for nutrient access, changing P absorption kinetics and solubilization, and improving soil aggregation and stability [83,86,88]. Our results contribute to providing evidence of the high potential of agroforestry to create favorable conditions for AMF root colonization, thus improving soil characteristics and plant nutrition.

4.6. Durum Wheat Performances

Despite the positive impact of agroforestry treatments on the microclimatic conditions and edaphic environment, durum wheat yield was significantly reduced when intercropped with olive trees; productivity was halved in the moderate shading treatment (AF) and decreased even by 76% in the severe shading treatment (AF+). Among yield components, the most affected by agroforestry conditions was the number of grains per spike, which derives by the number of fertilized flowers per spike, which is determined at anthesis and strongly dependent on the PAR availability. The two agroforestry systems of our study were characterized by an average PAR reduction of −30% and −51% respectively in the moderate (AF) and severe (AF+) shading treatments, compared to full sun conditions. These shading levels are similar to those recorded in other alley-cropping designs within temperate climates [68,89,90]. In a walnut-durum wheat intercropping located at Restinclières, 20 km N from our study site, a PAR reduction comparable to our AF, i.e., −31%, led to a similar wheat yield reduction, i.e., −50% [90]. In recent studies, severe shading was linked to a decrease in stomatal conductance and photosynthetic rate [91]. Low shading levels, on the contrary, may increase the fraction of diffuse light, which is more efficiently used by plants, and might enhance CO₂ uptake, photosynthesis and plant growth. With PAR reduction below 15%, Li et al. [92] observed enhanced plasticity of light-harvesting variables (leaf area, pigment contents, canopy architecture), and increased wheat yield. In this way, it is crucial to identify appropriate tree-crop combinations in order to define the most

suitable system designs, and to manage tree growth properly to limit PAR reductions for the understorey crop. Li et al. [89] highlighted that tree growth and pruning, tree row orientation and spacing, and also tree phenology can reduce significantly the extent of shading. For instance, by intercropping durum wheat with Paulownia trees, these authors recorded PAR reductions by -22% , -44% and -56% during flowering, grain filling and maturity, respectively. The association of a winter cereal and a late sprouting deciduous tree species showed to be favorable, as walnuts budburst occurs when wheat has already reached the maximum leaf area index. On the opposite, olive trees, as evergreen species, lead to significant shade on the understorey cereal during its whole growth cycle. The orientation of tree rows has also an impact, N-S orientations being less competitive for light than E-W [55,68,90,93], especially at high and medium latitudes [94]. In this experiment, therefore, the NW-SE orientation of trees might have led to a higher shade impact than ideal N-S orientation. The distance between the olive tree rows (6 m both in AF and AF+) is common in the Mediterranean region for olive orchards, but is particularly challenging for the growth and development of the associated crop. The narrow inter-rows combined with the ever-green trait of the trees increased tree-crop competition for soil resources, but mainly for light. Therefore, the strong reduction of crop biomass observed in agroforestry was presumably due to the decrease of light availability, and this may also explain the higher soil water content measured in the alleys. It is not a speculation to hypothesize that a larger inter-row could reduce light competition and improve wheat productivity, with better exploitation of soil moisture. There are several examples in the literature of silvopastoral agroforestry systems in a temperate climate with larger inter-rows (from 15 to 90 m) [14,90,95,96], where the authors investigated the effect of the distance from the tree line on light availability, crop physiology and yield [95–97]. We agree on the relevance of AF design and management in order to modulate the occurrence and the magnitude of multiple potential interactions between trees and intercrops. This trial anyhow contributed to evidence the high potential of olive alley systems to provide adequate microclimatic and edaphic conditions for an understorey winter durum wheat, in the context of climate change. The screening of cereal ideotypes for agroforestry conditions, taking advantage of participatory ecobreeding approaches [98], and searching for useful traits, will further contribute to improving the sustainability of alley-cropping farming systems.

5. Conclusions

The sustainability of organic olive groves in the Mediterranean area and their ability to provide a microclimatic and edaphic environment suitable for an associated understorey crop, such as durum wheat, were the challenging questions at the origin of this study. These results demonstrate the high potential of olive alley-cropping systems to provide relevant ecosystem services regarding temperature buffering, windbreak effects and soil water conservation, which are strategic in drought-stressed areas, such as the Mediterranean one. Olive trees were also able to modify the edaphic environment by creating favorable conditions for arbuscular mycorrhizal fungi growth, which is fundamental in low-input farming systems to enhance plant nutrient uptake. However, these microclimatic and edaphic changes were not translated into higher yield in the considered durum wheat variety. The strong competition for light due to the narrow inter-row and to the evergreen trait of olive trees appeared as the main limiting factor. A key strategy to promote the reintroduction of alley-cropping systems mixing olive trees and cereals in the Mediterranean area is to adopt olive alley-cropping designs with larger inter-row in order to decrease the shade pressure on crops; however, this would also act on microclimate and edaphic parameters, probably reducing the extent of buffering and windbreak effects. An optimal compromise between the requirements of the crop and the tree components remains to be assessed and requires further investigations.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agronomy12020527/s1>, Figure S1. Location of the experimental site in the South of France (a, b), 15 km east from Montpellier; the fields hosting the three treatments (C, AF and AF+) at the INRAE experimental station (c); and the durum wheat–olive trees intercropping in AF and AF+ treatments (d).; Table S1. Dates of sowing and harvesting of durum wheat, and average values of the main climatic indicators recorded between sowing and harvesting dates in 2015–16 and 2016–17 growing seasons. Climatic data are from a Meteo–France weather station located at the INRAE station, 100 m from the experimental fields.; Table S2. Details of the sensors used for recording microclimatic and edaphic parameters in the 3 treatments (C, AF, and AF+) from wheat sowing to harvesting during 2015–16 and 2016–17 growing seasons; Table S3. Average air temperature and relative humidity recorded in C and AF treatments within three times of the day (Time1 = 12 p.m.–5 a.m., Time2 = 6 a.m.–12 a.m., Time3 = 1 p.m.–11 p.m.), during 2016–17 growing season at stem elongation, heading and anthesis, and maturity. Within the same wheat cycle period and time of the day, air temperature (°C) and relative humidity (%) are also expressed as difference between AF and C treatments. For each microclimate parameter, in a same line, different letters indicate significant difference according to the Tukey’s HSD test ($p \leq 0.05$).

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